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Final report on sustainability assessment results of INNTERESTING solutions

WP6, Task 6.3

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Authors:	Wai Chung Lam, Karolien Peeters, Mohammed Nazeer Khan, Sofie De Regel, Veronique Van Hoof, Carolin Spirinckx (VITO)
Contributors:	Mireia Olave, Mario Alvarez (Ikerlan) Mikko Järvinen, Taneli Rantala (Moventas) Helena Ronkainen (VTT) Jone Irigoyen (Basque Energy Cluster) Arkaitz Lopez, Aitor Zurutuza (Laulagun)

Document History

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DoA	Based on the work done in the technical work packages, the assumptions and screening assessment made in Task 6.2 will be validated and completed in order to finalise the iterative sustainability assessment within this project. The S-LCA will consider the stakeholder groups local communities and society and assesses the consequences of the implementation of the new technology for these stakeholder groups.		
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20/12/2022	0.1	VITO	Draft for internal review
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Abbreviations and acronyms

Acronym	Description
ABEX	Abandonment expenditure
AEP	Annual Energy Production
BAU	Business-As-Usual
BOP	Balance Of Plant
CAPEX	Capital expenditures
CS	Case Study
CSP test	Component-Scale Performance test
DALYs	Disability Adjusted Life Years
DEVEX	Development expenditure
EMS	Environmental Management System(s)
EOL	End Of Life
eq.	Equivalent
FU	Functional Unit
JBL test	Journal Bearing Laboratory-scale test
LCA	(environmental) Life Cycle Assessment
LCC	(economic) Life Cycle Costing
LCI	Life Cycle Inventory (analysis)
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Cost Of Energy
LCSA	Life Cycle Sustainability Assessment
NORCOWE	Norwegian Centre for Offshore Wind Energy
O&M	Operations and Management
OEM	Original Equipment Manufacturer
OPEX	Operational expenditures
PSILCA	Product Social Inventory Life Cycle Assessment
RCF	Rolling Contact Fatigue
RE test	Rolling Element test
RS	Reference Scenario
RSF	Ring Structural Failure
RWT	Reference Wind Turbine
SETAC	Society of Environmental Toxicology and Chemistry
S-LCA	Social Life Cycle Assessment
S-LCIA	Social Life Cycle Impact Assessment
UNEP	United Nations Environment Program

Executive summary

This deliverable is the final report of WP6 of the INNTERESTING project. WP6 revolves around the environmental, social and economic assessment of the three cases 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 have been developed. In addition, hybrid testing methods have been 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) has been performed iteratively in WP6.

This report describes the final results of the LCSA of the two case studies in combination with their hybrid testing methods in comparison with the business-as-usual reference scenarios, i.e. case 1 regarding pitch bearings and case 2 regarding the gearbox.

The proposed hybrid testing methods are significantly cheaper, less time-consuming, and have much smaller impacts on the environment and social risks when comparing them with the BAU testing methods. Although, when allocating the impacts of the testing to one wind turbine, the impacts are insignificant compared to impacts caused by the initial material use of the whole turbine. Nevertheless, with the proposed hybrid testing methods the reliability of the design of critical components is increased which is a necessity to ensure a longer lifetime of the components and as a result also ensuring a longer service life of the wind turbine. The prolongation of the service life and reduction of the down-time of a wind turbine due to the proposed solutions have a more significant effect. In that case, the energy production will be significantly higher which consequently will reduce the environmental, economic and social impacts per kWh generated with the wind turbine.

Additionally, this report also includes the final results of the LCSA of the third case study regarding the developed repair and stiffening concept for lifetime extension of existing pitch bearings. The proposed repair and stiffening solution compared to the BAU replacement process is relevant in the year in which the failure occurs, which is mainly due to the reduced down time. However, when looking at the total service life of the wind turbine, the differences between RS3 and CS3 are considered as small.

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 have been 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 have been developed for the two mentioned critical components 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) has been 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, and economic aspects of wind turbines are assessed respectively (see Figure 1). By doing so we have gained 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.
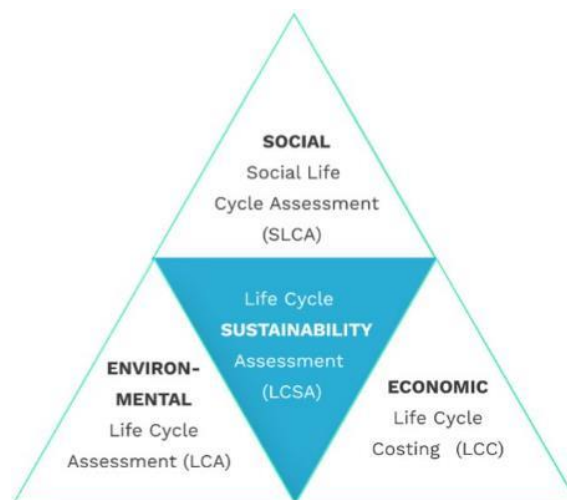
Work Package 6 of the INNTERESTING project is fully dedicated to the execution of the LCSA and consists of three tasks corresponding with the three LCSA iterations that have been performed throughout the project:

- 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) (ended in June 2022).
- Task 6.3: validation/final assessment of the INNTERESTING solutions.

This report (D6.3) describes the results of Task 6.3 of the INNTERESTING project.

1.1. Purpose and content of this deliverable

As mentioned above, D6.3 presents the results of the final iteration of the LCSA of the INNTERESTING solutions. The purpose of assessing the INNTERESTING solutions is to gain insights in the environmental, economic, and social performance during their life cycle (see Figure 2).

Figure 2: The life cycle of a wind turbine

(image from WindEurope)
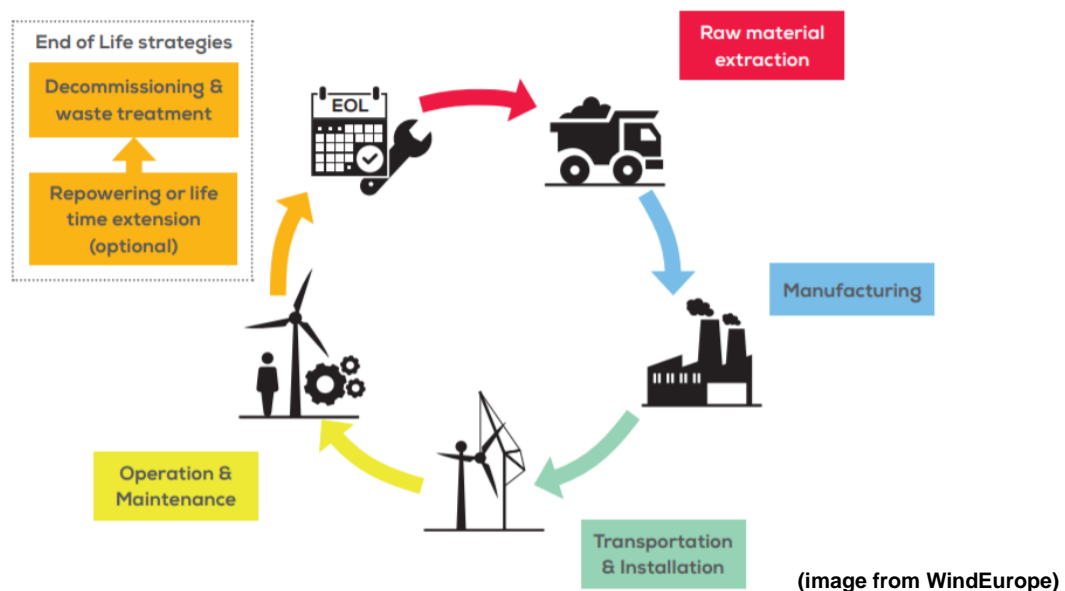
The three case studies are presented in the next figure. For more technical information on the three case studies, please refer to section 6 of D1.1[2] (page 60-73).

Figure 3: The three case studies of the INNTERESTING project.
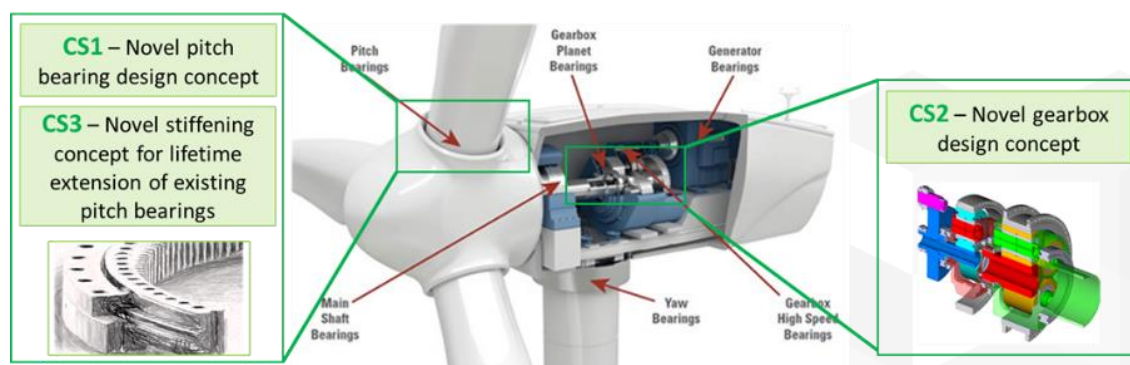
1.1.1. Structure of this deliverable

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

- Subsection 1.2 summarises the overall approach of the LCSA and gives the updated methodological aspects (with respect to the approach of the previous LCSA iterations).
- Section 2 describes the overarching general goal and the scope of the LCSA.

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[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

- Section 3, 4 and 5 are dedicated sections with regard to LCSA case 1, case 2, and case 3 respectively. Each case consists of a case study (CS) for which technological developments have been made in the project and a corresponding BAU reference scenario (RS). The cases are:
    - CS1 – novel pitch bearing design and hybrid testing method for pitch bearings – in comparison to the BAU RS1 with BAU ball pitch bearings and a current blade bearing testing method.
    - CS2 – novel gearbox design and hybrid testing method for gearboxes – compared with the BAU RS2 with BAU gearbox design and current full-scale gearbox testing method.
    - CS3 – novel repair and stiffening concept for lifetime extension of existing pitch bearings – compared with the BAU RS3 in which failed pitch bearings are replaced after redesign.

  Each section presents: the scope, (restricted) overviews of the collected life cycle inventory (LCI) data, the life cycle impact assessment (LCIA) results including the interpretation of them, and conclusions of the comparative LCSA of each case.
- Section 6 concludes this deliverable with the general conclusions and recommendations for further research.

1.2. Overall methodological approach

The methodological framework of the LCSA was extensively described in section 1.2 of D6.1[3] (page 14-26). As main framework for the LCSA the ISO standards 14040:2006 and 14044:2006 are applied. In addition:

- the LCA is in line with the EN 15804:2012+A2:2019 standard (CEN/TC 350, 2019),
- the LCC methodological rules are based on SETAC "Environmental Life Cycle Costing: a code of practice" (Swarr et al., 2011), and
- in the S-LCA the UNEP/SETAC Guidelines for S-LCA (Benoît-Norris et al., 2020; UNEP/SETAC, 2009) are applied.

Please refer to section 1.2 of D6.1[3] for the full methodological framework. The following methodological aspects have been changed in Task 6.3 compared to Task 6.1, mainly due to updates of software or databases:

- In the LCA:
    - Used software package: SimaPro version 9.3.0.3 (instead of version 9.1.0.7).
    - Used generic LCI database: ecoinvent 3.8 (instead of 3.6).
    - Regarding the environmental impact category 'water use', the older 'water scarcity/use' LCIA method is used in the LCA calculations of D6.3 (instead of applying the most current LCIA method). This is done as the most current LCIA method calculates big environmental benefits (i.e. negative loads) caused by

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[3] D6.1 can be downloaded via: http://www.innterestingproject.eu/downloads/d6-1-report-on-sustainability-assessment-of-bau-reference-situation.pdf

the water scarcity factor for Saudi Arabia which is many times higher than the global water scarcity factor[4]. Which results in an environmental profile for the category 'water use' that is difficult to explain and difficult to link with the assessment subject.

- In the LCC:
  - o No methodological changes.
- In the S-LCA:
  - o Used software package: SimaPro version 9.3.0.3 (instead of SimaPro version 9.1.0.7).
  - o The materiality assessment performed in D6.1 identified 'Fair salary' and 'Health and safety (workers)' as the two most material subcategories for the product group (see subsections 1.2.3.2 – 1.2.3.4 of D6.1, page 22-26). In addition to these two material subcategories, this deliverable also reports in more detail on the stakeholder categories 'Local communities' and 'Society', because of the consortium's interest in these two stakeholder categories (see below for the descriptions of the two additional stakeholder categories).

By applying this methodological approach the results of the LCSA will be expressed in:

- the sixteen main environmental impact indicators in line with the EN 15804+A2:2019, such as Global Warming Potential (in unit kg CO_2 eq.), resulting from the LCA,
- the Levelized Cost of Energy (LCOE) as result a from the LCC, and
- social risk and opportunity indicators (expressed in medium risk hours), focussing on those relevant to the sector, calculated with the S-LCA.

The LCA results will be classified in the life cycle stages/information modules based on the modular approach of the EN 15804+A2:2019. The considered modules are:

- A1-A3 production stage consisting of raw materials, their transport, and the manufacturing process;
- A4 transport to the site;
- A5 installation/assembly;
- B2 maintenance;
- B5 refurbishment;
- B6 operational energy use;
- B7 operational water use;
- C1 demolition/deconstruction,
- C2 transport to end of life (EOL), and
- C3-C4 EOL processes consisting of waste processing and disposal.

The next sections describe in more detail the stakeholder categories 'local communities' and 'society' together with their subcategories and indicators as available in PSILCA (Product Social Impact Life Cycle Assessment database). The subcategories 'Fair salary' and 'Health and safety' affecting the stakeholder group workers are described in D6.1 (page 25-26).

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[4] Based on personal communication with the helpdesk of SimaPro, the following explanation can be given: the benefits are related to background processes implemented in datasets used in the developed LCA models that consider electricity used from all over the world, including Saudi Arabia. Electricity in Saudi Arabia is made by using cooling water while returning more water caused by their import of decarbonised water from the global market. The imported water is characterized with a much lower factor and the net Saudi Arabian water flow (i.e. given more water back to nature) is characterized by a really negative factor, hence the negative loads.

• **Stakeholder category 'Local communities' in PSILCA**

This stakeholder category aims to assess the social risks encountered by local communities. Together with the stakeholder category workers, this subcategory is frequently included in existing social life cycle assessment studies (UNEP, 2020). The subcategories for this stakeholder group are: 'Access to material resources', 'Respect of indigenous rights', 'Safe and healthy living conditions', 'Local employment' and 'Migration'. The subcategories and indicators used to quantify the social risk in each of the subcategories are shown in Table 1. The subcategories and indicators are those put forward by PSILCA for this stakeholder group.

There is an overlap between some of the indicators in Table 1 and the environmental impact indicators of the life cycle assessment. Quantification of those indicators with environmental life cycle assessment is typically done with greater precision. It concerns the indicators 'level of industrial water use', 'extraction of material resources (other than water)' and 'contribution of the sector to environmental load' – indicated in grey text colour in Table 1. Results for these three indicators are not discussed in the sections on S-LCA, we refer the reader to the results regarding the impact category 'water use' presented in the LCA.

Table 1: Subcategories and indicators for stakeholder category 'Local communities'.

Subcategory	Indicator
Access to material resources	Level of industrial water use
	Extraction of material resources (other than water)
	Certified environmental management systems
Respect of indigenous rights	Presence of indigenous population
	Human rights issues faced by indigenous people
Safe and healthy living conditions	Contribution of the sector to environmental load
	Pollution level of the country
	Drinking water coverage
	Sanitation coverage
Local employment	Unemployment rate
Migration	International migrant workers in the sector
	International migrant stock
	Net migration rate

The indicator 'certified environmental management systems' assesses the number of certified environmental management systems (EMS) per sector, in relation to the number of employees in the same sector. This indicator is an indication for the engagement of companies to mitigate environmental and therefore health impacts (Eisfeldt and Ciroth, 2018).

The indicator 'presence of indigenous population' serves to verify if this stakeholder group, indigenous population' is a relevant group for the country and its industry sectors. This indicator is evaluated together with the indicator, 'human rights issues faced by indigenous people', because the latter is only relevant when an indigenous population is present. Results for 'indigenous rights' are shown at subcategory level and are supposed to describe and assess the legal situation of indigenous people (Eisfeldt and Ciroth, 2018).

The indicator 'pollution level of the country' assesses the overall level of pollution in a country in order to describe the situation in that a company or industry is operating, providing evidence on the importance of clean economic activities and compensation efforts. The indicator 'drinking water coverage' assess the availability and accessibility of uncontaminated water for domestic use. The indicator 'sanitation coverage' evaluates the proportion of the population

which has access to improved and safely managed sanitation facilities, implicitly measuring the risk exposure to infectious diseases and epidemics (Eisfeldt and Ciroth, 2018).

The 'unemployment rate' within a country is taken as a measure for the evaluation of the share of work force hired locally and for the percentage of spending on locally based suppliers (Eisfeldt and Ciroth, 2018).

Finally, the subcategory migration is measured with three indicators. The indicator 'international migrant workers in the sector' provides information on the share of international migrant workers of the total employed population and can be seen as an indication of potential conflicts. It has to be evaluated together with the indicator 'international migrant stock', which serves to put into perspective the share of migrant workers in the labour force. The 'net migration rate' gives an idea on the number of persons entering and leaving a country, it should be close to 0% in order to maintain labour markets stable (Eisfeldt and Ciroth, 2018).

- **Stakeholder category 'Society' in PSILCA**

This stakeholder category evaluates the social risks incurred by society as whole. The subcategories and indicators available in PSILCA to evaluate this stakeholder category are provided in Table 2.

Table 2: Subcategories and indicators for stakeholder category 'Society'.

Subcategory	Indicator
Contribution to economic development	Contribution of the sector to economic development
	Public expenditure on education
	Illiteracy rate
	Youth illiteracy rate
Health and safety (society)	Health expenditure
	Life expectancy at birth
	Net migration rate

The indicator 'contribution of the sector to economic development' assesses to what extent the sector contributes to the economic development of a country. It is an opportunity indicator and gives information on a positive impact. 'Public expenditure on education' is expressed as percentage of the gross domestic product and is an indication for fair and equal access to education for all social strata. 'Illiteracy rate' and 'youth illiteracy rate' aim to assess the effectiveness of the primary education system in a country, with youth illiteracy being more focused on the current primary education system (Eisfeldt and Ciroth, 2018).

The indicator 'health expenditure' assesses the health system in a country and as such a countries ability to combat disease and improve health of populations. The indicator 'life expectancy at birth' is a useful indicator to reveal critical living conditions in different countries and can be an indication of a good/bad national health system (Eisfeldt and Ciroth, 2018).

2. Overarching goal and scope, and data assumptions of the LCSA

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[5].

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[5] Section 7.2 of D1.1 (page 74-75) includes a mapping of identified stakeholders for this project.

2.2. Scope of the LCSA

The product system under study is like in D6.1: a wind turbine (excluding balance of plant (BOP) for the LCA and S-LCA and including the BOP for the LCC[6]) developed, produced, installed, used and decommissioned on the European market.

In the first iteration of the LCSA (see D6.1) the three BAU reference wind turbines were assessed – with specific data on the pitch bearing and the gearbox but without any testing methods – i.e. one RS per CS. The final LCSA iteration reported in this report consists of a revision of the BAU RSs including an assessment of the BAU testing methods and the assessment of the INNTERESTING solutions including the hybrid testing methods.

The specific functional unit and characteristics of each case are given in subsections 3.1, 4.1 and 5.1 regarding case 1, case 2 and case 3 respectively. 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 the 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 general functional unit (FU) is still 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. As mentioned above, this FU is made specific per case in dedicated sections per case.

Figure 4: Illustration of the scope of the LCSA.
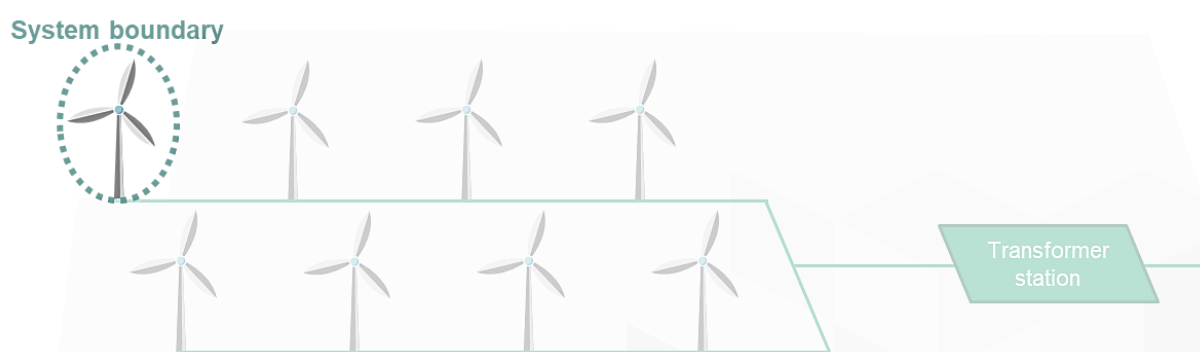
- **System boundaries**

The system boundaries have stayed the same compared to the previous LCSA iterations. Please refer to Table 8 of D6.1 (page 29) for the full details on the defined system boundaries.

2.3. General data assumptions in LCI of all cases

This subsection describe the data assumptions that have been updated in comparison to D6.1.

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[6] This difference in scope between the LCA and the other two parts of the LCSA was initially not preferred, but after some consideration the BOP was included in the LCC so, if desired, the LCC-results could be compared with LCC-results of other wind energy (research) projects. The BOP could not be included in the other LCSA parts due to a lack of environmental LCI data on the components of a BOP.

- **General scenario assumptions**

For the production location of the different components we have assumed that for all three cases the gearbox is produced in Finland and the pitch bearings and other components are made in Spain. The BAU as well as the hybrid prototype testing of case 1 is assumed to occur in Spain. Regarding the testing of case 2, it is assumed to take place in Finland. No impact of prototype testing is included in case 3, as the focus of that case is on the novel repair and stiffening concept for lifetime extension of existing pitch bearings. Each specific scenario per case is described in the introduction of the sections dedicated per case.

- **Specific (foreground) and generic (background) data**

Within LCSA, a difference is made between specific (foreground) data and generic (background) data. For all three parts of the LCSA, the foreground data concerns data for specific components (i.e. the pitch bearings in RS1 and RS3, and the gearbox in RS2), the different other wind turbine components (e.g. the tower, blades, etc.), and the testing methods. More specifically, for LCA it concerns the amount and type of input and output flows (such as materials, energy use, waste, etc.) and for the LCC and S-LCA it concerns cost data.

Regarding the LCC, foreground cost data for the wind turbine components (other than the specific components) were collected through literature review such as technical reports and scientific papers, as described in D6.1. The S-LCA uses the same foreground cost data as the LCC. Foreground data about risks occurring during the different life cycle steps, for example, on worker conditions have been collected from two companies, being a company producing gearboxes and a company producing pitch bearings. For all other steps in the life cycle, this study makes use of the risks levels from the PSILCA v2 database. The database makes use of the Eora multi-regional I/O model (Eora, 2015) with the reference year 2015.

Background data concerns data of processes that are input or output flows to foreground processes in which the foreground process has no or indirect influence (e.g. the production process of the steel used in the specific components or of the trucks used for transport). The generic data for this study have been taken from the ecoinvent 3.8 and PSILCA v2 database for the LCA and S-LCA respectively.

- **Economic parameters**

Regarding the LCC, the following economic input parameters and assumptions have been applied.

LCOE comparisons between wind turbine cases require the same starting point. Therefore, the investment date in year 2019 is selected as the date of comparison (year 0). Energy production starts in year 2020 (year 1) and continues over the reference service lifetime over the wind turbine until year 2044 (year 25) for CS1 or year 2039 (year 20) for CS2 and CS3. The abandonment of the wind farm is assumed to take place in year 2044 or 2039 respectively.

The average inflation is assumed to be 2% and constant over the lifetime of the wind turbine. For discounting, a WACC (weighted average cost of capital) is used to reflect the market value of both equity and debt and to include project risk and return yield of the wind farm. For this study, the nominal WACC is set to 7.5% and is assumed to be time independent. Exchange rate conversions to EUR 2019 are based on International Revenue Service[7] data. To forecast

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[7] https://www.irs.gov/individuals/international-taxpayers/yearly-average-currency-exchange-rates

the residual value of wind turbine components at decommissioning, Worldbank Commodities Prices Forecasts[8] are used.

Regarding the S-LCA, all prices have been recalculated to USD 2015 (as the database makes use of the Eora multi-regional I/O model with reference year 2015). To adapt prices from reference year 2019 to reference year 2015, the following sources have been used:

- For wind turbine components: according to price evolutions reported in IRENA (2019);
- For transportation a 2% inflation has been considered;
- For installation: price level kept constant between 2015 and 2019 after comparison of assembly and installation cost for the years 2010, 2014, 2015, 2016, 2017 and 2018 reported by NREL (Tegen et al., 2012; Moné et al., 2015; Mone et al., 2017; Stehly et al., 2017; Stehly et al., 2018; Stehly & Beiter, 2020). A decrease was observed between 2010 and 2014 and a slight increase between 2014 and 2018, however no general trend was observed;
- For maintenance a 2% inflation has been considered;
- For end-of-life, 2015 scrap values were used.

The S-LCA study makes use of the same cost data as the LCC study, however, the costs considered in the S-LCA are valid for the year 2015 and costs occurring in future have not been discounted. The cost for maintenance, for example, is multiplied with the life span and not discounted. The scope of the S-LCA study is the same as the scope of the LCA study (as mentioned in section 2.2). The costs for installation, transport to installation and maintenance considered in the S-LCA study relate to the turbine only (and not the BOP).

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[8] http://pubdocs.worldbank.org/en/633541587395091108/CMO-April-2020-Forecasts.pdf

3. LCSA case 1

The scenario depicted in Figure 5 of RS1 and CS1 has been analysed as first comparative case of the LCSA within this project. This figure shows that the year 2020 is taken as starting date of operation of the wind turbine, while wind turbines with a nominal power of 20 MW is not yet current practice and prognosed to be a possible maximum size from 2030 onwards (see section 2.8 of D1.1; page 38-39). The reason behind this is that if 2030 would be taken as starting date it will increase the uncertainty due to additional assumptions and for LCOE comparisons between cases it is required that the same starting point is considered. In addition, the conclusion of the comparison will not change with a later starting date. As the difference between RS1 and CS1 would still be similar.

Figure 5: Scheme of the assessed scenario of the comparison between RS1 and CS1.

2019: investment date / (finalising) product development process of 20 MW offshore wind turbine

BAU **full-scale prototype testing** with Windbox blade bearing test bench	**INNTERESTING** **experimental hybrid testing** consisting of: - Rolling contact fatigue (RCF) test - Ring structural fatigue (RSF) test - Rolling element (RE) test

2020: start operation of 20 MW offshore wind turbine in NORCOWE

BAU Ball pitch bearings of current BAU technology 25 years of service life	**INNTERESTING** Innovative pitch bearing with a new rolling element design 40 years of service life

End of 2044: end of operation	**Beginning of 2045**: overhaul
BAU Decommissioning of the wind turbine	**INNTERESTING** Refurbishment of the wind turbine 6 months downtime

End of 2059: end of operation

INNTERESTING Decommissioning of the wind turbine

In the scenario of CS1, the service life of the innovative pitch bearing is 40 years due to a new rolling element design and a better reliability due to hybrid testing method that has been applied

instead of the BAU full-scale prototype testing. We have included an overhaul in the beginning of 2045, as the service life of the other wind turbine components generally ranges from 20-25 years. To extend the service life of the other components to 40 years, an overhaul or refurbishment is required (Danish Wind Industry Association, 2003). Therefore, a refurbishment period of 6 months was assumed. More details over the assumed overhaul are included in subsection 3.2.

3.1. Scope RS1 and CS1

- **Functional units RS1 and CS1**

The table below gives the specific FU of RS1 and CS1 based on the general FU and the parameters considered to calculate the total electricity output of the two wind turbines.

Table 3: Specific FU and electricity output parameters of RS1 and CS1

	RS1	**CS1**
Specific FU	1 kWh of the total electricity output delivered to the grid over the service life of **25 years** by a 20 MW offshore wind turbine with **BAU ball pitch bearings** which was prototype tested in a **full-scale BAU blade bearing test**	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** which was prototype tested with the **INNTERESTING hybrid testing method for pitch bearings**
Capacity factor	49.1%[9]	Same as BAU
Annual Energy Production (AEP)	86 023.2 MWh/y[10]	Same as BAU
Total energy output	2 150 580 000 kWh	3 397 916 400 kWh

- **Specifications RS1 and CS1**

The next table and figure present the assumed specifications of the wind turbine and wind farm of case 1.

Table 4: Specifications of the Reference Wind Turbine (RWT) and wind farm of RS1/CS1.

Dimensions wind turbine	276 m rotor diameter 160 m hub height 3 blades
Assumptions wind farm	Located in NORCOWE virtual wind farm, at the Danish-German border Total capacity of 100x20 MW
Specific component RS1	BAU ball pitch bearing with a diameter of 7 m Specific data provided by Laulagun Bearings SA
Specific component CS1	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)

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[9] Calculated based on an annual energy production (AEP) of 86 GWh/year (Ashuri et al., 2016).
[10] Calculated based on the capacity factor.

Figure 6: Left – Schematic view of the 20 MW RWT (Ashuri et al., 2016).
Right – Location of the NORCOWE virtual wind farm.
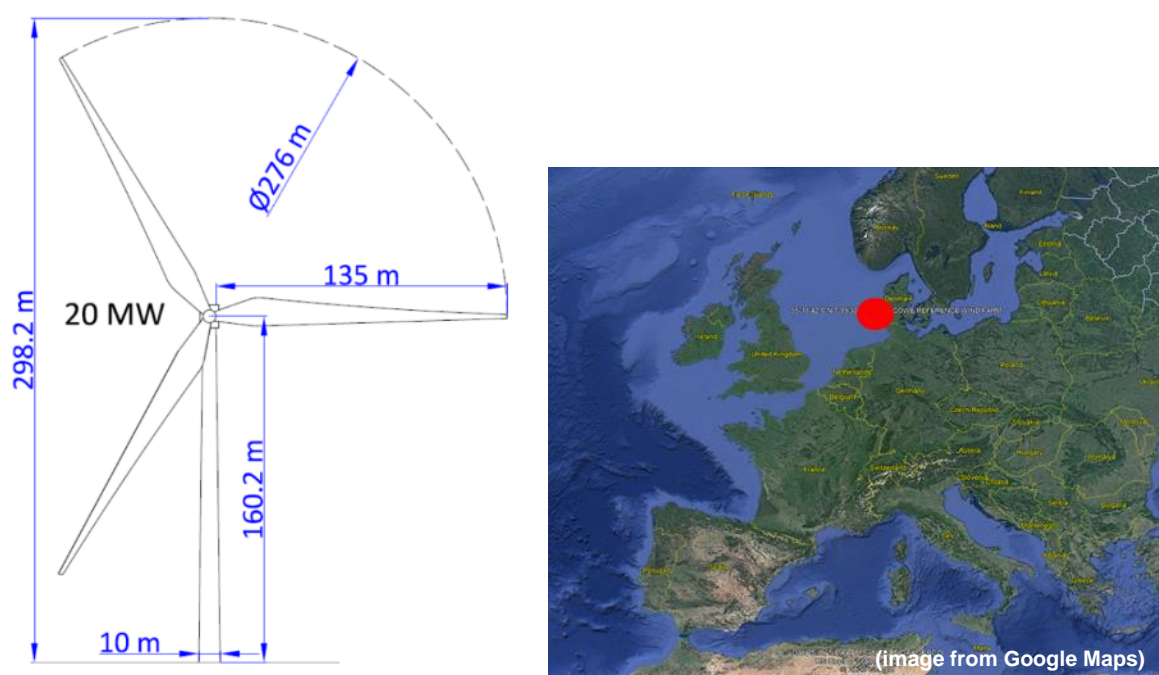
- **Specifications and allocation testing methods in RS1 and CS1**

As mentioned in Figure 5, full-scale prototype testing with the Windbox blade bearing test bench[11] is considered in the assessment of BAU RS1. While in CS1, the developed INNTERESTING experimental hybrid testing method for pitch bearings is included. The developed hybrid testing method in CS1 consist of: a rolling contact fatigue (RCF), ring structural fatigue (RSF), and rolling element (RE) tests. The first two tests take place at the facilities of IKERLAN and the last test at the premises of Laulagun. Please refer to D6.2[12] (page 19-20) for the detailed specifications of the four assessed testing methods of case 1.

Only a part of the environmental, economic and social impacts of the testing methods have been assigned to the impacts of the wind turbine by dividing the impacts of testing methods with an allocation factor. This allocation factor is determined by multiplying the (estimated) number of wind turbine models tested during the lifespan of the test bench (see Table 5) with the number of wind turbines in the wind farm – which is 100 wind turbines for case 1 (see Table 4). E.g. the allocation factor of the BAU blade bearing test in RS1 equals (20*100).

Table 5: Estimated number of wind turbine models tested during the lifespan of the test benches assessed in case 1.

	Blade bearing test	RCF test	RSF test	RE test
Estimated number of wind turbine models tested during lifespan	20	30	15	40

The testing cost in both RS1 and CS1 are assumed to be a part of pitch bearing mechanism costs. Contrary to the other test benches assessed in the LCSA, the CAPEX of the BAU blade bearing test could not be shared for the LCSA and only the OPEX from a test bench user's perspective was shared. The BAU testing method costs € 85 000 per month and takes about 8 months for the case 1 pitch bearing, which adds up to a total of € 680 000. However, these costs are allocated to each turbine in a wind farm (100 wind turbines) which results in € 6 800 for each wind turbine model. On the other hand, the INNTERESTING hybrid testing consists of three different tests as explained above. With regards to these three tests, the test bench and the general model cost for virtual testing are divided by the above explained allocation factor (i.e. number of wind turbine models that could be tested during the test bench lifespan*number of wind turbines in a wind farm). The cost breakdown of each of these tests is shown in Table 6.

Table 6: Cost estimation of hybrid testing methods in CS1 allocated to one wind turbine.

RCF test [€]		RSF test [€]		RE test [€]	
Test bench	40	Test bench	198	Test bench	18
Sample prep.	70	Sample prep.	80	Testing	55
Other materials	10	Electricity	10		
Personnel	60	Test prep.	20		
Model development	23	Testing	56		
Case evaluation	56	Model development	47		
		Case evaluation	56		
Total	**259**	**Total**	**466**	**Total**	**73**

3.2. LCI RS1 and CS1

Please refer to section 3.2 of D6.1 (page 37-40) for the tables with the complete overview of the life cycle inventory (LCI) data of RS1. Some corrections on those LCI data were made for this deliverable and are listed next.

Corrections on specific LCI data of RS1 compared to D6.1:

1. In deliverable D6.1, the CAPEX of blades was mentioned more by a factor of 10. The original value of CAPEX is $ 4 051 700 (and not $ 40 517 000).
2. The data source (Ashuri et al., 2016), does not show the marinization cost though it is reflected in the total CAPEX. The balance of CAPEX is assumed to be the marinization cost based on a previous publication from the same author (Ashuri et al., 2014) and is $ 8 103 800. These costs have been considered as such in this final LCSA.
3. No specific data on maintenance (B2) was included in D6.1. However after the publication of D6.1, specific maintenance data of the pitch bearings were received from Laulagun and are added in this final LCSA. Costs for maintenance of the other components were already included in D6.1 based on a report by Stehly & Beiter (2020). Generic data on amounts of material use due to maintenance of the other component for the LCA is still lacking. Based on inquiry with Iberdrola (one of the members of the project's Technical Advisory Group) and several online sources[13], the main regular maintenance activities consists of inspections/checks, cleaning, replenishing

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[13] E.g. https://safetyculture.com/topics/wind-turbine-maintenance/, https://www.renolit.com/en/industries/wind-energy/renolit-cp/wind-turbines-maintenance-and-reparation/wind-turbines-maintenance-and-reparation, https://www.upkeep.com/learning/wind-farm-maintenance

lubrication, replacing filters, and small repairs. The environmental impact of these maintenance activities is assumed to be limited. Also seeing that the environmental impact of the maintenance of the pitch bearing is insignificant when assessing the total life cycle of the pitch bearing based on the data received from Laulagun. Therefore, in the LCA, the maintenance of the other components is seen as an acceptable cut-off that would not affect the results and conclusions of the LCA.

To compose the dataset of CS1, some data of RS1 have been changed so that it corresponds with the situation of CS1. These changes are listed below.

Changes in RS1 data for CS1:

1. The data of the BAU pitch bearings are replaced by the data of the innovative pitch bearings. Based on the input from Laulagun, the design of the bearings are different due to the use of rollers without affecting the amounts of material used. The longer lifetime of the innovative bearings is made possible due to a more reliable design with the hybrid testing method for pitch bearings.
2. The data of the BAU testing method are replaced by the data of the hybrid testing method.
3. Improvement in the lifetime of pitch bearing to 40 years (until 2059) is considered, also resulting into a longer lifetime of the turbine. The service life of the other wind turbine components generally ranges from 20-25 years and thus requires an overhaul or refurbishment to extend the service life to 40 years. Therefore, a refurbishment period of 6 months was assumed and required an additional investment of 25% of the initial investment in the 25th year (Danish Wind Industry Association, 2003). During the refurbishment period, there will be no energy production. To assess the environmental impact of this overhaul, assumptions were made based on information from DC21 Group (2022). To model the overhaul in the LCA, we took 25% of the initial material use, transport to the wind farm, installation and EOL processes of the following components: main shaft, hub, gearbox, generator, yaw system, drive train and glass fibre fabric of the blades.
4. All the costs are updated to reflect the inflation of 2% until the year 2059.
5. The scrap value of wind turbine components is also updated by using the inflation-adjusted prices of iron and copper in the year 2059.

Additional changes regarding the S-LCA of RS1 as well as CS1 are described in the next subsection.

3.2.1. S-LCA data

In the first deliverable D6.1, social risks related to the manufacturing of the pitch bearings and gearbox were approached by generic data from the PSILCA database (see section 1.2.3.1 of D6.1, page 20-22). For this deliverable, Laulagun and Moventas provided company specific data for the pitch bearing production and gearbox production respectively for several social aspects which are covered in this S-LCA. It concerns data related to the stakeholder groups 'Workers', 'Local community' and 'Value chain actors'. Data on 'Society' are assessed at country level and have not been requested from the companies, instead the generic sector data were retained. Also, the companies were not asked to provide information on the stakeholder group 'Consumers' as it concerns B2B products and the indicator 'Presence of business practices deceptive or unfair to consumers' is deemed less relevant for the products. An overview of the company specific data is presented in Annex A (page 64).

3.3. LCIA RS1 and CS1

The following subsections present the results and interpretation of the life cycle impact assessment (LCIA) of case 1 comprising of the comparison between RS1 and CS1. First the environmental LCA findings are given, followed by the economic LCC results and the S-LCA results. As already explained in the introduction of section 4 of D6.1 (page 47), the LCIA of the LCSA predicts *potential* environmental, economic or social damages (impacts) related to the system under study; and cannot and is not intended for identifying or predicting *actual* impacts.

3.3.1. Findings LCA

Table 7 and Table 8 (on the next page) provide the environmental impact results in absolute values for 1 kWh of electricity generated to the grid by a 20 MW offshore wind turbine installed in NORCOWE with respect to RS1 with a service life of 25 years and to CS1 with a service life of 40 years. The total life cycle impact of the testing methods – i.e. the impacts caused by the production, transport, (dis)assembly, operational energy use, and EOL of the test benches – allocated to one wind turbine (as explained in the third part of section 3.1) are included in the first column with results. In RS1 it concerns the full-scale prototype testing with the Windbox blade bearing test bench and in CS1 the developed hybrid testing method with the RCF, RSF and RE tests.

An important difference between RS1 and CS1 is the additional life cycle stage B5 for CS1 in which the impacts of the overhaul in the beginning of year 2045 is considered.

The cell shading colours indicate per row/impact category the relevance of the contribution of a life cycle stage on the total life cycle.

Table 7: Environmental profile of RS1, in absolute values per FU.

Contribution to impact category	X < 2.5%	2.5% < X < 10%	10% < X < 25%	25% < X < 50%	X > 50%

	Testing (A-C)	Production (A1-A3)	Transport to site (A4)	Assembly (A5)	Maintenance (B2)*	Deconstruction (C1)	(Transport to) EOL (C2-C4)	Total life cycle
Climate change - total [kg CO2 eq]	1,58E-04	6,97E-03	9,25E-05	1,58E-04	7,82E-07	6,77E-05	6,89E-05	**7,51E-03**
Ozone depletion [kg CFC11 eq]	9,43E-12	5,28E-10	2,11E-11	4,02E-12	1,51E-13	1,72E-12	1,00E-11	**5,74E-10**
Acidification [mol H+ eq]	1,24E-06	5,55E-05	1,40E-06	5,71E-07	2,82E-09	2,45E-07	2,60E-07	**5,93E-05**
Eutrophication, freshwater [kg P eq]	6,81E-09	4,33E-07	5,26E-10	1,34E-08	1,75E-11	5,74E-09	4,00E-10	**4,60E-07**
Eutrophication, marine [kg N eq]	1,89E-07	7,60E-06	3,39E-07	1,11E-07	4,44E-10	4,78E-08	7,47E-08	**8,37E-06**
Eutrophication, terrestrial [mol N eq]	2,11E-06	7,89E-05	3,77E-06	1,50E-06	5,00E-09	6,42E-07	8,24E-07	**8,77E-05**
Photochemical ozone formation [kg NMVOC eq]	5,96E-07	2,80E-05	1,03E-06	3,37E-07	3,86E-09	1,44E-07	2,49E-07	**3,03E-05**
Resource use, minerals and metals [kg Sb eq]	7,75E-10	8,68E-07	1,83E-10	6,53E-10	6,68E-12	2,80E-10	1,24E-10	**8,70E-07**
Resource use, fossils [MJ]	3,31E-03	9,12E-02	1,37E-03	2,25E-03	1,52E-05	9,65E-04	6,82E-04	**9,98E-02**
Water use [m³ depriv.]	8,61E-05	6,89E-04	1,11E-06	1,51E-05	3,22E-08	6,49E-06	1,14E-06	**7,99E-04**
Particulate matter [disease inc.]	5,05E-12	4,60E-10	7,52E-12	3,28E-12	2,93E-14	1,41E-12	5,15E-12	**4,83E-10**
Ionising radiation [kBq U-235 eq]	3,25E-05	3,20E-04	5,93E-06	1,73E-05	5,73E-08	7,43E-06	2,91E-06	**3,86E-04**
Ecotoxicity, freshwater [CTUe]	2,82E-03	3,61E-01	9,92E-04	3,39E-03	1,06E-05	1,45E-03	7,36E-04	**3,70E-01**
Human toxicity, cancer [CTUh]	3,42E-13	4,48E-11	4,17E-14	6,19E-14	2,86E-16	2,65E-14	2,52E-14	**4,53E-11**
Human toxicity, non-cancer [CTUh]	2,19E-12	5,68E-10	9,24E-13	1,75E-12	6,64E-15	7,50E-13	1,20E-12	**5,75E-10**
Land use [Pt]	7,04E-04	3,86E-02	1,09E-03	2,80E-03	3,34E-06	1,20E-03	7,43E-04	**4,52E-02**

* only considering the maintenance of the pitch bearings

Table 8: Environmental profile of CS1, in absolute values per FU.

Contribution to impact category	X < 2.5%	2.5% < X < 10%	10% < X < 25%	25% < X < 50%	X > 50%

	Testing (A-C)	Production (A1-A3)	Transport to site (A4)	Assembly (A5)	Maintenance (B2)*	Overhaul (B5)	Deconstruction (C1)	(Transport to) EOL (C2-C4)	Total life cycle
Climate change - total [kg CO2 eq]	3,24E-06	4,41E-03	5,86E-05	1,00E-04	9,38E-07	6,16E-04	4,29E-05	7,38E-06	**5,24E-03**
Ozone depletion [kg CFC11 eq]	2,04E-13	3,34E-10	1,34E-11	2,54E-12	1,79E-13	2,84E-11	1,09E-12	9,84E-13	**3,81E-10**
Acidification [mol H+ eq]	2,73E-08	3,52E-05	8,84E-07	3,62E-07	3,37E-09	4,07E-06	1,55E-07	1,95E-08	**4,07E-05**
Eutrophication, freshwater [kg P eq]	1,39E-10	2,74E-07	3,33E-10	8,48E-09	2,10E-11	2,03E-08	3,63E-09	4,20E-11	**3,07E-07**
Eutrophication, marine [kg N eq]	4,01E-09	4,81E-06	2,14E-07	7,05E-08	5,30E-10	7,38E-07	3,02E-08	5,93E-09	**5,88E-06**
Eutrophication, terrestrial [mol N eq]	4,49E-08	4,99E-05	2,38E-06	9,49E-07	5,96E-09	5,82E-06	4,07E-07	6,52E-08	**5,96E-05**
Photochemical ozone formation [kg NMVOC eq]	1,21E-08	1,77E-05	6,54E-07	2,13E-07	4,55E-09	2,02E-06	9,14E-08	2,06E-08	**2,07E-05**
Resource use, minerals and metals [kg Sb eq]	9,34E-12	5,50E-07	1,16E-10	4,13E-10	7,99E-12	4,12E-08	1,77E-10	1,27E-11	**5,92E-07**
Resource use, fossils [MJ]	7,48E-05	5,77E-02	8,69E-04	1,42E-03	1,81E-05	8,88E-03	6,10E-04	6,75E-05	**6,97E-02**
Water use [m³ depriv.]	2,05E-06	4,36E-04	7,04E-07	9,58E-06	3,86E-08	3,55E-05	4,10E-06	1,27E-07	**4,88E-04**
Particulate matter [disease inc.]	6,32E-14	2,91E-10	4,76E-12	2,08E-12	3,51E-14	3,76E-11	8,91E-13	5,41E-13	**3,37E-10**
Ionising radiation [kBq U-235 eq]	7,90E-07	2,02E-04	3,75E-06	1,10E-05	6,82E-08	2,00E-05	4,70E-06	2,87E-07	**2,43E-04**
Ecotoxicity, freshwater [CTUe]	4,96E-05	2,28E-01	6,28E-04	2,15E-03	1,26E-05	1,70E-02	9,20E-04	8,01E-05	**2,49E-01**
Human toxicity, cancer [CTUh]	1,35E-15	2,84E-11	2,64E-14	3,92E-14	3,42E-16	2,34E-12	1,68E-14	2,84E-15	**3,08E-11**
Human toxicity, non-cancer [CTUh]	3,63E-14	3,60E-10	5,85E-13	1,11E-12	7,91E-15	3,40E-11	4,74E-13	1,24E-13	**3,96E-10**
Land use [Pt]	1,17E-05	2,45E-02	6,90E-04	1,77E-03	3,99E-06	2,41E-03	7,59E-04	7,70E-05	**3,02E-02**

* only considering the maintenance of the pitch bearings

Both tables show that the production stage (A1-A3) is the most relevant life cycle stage for RS1 as well as CS1, as for all impact categories the production stage contributes more than 50% of the assessed life cycle. This is caused by the high amounts of material use. The BAU testing method is of little relevance in the impact categories 'fossil resource use' and 'ionising radiation'. Furthermore, the testing method has a bigger relevancy in contributing to the total life cycle impacts in the impact category 'water use'. This is due to the operational water use by the Windbox. In CS1, the hybrid testing method does not pop-up as a relevant contributor in any of the impact categories. However, the overhaul of CS1 is a relevant life cycle stage in all impact categories.

Based on the above environmental profiles, a graph has been composed in which the relative comparison between RS1 and CS1 is shown, see Figure 7 below. In this figure, the scenario (RS1 or CS1) with the highest total life cycle impact per FU is set to 100% and the remaining scenario is shown relative to the one with the highest impact. This is done per impact category. The graph clearly shows that in all impact categories RS1 is at least around 30% more

impacting per kWh generated than CS1. Based on the LCA results, it is also noticeable that for all impact categories, the total life cycle impact of CS1 per FU is smaller than the impact of only the production stage of RS1 per FU.

Figure 7: Comparison between RS1 and CS1 – relative contribution of all life cycle stages of case 1 wind turbines including testing based on environmental profiles in Table 7 and Table 8.
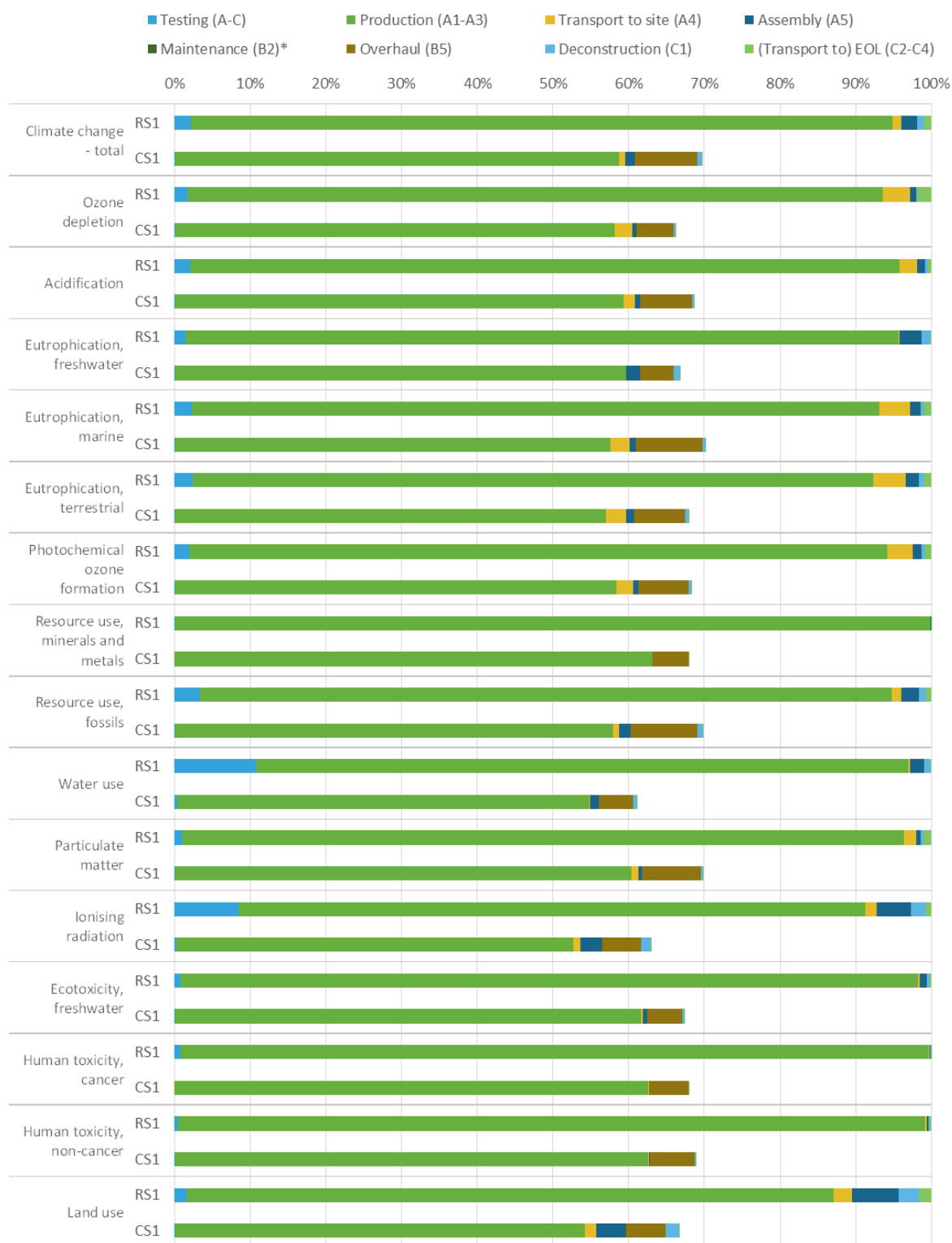
3.3.2. Findings LCC

Figure 8 shows the detailed life cycle cost breakdown of RS1 and CS1 including DEVEX (development), CAPEX (turbine, balance of plant, assembly & installation, transport and refurbishment), OPEX (O&M), and ABEX (EOL). These costs are discounted and are based on the year 2019. An additional € 7 748 719 is required for CS1 which is mainly represented in O&M and refurbishment costs. The O&M costs in CS1 increased due to an increase in service life to 40 years. Please note that the refurbishment costs are considered as CAPEX and are required in the 25th year.

Figure 8: Life cycle cost breakdown for (a) RS1 and (b) CS1 – costs in € discounted to 2019.
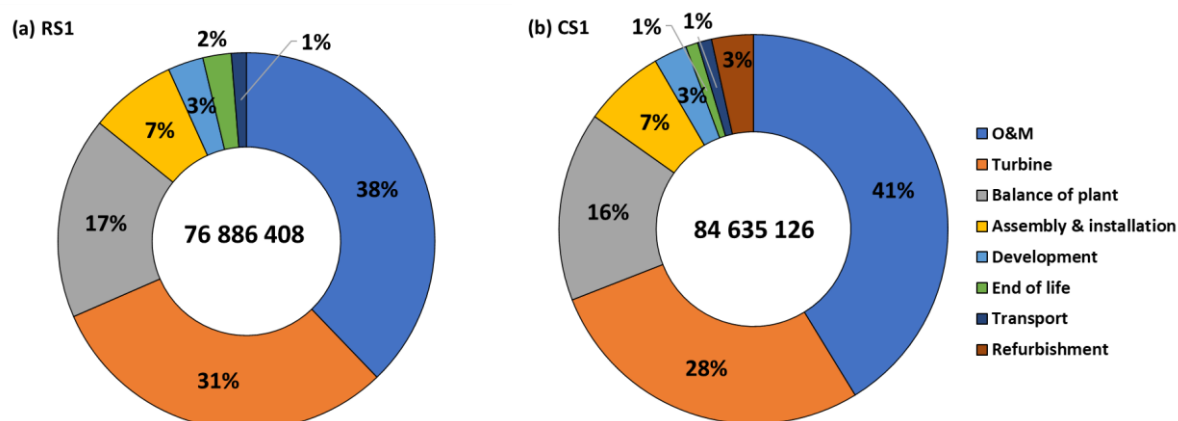
The LCOE estimates of the RS1 with the BAU testing method and the CS1 with the hybrid testing method for pitch bearings are shown in Table 9. The LCOE decreased by 8.2% in CS1 due to improved pitch bearing service life (40 years) and hybrid testing methods that make the bearings reliable. The denominator values represent the discounted AEP used in the LCOE estimation. However, the corresponding net AEP values are 2 150 580 000 kWh and 3 397 916 400 kWh for RS1 and CS1 respectively. Due to the improvement in the service life, an additional 1 247 336 400 kWh of energy is produced over the wind turbine service life in CS1. Using the difference in LCOE (0.005 €/kWh) and multiplying by the additional energy produced, the potential savings are € 6 211 074 for a single wind turbine over 40 years of service life with the innovative pitch bearing and hybrid testing methods.

Table 9: LCOE comparison between RS1 and CS1.

	LCOE [€/kWh]	Numerator [€]	Denominator [kWh]
RS1	0.066	76 886 408	1 166 153 131
CS1	0.061	84 635 126	1 388 549 466

Figure 9 shows the detailed LCOE breakdown comparison for RS1 and CS1 in €/MWh. In the CS1 scenario, the O&M costs increase by € 0.2 /MWh while the turbine, BOP, installation, development, EOL, and transport costs decrease by € 3.2, € 1.8, € 0.8, € 0.3, € 1, and € 0.1 per MWh respectively. Since there is a refurbishment of wind turbine components – other than the pitch bearings – included in the CS1, there is an increment of € 2.1 /MWh which is just 3.4% of the total LCOE. However, with further developments in other wind turbine components in the future to extend the service life, the refurbishment may not be required which can

potentially save € 2.1 /MWh. In that case, the downtime of 6 months allocated for refurbishment also will not be required which may reduce the LCOE further.

Figure 9: Detailed LCOE breakdown [€/MWh] for RS1 and CS1 – cost discounted to 2019.
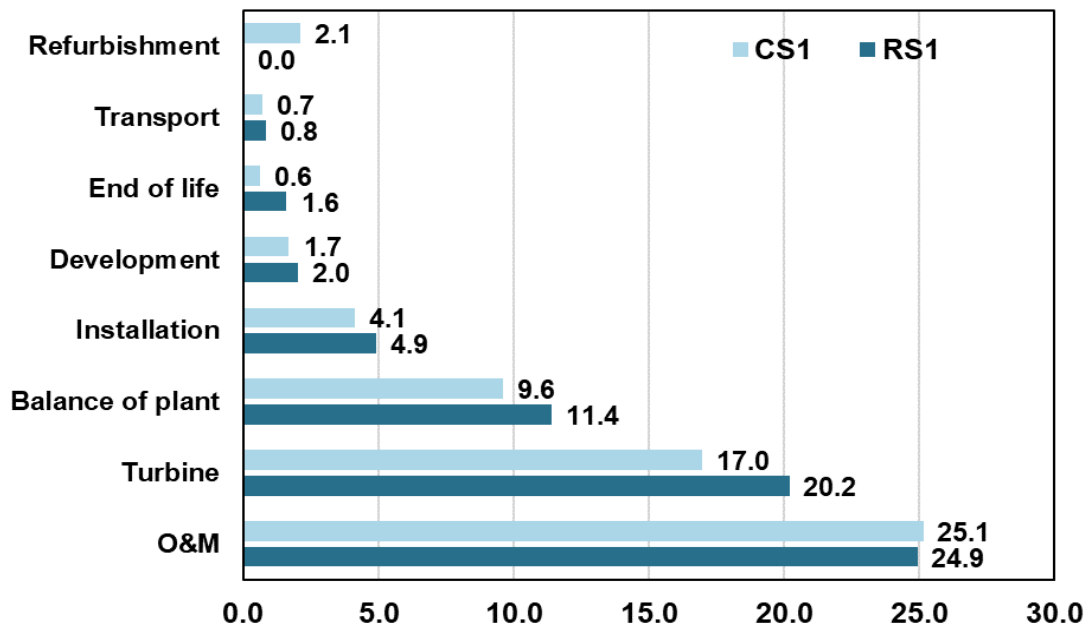
- **LCC findings related to the pitch bearing and testing methods in RS1 and CS1**

The cost of the pitch bearing remained the same in both RS1 and CS1. The cost of the pitch mechanism is about 1.7% and 1.6% of overall discounted costs in RS1 and CS1, respectively. However, the differences are in the BAU and hybrid testing methods. The costs of the three hybrid testing methods are RCF = € 259, RSF = € 466, and RE = € 73 which adds to € 798 per wind turbine and is 752% less than the BAU testing method. However, this large improvement in cost is not reflected in the overall LCOE as these costs are insignificant. In addition to cost reduction, the time for testing is also considerably reduced. Using a virtual model to test different scenarios of failure also increases the reliability of the testing process and the pitch bearing, resulting in a lower risk of failure.

3.3.3. Findings S-LCA

The aim of the social life cycle assessment is to quantify the social risks occurring along the life cycle applicable to different stakeholders. The stakeholder categories are workers, society, local community, value chain actors and consumers. The materiality assessment revealed that workers are the most important stakeholder category for this product group, with 'fair salary' and 'health and safety' the two most material subcategories (see subsections 1.2.3.2 – 1.2.3.4 of D6.1, page 22-26). The results presented in the current deliverable focus on these material subcategories. In addition, the results for the stakeholder categories 'local communities' and 'society' are presented, due to the consortium's interest in these two stakeholder categories. Finally, absolute values for all stakeholder categories and social indicators of PSILCA are available in Annex B for both the BAU reference scenario (RS1) and the INNTERESTING case study (CS1). The results are always calculated for the functional unit, being 1 kWh of electricity output delivered to the grid.

The results for case 1, **stakeholder category 'workers'**, are presented in Figure 10. The result for the scenario (RS1 or CS1) with the highest contribution is set to 100% in the figure. The result of the other scenario is shown relative to the scenario with the highest contribution. Negative contributions or benefits are also shown relative to the highest positive contribution. An extension of the life span from 25 years to 40 years by means of a refurbishment results in lower social risks along the life span. This observation is valid for each of the investigated impact categories. The main driver is the reduced LCOE. This results in lower social risks along over the life cycle per FU, being 1 kWh of electricity output delivered to the grid.

Hotspots over the life cycle occur in life cycle stages 'production of all other components, mainly metal[14]' and 'maintenance'. These are also the life cycle stages with the largest cost contribution, the first two bars in the graph show the distribution of costs over the life cycle for RS1 and CS1. This is useful information as social risks are calculated by multiplying the risk level with cost and worker hours. 'Maintenance' is the most important life cycle stage in the impact categories 'fair salary' and 'fatal accidents'. 'The production of all other components' is the most important life cycle stage in the impact categories 'non-fatal accidents', 'safety measures' and 'indoor/outdoor pollution'.

Figure 10: Comparison of RS1 and CS1 over the life cycle – social risks for 'workers', cost provided as a reference.
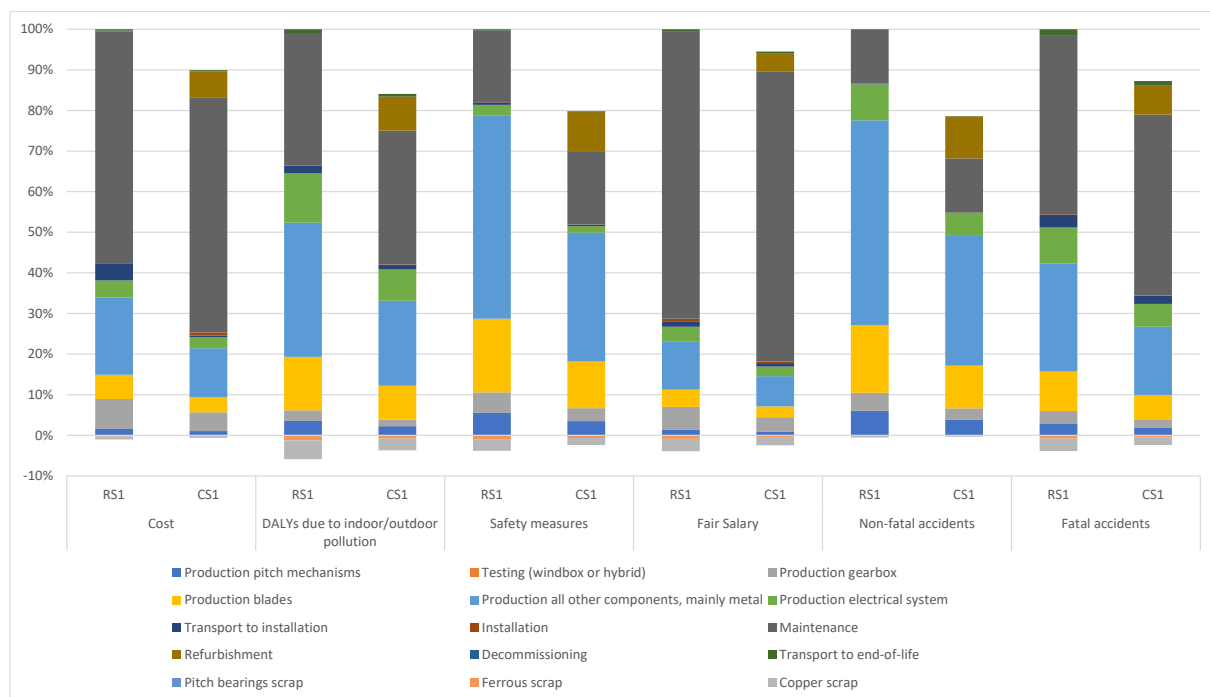
Costs for refurbishment account for 7% of the cost of CS1. The relative contribution of refurbishment to social risks is between 5% and 13% depending on the impact category. Social risks arising from either BAU testing in the Windbox or hybrid testing are irrelevant when looking at the whole life cycle.

The results for the stakeholder category **'local communities'** are presented in Figure 11. 'Local communities' in this analysis are the communities living close to where the specific step in the life cycle takes places. For example, pitch bearing production takes place in Spain, then

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[14] Included are all turbine components except for gearbox, blades, pitch mechanism and electrical system.

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social indicators are calculated for the communities near the pitch bearing production site in Spain. Maintenance takes place in Germany, so social risks apply to local communities in Germany. For each of the investigated impact categories the social risk is lower in the case study (CS1) compared to the reference case (RS1). The hotspots are 'the production of metal components' in Spain and Maintenance in Germany. In the impact category 'unemployment rate', the hotspots are clearly for the life cycle stages taking place in Spain. The unemployment rate is much lower in Germany where maintenance takes place (4.2% (low risk) for Germany and 19.7% (very high risk) for Spain (source: PSILCA (Eisfeldt and Ciroth, 2018)).

Figure 11: Comparison of RS1 and CS1 over the life cycle – social risks for 'local communities', cost provided as a reference.
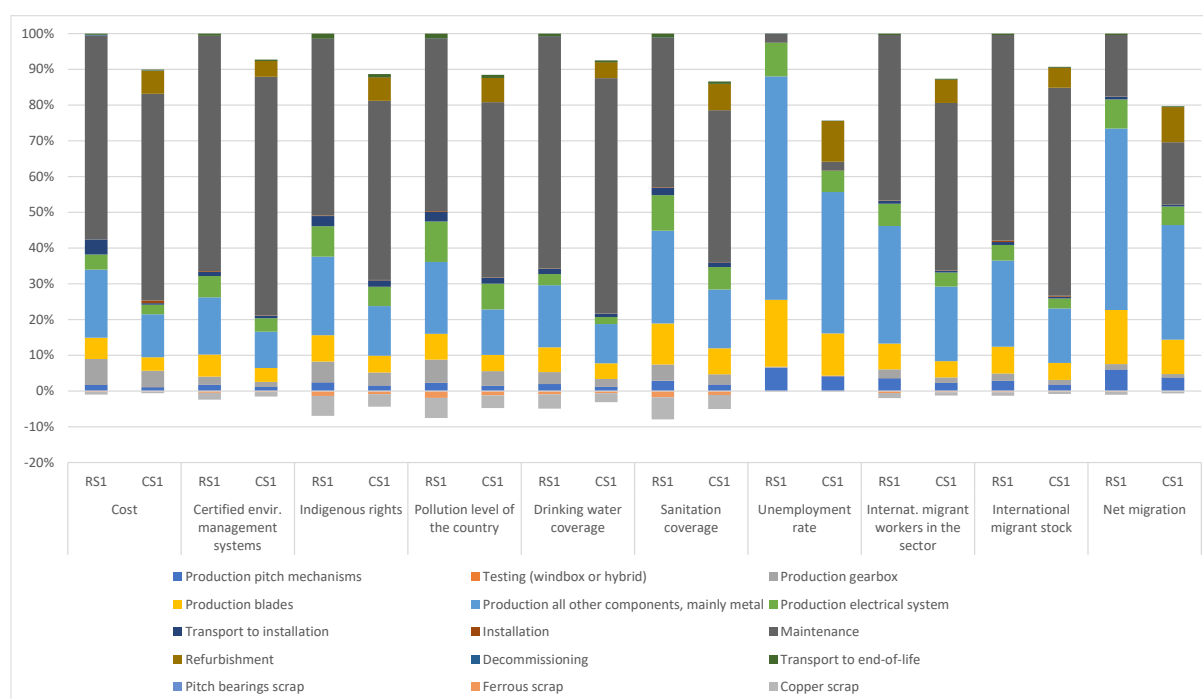
The results for the stakeholder category '**society**' are presented in Figure 12 and Figure 13. Figure 12 contains information on the risks for society and Figure 13 gives results on the opportunity 'contribution to economic development' for society. Where it is clear from Figure 12 that more social risks occur during the life span of RS1 compared to CS1, Figure 13 reveals that CS1 creates less opportunities for economic development compared to RS1. The latter is an important observation. The focus of a S-LCA is mainly on the identification of hotspots for social risks, economic actions. However, the focus can also be on creating opportunities, which are much less examined in a S-LCA. The indicator 'contribution to economic development' gives a first idea about the opportunities for society. It becomes clear that in the scenario where more risks were identified (RS1), also more opportunities are generated. So identified risks, should always be evaluated in the context of the generated opportunities.

Figure 12: Comparison of RS1 and CS1 over the life cycle – social risks for 'society', cost provided as a reference.
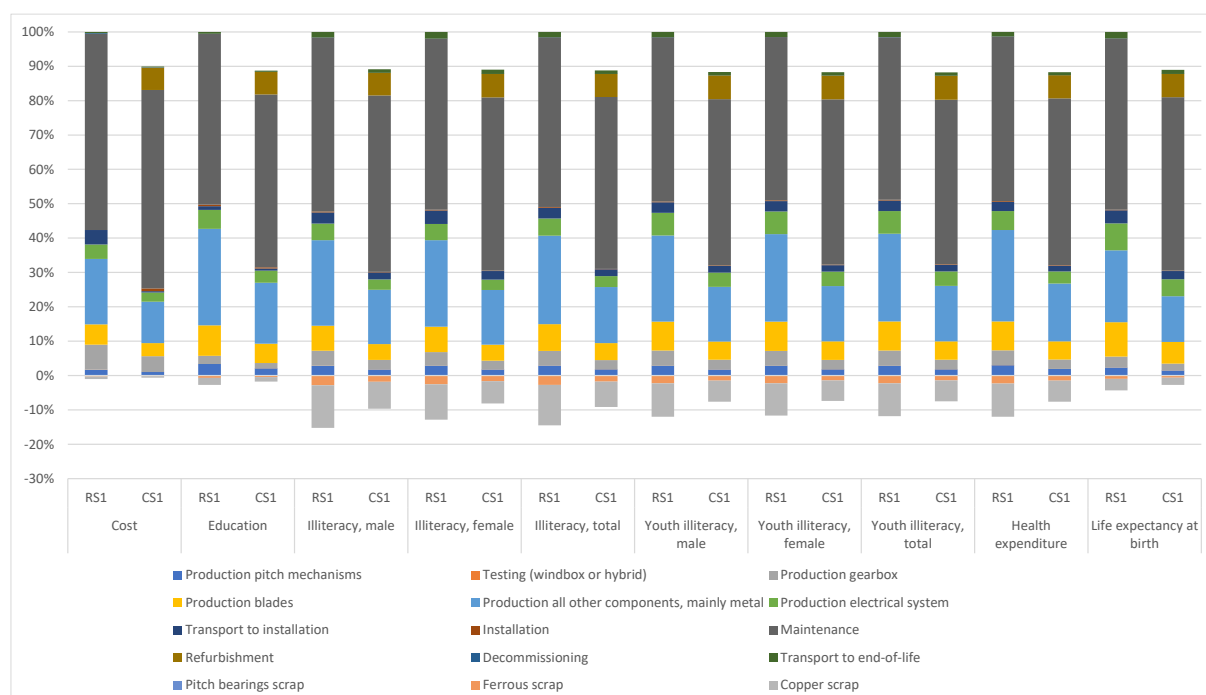
Figure 13: Comparison of RS1 and CS1 over the life cycle – opportunity 'contribution to economic development'.
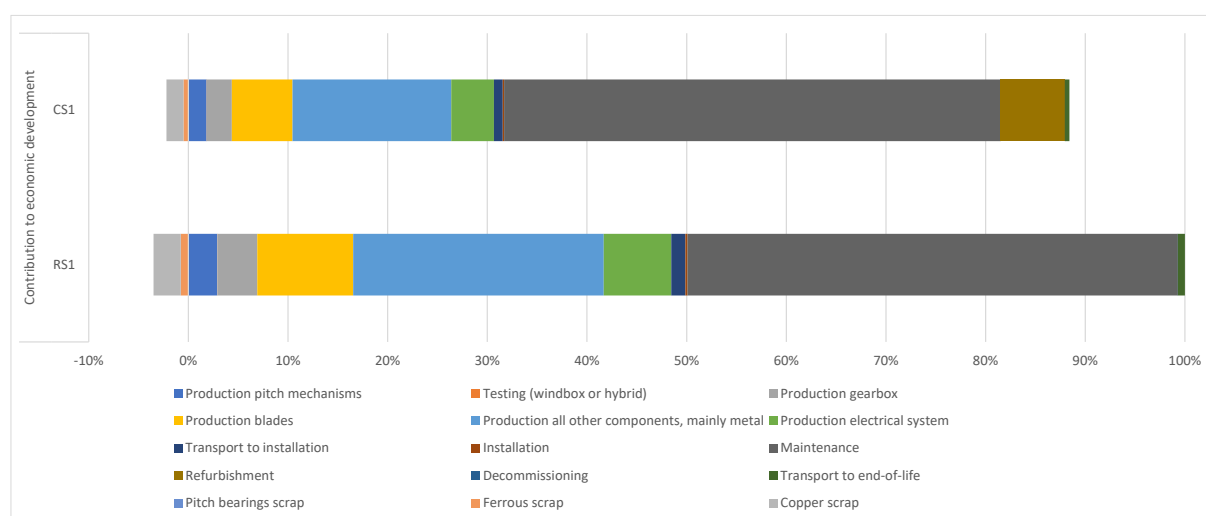
3.4. Conclusions comparative LCSA case 1

The environmental impact per FU of RS1 is much higher than RS1 on all assessed environmental impact categories - at least around 30% more impacting. This is mainly due to the increased total energy output by CS1, which is possible due to the longer life time. The total life cycle impact per FU of CS1 is even smaller than the impact per FU resulting from only the production stage (A1-A3) of RS1. The production stage has the biggest contribution on the total life cycle impact in both RS1 as CS1, due to the high amount of material use. The testing

methods has little to no contribution on the total life cycle impact for both scenarios of case 1. The overhaul (B5) included in CS1 does has an important contribution on the life cycle impacts after the production stage impacts.

The LCOE estimated for the RS1 is 0.066 €/kWh whereas the estimated value for CS1 is 0.061 €/kWh, which is a reduction of 8.2%. This is mainly due to increased service life resulting in higher net AEP over the turbine lifespan. Using the difference in LCOE (0.005 €/kWh) and multiplying by the additional energy produced, the potential savings are € 6 211 074 for a single wind turbine over 40 years of service life in the CS1. The testing costs are included in the pitch mechanism costs. A slight reduction of 0.1%-points is observed in the overall discounted costs of CS1 due to the cheaper hybrid testing method as the pitch bearing cost remains the same. The costs of the three hybrid testing methods add to € 798 per wind turbine which is 752% less than the BAU testing method in RS1. However, this large improvement in cost is not reflected in the overall LCOE as these costs are insignificant. Another advantage of hybrid testing developed in this project is the reduction of time for testing which reduces the time to market for innovative pitch bearings. Using a virtual model to test different scenarios of failure also increases the reliability of the testing process and the pitch bearing resulting in a lower risk of failure and improved service life.

The social risks occurring during the life cycle of the wind turbines are lower for the INNTERESTING case (CS1) compared to the BAU (RS1). The main driver is the reduced LCOE, which results in lower social risks per functional unit, being 1 kWh of electricity output delivered to the grid. Hotspots for social risks are the life cycle stages 'maintenance' and 'the production of all other components'. When it comes to social opportunities (contribution to economic development) created during the life cycle, higher opportunities are identified for RS1 compared to CS1. This observation shows that identified risks, should always be evaluated in the context of the generated opportunities. Social risks arising from either BAU testing in the Windbox or hybrid testing are irrelevant when looking at the whole life cycle, the relative contribution of refurbishment in CS1 to social risks is between 5% and 13% depending on the impact category.

Although all three assessments of the LCSA show that the contribution of the testing methods (BAU and hybrid) can be considered as insignificant on the total life cycle, the testing methods are a necessity in the development of the wind turbines. Especially in CS1, to ensure a higher reliability of the innovative pitch bearing design and by that making a longer service life possible and a higher total electricity output as a result.

4. LCSA case 2

As the second case of the LCSA, the scenario in Figure 14 has been analysed in the comparative assessment between RS2 and CS2. The innovative gearbox in the scenario of CS2 has a new journal bearing design, resulting in a 5-years longer service life. An overhaul – like considered in case 1 – is not included this case, as the increase of service life in CS2 is assumed still to be within the limits of the service life of the other wind turbine components, which generally ranges from 20-25 years.

Figure 14: Scheme of the assessed scenario of the comparison between RS2 and CS2.

2019: investment date / (finalising) product development process of 10 MW onshore wind turbine

BAU **full-scale prototype testing** with 10 MW test run facility	**INNTERESTING** **experimental hybrid testing** consisting of: - Component-scale performance test - Journal bearing lab-scale test - Gear contact RCF lab-scale test

2020: start operation of 10 MW onshore wind turbine in north Germany

BAU Gearbox of current BAU technology 20 years of service life	**INNTERESTING** Innovative gearbox with new journal bearing design 25 years of service life

Decommissioning of the wind turbine

BAU: end of 2039	**INNTERESTING: end of 2044**

4.1. Scope RS2 and CS2

- **Functional units RS2 and CS2**

The next table gives the specific FU of RS2 and CS2 based on the general FU and the parameters considered to calculate the total electricity output of the two wind turbines.

Table 10: Specific FU and electricity output parameters of RS2 and CS2

	RS2	CS2
Specific FU	1 kWh of the total electricity output delivered to the grid over the service life of **20 years** by a 10 MW onshore wind turbine with a so-called classical Danish design and a **gearbox of current BAU technology** which was prototype tested in a **full-scale BAU 10 MW test run facility**	1 kWh of the total electricity output delivered to the grid over the service life of **25 years** by a 10 MW offshore wind turbine with a so-called classical Danish design and an **innovative gearbox with new journal bearing design** which was prototype tested with the **INNTERESTING hybrid testing method for gearboxes**
Availability losses	6.78%[15]	5.25%[15]
Capacity factor	52.8% (Chaviaropoulos, 2016)	53.8%[16]
Annual Energy Production (AEP)	46 211 MWh/y (Chaviaropoulos, 2016)	47 135 MWh/y[17]
Total energy output	924 224 740 kWh	1 117 836 544 kWh

- **Specifications RS2 and CS2**

The table and figure below present the assumed specifications of the wind turbine and wind farm of case 2.

Table 11: Specifications of the RWT and wind farm of RS2/CS2.

Dimensions wind turbine	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 RS2	Gearbox constructed with current BAU technology with a torque density of ~125 Nm/kg[18] Specific data provided by Moventas Gears OY
Specific component CS2	Innovative gearbox with new journal bearing design and a torque density of ~200 Nm/kg 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)

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[15] Annual average calculated based on bathtub curve by Moventas, with production losses ranging from 6 to 10%.
[16] Calculated based on AEP.
[17] A 2% increase (with respect to BAU) was estimated by Moventas because of the innovative gearbox design.
[18] If a 10 MW gearbox would be constructed with the current BAU technology, this would result into a gearbox with a weight of 104 ton and large dimensions which would logistically not be possible to transport. The innovative gearbox design (CS2) would make transport still possible. Necessary solutions of the logistic problems of the BAU gearbox is out of scope of this LCSA and therefore the transport is just assessed in the LCSA as is.

**Figure 15: Left – Plot of the DTU 10 MW RWT (Bak et al., 2013).
Right – Wind farm of RS2/CS2 is located in north Germany.**

(image from Google Maps)
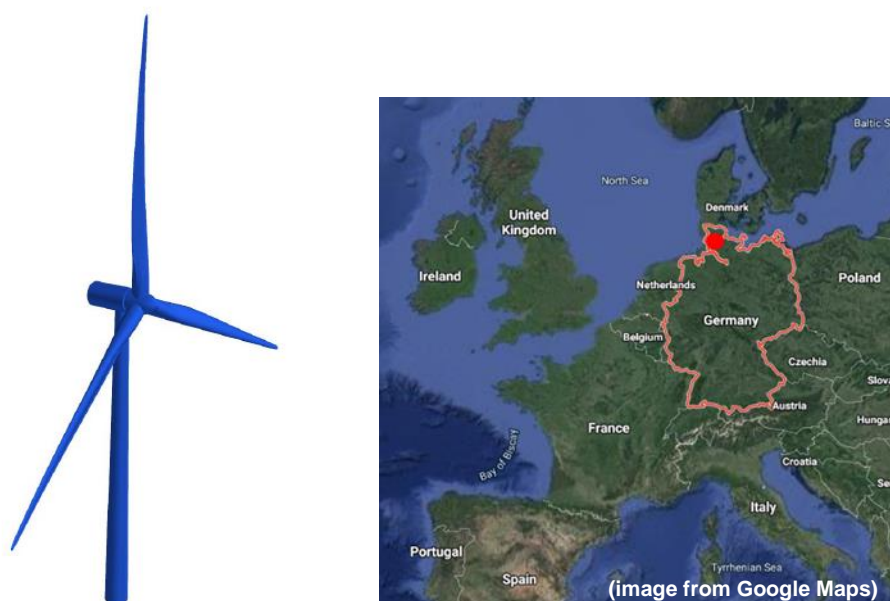
- **Specifications and allocation testing methods in RS2 and CS2**

A full-scale gearbox test in a 10 MW test run facility is included as BAU testing method in the assessment of BAU RS2. This fictive test run facility is assumed to be located at the premises of Moventas in the Jyväskylä area. In CS2, the INNTERESTING experimental hybrid testing method developed for gearboxes is considered. Which consists of the following three tests: (1) a component-scale performance (CSP) test which uses an existing down-scaled test run facility, (2) a journal bearing laboratory-scale (JBL) test, and (3) a gear contact RCF laboratory-scale test also called twin disc (TD) test. The first test occurs at the facilities of Moventas and two latter ones at VTT. Table 12 gives the estimated number of wind turbine models that can be tested per test during the lifetime of the test bench. These numbers are used to determine the allocation factor of the tests to one wind turbine like done for the testing methods in case 1, but with the number of wind turbines assumed in the wind park of case 2 which is 10. For more specifications of the four assessed test of case 2, please refer to D6.2 (page 21-23).

Table 12: Estimated possible number of wind turbine models tested during the lifespan of the test benches assessed in case 2.

	BAU test	CSP test	JBL test	TD test
Estimated number of wind turbine models tested during lifespan	4	100	100	100

The testing costs estimated in this LCC are included as part of the gearbox mechanism cost. The BAU testing method costs € 7 380 949 per wind turbine model and takes about 2 years. The building and test stand costs are divided by the number of wind turbine models that could be tested during the test stand lifespan. The final testing cost is dependent on the number of wind turbines in a wind farm. The costs obtained can further be allocated to each turbine in a wind farm which results in € 738 095 for each wind turbine model. The breakdown of the BAU testing method is shown in Table 13. On the other hand, the INNTERSTING hybrid testing in CS2 consists of the three different tests as explained above. It is to be noted that the CSP test

uses the existing BAU building and test stand for just 20 hours and as such the costs for these hours are allocated to this testing method. The hybrid testing costs a total of € 14 449 per wind turbine, the breakdown of which is shown in Table 14.

Table 13: Cost estimation of BAU testing methods in RS2 allocated to one wind turbine.

BAU test [€]	
Test rig incl. building	490 166
Operating cost	247 929
Total	**738 095**

Table 14: Cost estimation of hybrid testing methods in CS2 allocated to one wind turbine.

CSP test [€]		JBL test [€]		TD test [€]	
Test rig incl. building	639	Test rig	573	Test rig	270
Personnel (physical)	300	Testing (incl. setup prep, maintenance, electricity and personnel)	341	Testing (repair and maintenance)	540
Energy (physical)	500	Virtual testing (incl. electricity)	360	Electricity (testing)	638
Personnel (virtual)	8 000			Other testing costs (operator, lubricant, cooling water)	2 088
Computers (virtual)	200				
Total	**9 639**	**Total**	**1 274**	**Total**	**3 535**

4.2. LCI RS2 and CS2

The tables in section 3.3 of D6.1 (page 40-43) presents a complete overview of the LCI data of RS2. These data have been reused in the LCSA reported in this deliverable after applying the corrections listed below. Regarding the changed generic S-LCA data to company-specific S-LCA data, please refer to section 3.2.1.

Corrections on specific LCI data of RS2 compared to D6.1:

1. In deliverable D6.1, the labour costs for oil, hose, and filter element change in O&M are reflected for the entire lifespan of the wind turbine. However, these costs are corrected in this deliverable. The effect of these changes on the conclusion is negligible.
2. Similar to RS1, the environmental impact of the maintenance of the other components is seen as insignificant and considered as a cut-off that would not affect the results and conclusions of the LCA.

To compose the dataset of CS2, some data of RS2 have been changed so that it corresponds with the situation of CS2. These changes are listed next.

Changes in RS2 data for CS2:

1. The data of the BAU gearbox are replaced by the data of the innovative gearbox. Based on the input from Moventas, the new gearbox design in CS2 requires relatively less material compared to RS2. In addition, the longer lifetime of the new gearbox is made possible due to a more reliable design with the hybrid testing method for gearboxes.

2. The data of the BAU testing method are replaced by the data of the hybrid testing method.
3. Improvement in the service life of the gearbox by 5 years (until the year 2044) is considered, which also results in a linger lifetime of the turbine. No refurbishment of other wind turbine components was assumed as the service life of the other wind turbine components generally ranges from 20-25 years. In real practice, the O&M costs increase slightly every year as the wind turbine ages. However, this effect is not considered in the current LCC.
4. The scrap value at the end of life is also calculated using the per kg cost from RS2 and also adjusted for inflation wherever needed.

4.3. LCIA RS2 and CS2

The following subsections present the results and interpretation of the life cycle impact assessment (LCIA) of case 1 comprising of the comparison between RS2 and CS2. First the environmental LCA findings are given, followed by the economic LCC results and the S-LCA results. As already explained in the introduction of section 4 of D6.1 (page 47), the LCIA of the LCSA predicts *potential* environmental, economic or social damages (impacts) related to the system under study; and cannot and is not intended for identifying or predicting *actual* impacts.

4.3.1. Findings LCA

Table 15 and Table 16 present the environmental impact results in absolute values for 1 kWh of electricity generated to the grid by a 10 MW onshore wind turbine installed in the north of Germany with respect to RS2 with a service life of 20 years and to CS2 with a service life of 25 years. The total life cycle impact of the testing methods – i.e. the impacts caused by the production, transport, (dis)assembly, operational energy use, and EOL of the test benches – allocated to one wind turbine (as explained in the third part of section 4.1) are included in the first column with results. This regards in RS2 the full-scale 10 MW test run facility and in CS2 the developed hybrid testing method with the CSP, JBL and TD tests. The cell shading colours indicate per row/impact category the relevance of the contribution of a life cycle stage on the total life cycle.

Table 15: Environmental profile of RS2, in absolute values per FU.

Contribution to impact category	X < 2.5%	2.5% < X < 10%	10% < X < 25%	25% < X < 50%	X > 50%

	Testing (A-C)	Production (A1-A3)	Transport to site (A4)	Assembly (A5)	Maintenance (B2)*	Deconstruction (C1)	(Transport to) EOL (C2-C4)	Total life cycle
Climate change - total [kg CO2 eq]	5,15E-04	6,71E-03	8,38E-05	2,96E-04	3,18E-05	1,26E-04	4,46E-05	7,81E-03
Ozone depletion [kg CFC11 eq]	3,08E-11	5,01E-10	1,93E-11	8,28E-12	7,09E-12	3,08E-12	5,05E-12	5,75E-10
Acidification [mol H+ eq]	2,26E-06	5,02E-05	1,20E-06	6,60E-07	1,31E-07	2,78E-07	1,03E-07	5,48E-05
Eutrophication, freshwater [kg P eq]	2,07E-08	3,69E-07	4,84E-10	4,65E-08	8,15E-10	1,99E-08	2,37E-10	4,58E-07
Eutrophication, marine [kg N eq]	3,78E-07	7,25E-06	2,90E-07	1,20E-07	1,98E-08	5,07E-08	3,15E-08	8,14E-06
Eutrophication, terrestrial [mol N eq]	5,07E-06	7,25E-05	3,23E-06	1,49E-06	2,23E-07	6,30E-07	3,46E-07	8,35E-05
Photochemical ozone formation [kg NMVOC eq]	1,27E-06	2,58E-05	8,90E-07	4,01E-07	2,06E-07	1,56E-07	1,08E-07	2,88E-05
Resource use, minerals and metals [kg Sb eq]	3,90E-09	6,97E-07	1,68E-10	6,18E-10	3,38E-10	2,53E-10	7,10E-11	7,02E-07
Resource use, fossils [MJ]	1,39E-02	9,12E-02	1,25E-03	4,10E-03	7,01E-04	1,72E-03	3,51E-04	1,13E-01
Water use [m³ depriv.]	4,97E-05	6,00E-04	1,02E-06	4,31E-06	1,44E-06	1,81E-06	7,85E-07	6,59E-04
Particulate matter [disease inc.]	1,53E-11	4,32E-10	7,00E-12	2,26E-12	1,26E-12	9,32E-13	2,80E-12	4,61E-10
Ionising radiation [kBq U-235 eq]	2,98E-04	3,74E-04	5,41E-06	1,35E-05	2,64E-06	5,64E-06	1,49E-06	7,01E-04
Ecotoxicity, freshwater [CTUe]	9,32E-03	3,06E-01	9,09E-04	2,42E-03	5,22E-04	1,01E-03	4,46E-04	3,21E-01
Human toxicity, cancer [CTUh]	5,12E-13	4,26E-11	3,71E-14	5,85E-14	5,85E-14	2,46E-14	1,58E-14	4,33E-11
Human toxicity, non-cancer [CTUh]	5,21E-12	4,82E-10	8,55E-13	2,20E-12	3,26E-13	9,28E-13	7,72E-13	4,92E-10
Land use [Pt]	4,72E-03	3,64E-02	1,03E-03	5,87E-04	1,41E-04	2,46E-04	3,96E-04	4,35E-02

* only considering the maintenance of the gearbox

**Table 16: Environmental profile of CS2, in absolute values per FU.**

Contribution to impact category	X < 2.5%	2.5% < X < 10%	10% < X < 25%	25% < X < 50%	X > 50%

	Testing (A-C)	Production (A1-A3)	Transport to site (A4)	Assembly (A5)	Maintenance (B2)*	Deconstruction (C1)	(Transport to) EOL (C2-C4)	Total life cycle
Climate change - total [kg CO2 eq]	1,39E-05	5,34E-03	6,72E-05	2,38E-04	3,31E-05	1,01E-04	3,50E-05	5,83E-03
Ozone depletion [kg CFC11 eq]	8,70E-13	4,01E-10	1,55E-11	6,68E-12	6,93E-12	2,47E-12	4,06E-12	4,37E-10
Acidification [mol H+ eq]	6,30E-08	4,04E-05	9,61E-07	5,31E-07	1,64E-07	2,23E-07	8,32E-08	4,24E-05
Eutrophication, freshwater [kg P eq]	7,04E-10	2,96E-07	3,88E-10	3,73E-08	1,06E-09	1,60E-08	1,92E-10	3,52E-07
Eutrophication, marine [kg N eq]	1,34E-08	5,81E-06	2,33E-07	9,65E-08	2,55E-08	4,07E-08	2,54E-08	6,24E-06
Eutrophication, terrestrial [mol N eq]	1,44E-07	5,79E-05	2,59E-06	1,20E-06	2,84E-07	5,06E-07	2,78E-07	6,29E-05
Photochemical ozone formation [kg NMVOC eq]	3,57E-08	2,07E-05	7,14E-07	3,22E-07	2,29E-07	1,25E-07	8,72E-08	2,22E-05
Resource use, minerals and metals [kg Sb eq]	1,39E-10	5,73E-07	1,35E-10	4,97E-10	5,23E-10	2,03E-10	5,75E-11	5,74E-07
Resource use, fossils [MJ]	3,60E-04	7,21E-02	1,00E-03	3,29E-03	7,13E-04	1,38E-03	2,83E-04	7,92E-02
Water use [m³ depriv.]	1,30E-06	4,80E-04	8,17E-07	3,46E-06	1,78E-06	1,46E-06	6,19E-07	4,89E-04
Particulate matter [disease inc.]	4,64E-13	3,45E-10	5,62E-12	1,82E-12	1,70E-12	7,48E-13	2,25E-12	3,57E-10
Ionising radiation [kBq U-235 eq]	7,51E-06	2,77E-04	4,34E-06	1,08E-05	2,69E-06	4,53E-06	1,20E-06	3,08E-04
Ecotoxicity, freshwater [CTUe]	3,26E-04	2,47E-01	7,30E-04	1,94E-03	7,49E-04	8,13E-04	3,59E-04	2,52E-01
Human toxicity, cancer [CTUh]	1,67E-14	3,25E-11	2,98E-14	4,70E-14	2,55E-13	1,97E-14	1,27E-14	3,28E-11
Human toxicity, non-cancer [CTUh]	1,72E-13	3,92E-10	6,86E-13	1,76E-12	5,10E-13	7,45E-13	6,31E-13	3,96E-10
Land use [Pt]	1,24E-04	2,86E-02	8,25E-04	4,71E-04	1,78E-04	1,98E-04	3,19E-04	3,07E-02

* only considering the maintenance of the gearbox

Similar to case 1, this second case also shows that the production stage (A1-A3) is the most relevant life cycle stage. For all impact categories the production stage contributes more than 50% of the assessed life cycle for RS2 as well as CS2, which is caused by the high amounts of material use. In contrary to CS2 – in which the hybrid testing method shows insignificant contribution to the total life cycle impact – the BAU testing method in RS1 does show to be of some relevance in the contribution to the total life cycle impact. Especially, in the impact category 'ionising radiation' it can be considered significant. This is due to the high amount of electricity use during the test run and the big part of nuclear energy considered in the Finish electricity mix.

Figure 16 on the next page shows the relative comparison between RS2 and CS2 based on the two environmental profiles above. In this figure, the scenario (RS2 or CS2) with the highest total life cycle impact per FU is set to 100% and the remaining scenario is shown relative to the one with the highest impact. This is done per impact category. The graph clearly shows that in all impact categories RS1 results in a higher environmental impact per kWh generated than CS1. The reduction of almost 55% in the impact category 'ionising radiation' strikes the most. Also like in case 1, the total life cycle impact of the INNTERSTING scenario per FU in case 2 is smaller than the impact of only the production stage of the BAU reference of case 2 per FU.

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

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Figure 16: Comparison between RS2 and CS2 – relative contribution of all life cycle stages of case 2 wind turbines incl. testing based on environmental profiles in Table 15 and Table 16.
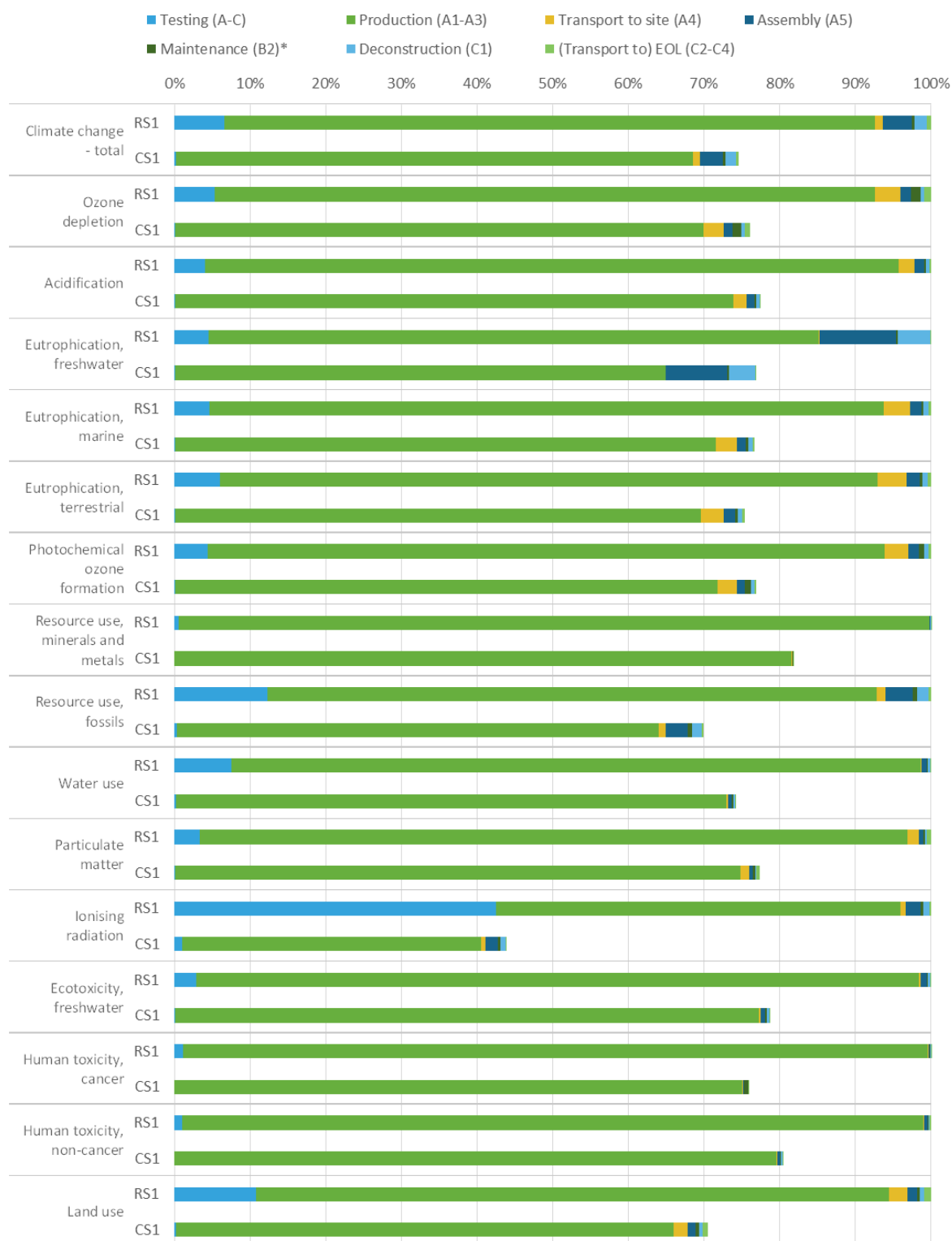
- ## LCA findings related to the gearbox

The next figure show the relative comparison between the BAU gearbox of RS1 and the innovative gearbox of CS1, in which per impact category the gearbox with the highest total life

cycle impact is set to 100% and the other gearbox is shown relative to the one with the highest impact. The figure below clearly shows that the innovative gearbox has significant less environmental impact in all impact categories

Figure 17: Relative comparison between RS2 gearbox and CS2 gearbox.
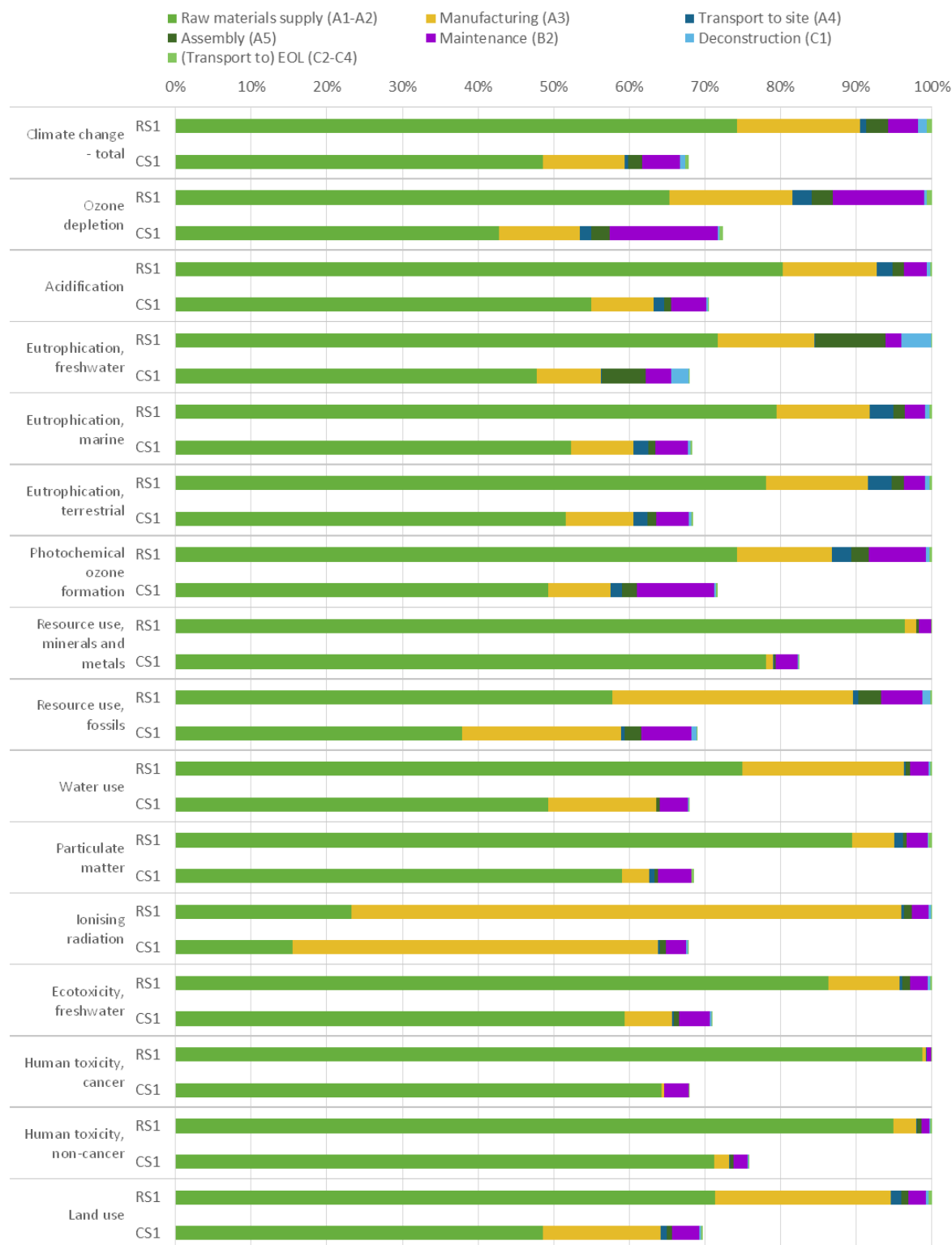
4.3.2. Findings LCC

Figure 18 shows the detailed life cycle cost breakdown of RS2 and CS2 including DEVEX (development and engineering & management), CAPEX (turbine, balance of plant, assembly & installation, transport and financial), OPEX (O&M), and ABEX (end of life). These costs are discounted and are based on the year 2019. A reduction of investment of about € 75 898 is estimated for CS2. This is mainly reflected by the reduction in turbine costs, specifically the gearbox manufacturing and testing costs. A part of the cost reduction is due to the improvement of the service life by 5 years. However, the O&M costs in CS2 increased due to an increase in service life.

Figure 18: Life cycle cost breakdown for (a) RS2 and (b) CS2 – costs in € discounted to 2019
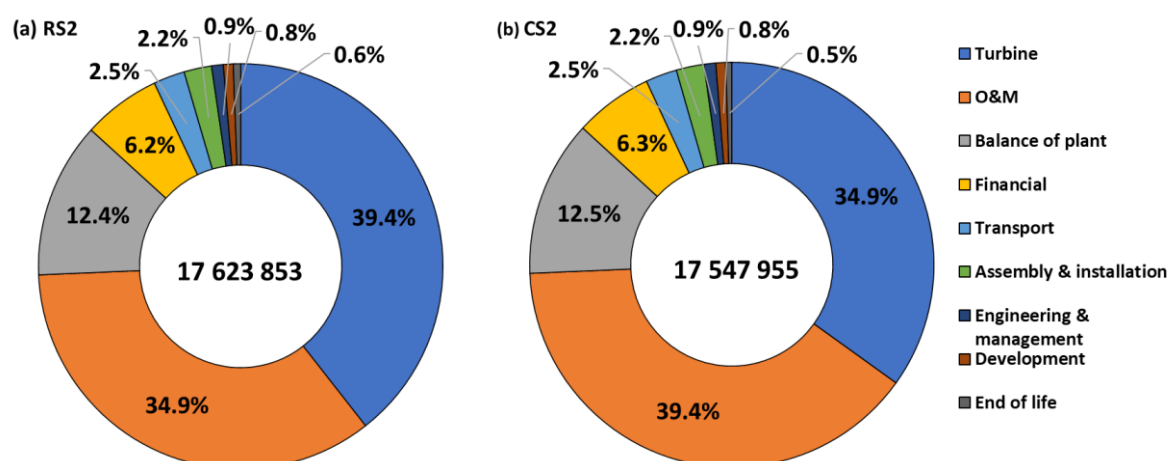
The LCOE estimates of the RS2 with the BAU testing method and the CS2 with the hybrid testing method for the gearbox are shown in Table 17. The LCOE is decreased by 15.2% in CS2 due to an improved gearbox life (25 years), relatively less manufacturing cost, and hybrid testing methods that make the gearbox more reliable. The denominator values represent the discounted AEP used in LCOE estimation. However, the corresponding net AEP values are 924 224 740 kWh and 3 397 916 400 kWh. Due to an improvement in the service life, an additional 1 178 386 544 kWh of energy is produced over the wind turbine service life. Using the difference in LCOE (0.004 €/kWh) and multiplying by the additional energy produced, the potential savings are € 1 058 821 for a single wind turbine over 25 years of service life with innovative gearbox and hybrid testing methods.

Table 17: LCOE comparison between RS2 and CS2

	LCOE [€/kWh]	Numerator [€]	Denominator [kWh]
RS2	0.032	17 623 853	557 216 956
CS2	0.027	17 547 955	638 980 720

Figure 19 shows the detailed LCOE breakdown comparison for RS2 and CS2 in €/MWh. In the CS2 scenario, the turbine cost is reduced by € 2.9 /MWh which is a significant reduction owing to innovative gearbox design with longer service life and hybrid testing methods. The O&M cost decreased by € 0.2 /MWh while the BOP, financial, transport, installation, and end-of-life

decreased by € 0.5, € 0.3, € 0.1, and € 0.1 per MWh, respectively. No changes were observed in engineering & management and development costs.

Figure 19: Detailed LCOE breakdown [€/MWh] for RS2 and CS2 – cost discounted to 2019
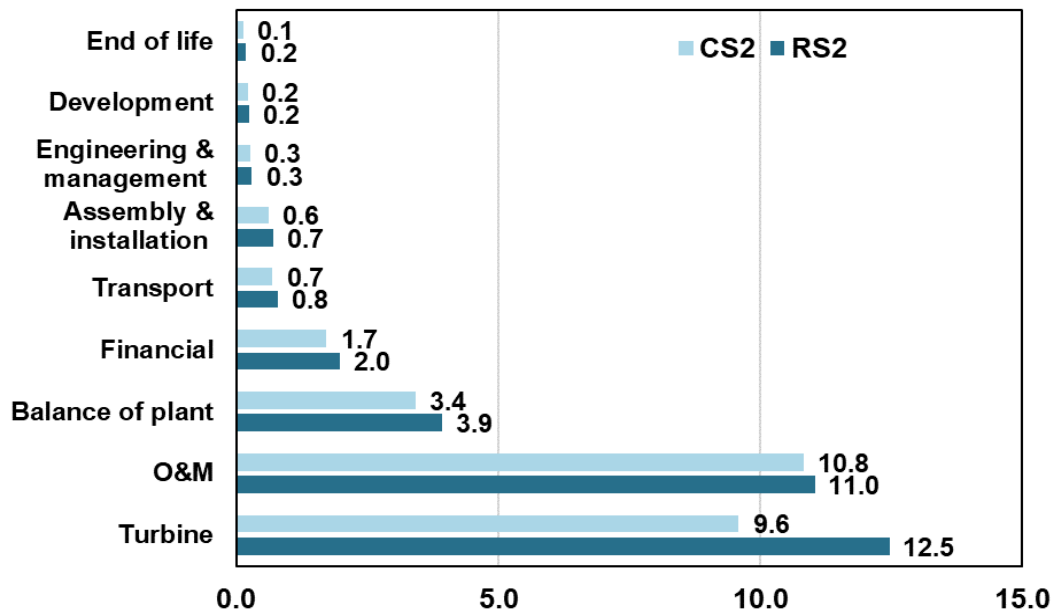
- **LCC findings related to the gearbox and testing methods in RS2 and CS2**

The cost of the innovative gearbox proposed in CS2 is lower than the cost in RS2 due to a lower material requirement. The cost of the gearbox mechanism is about 6.1% (€ 1 073 524) and 5.6% (€ 976 888) of the overall discounted costs in RS2 and CS2, respectively. There is about a 10% reduction in the gearbox manufacturing costs since less material is used in the innovative design. The hybrid testing methods proposed in the INNTERESTING project are significantly cheaper and less time-consuming when compared to BAU RS2 testing methods. The costs of the three hybrid testing methods are CSP = € 9 639, JBL = € 1 274, and TD = € 3 535 which adds to € 14 449 per wind turbine and is 5000% less than the BAU testing method. However, this large improvement in costs is not reflected in the overall LCOE as these costs are insignificant. In addition to a cost reduction, the time for testing is also significantly reduced compared to the BAU testing method taking 2-3 years. Using a virtual model and testing for different ways of failure increases the reliability of the testing process and the gearbox resulting in a lower risk of failure.

4.3.3. Findings S-LCA

Also for case study 2, hotspots for social risks and opportunities along the life cycle have been identified. Absolute values for all stakeholder categories and social indicators of PSILCA are available in Annex B for both the BAU RS2 and the INNTERESTING CS2. In this section, the discussion is limited to a selection of material impact categories as described in section 1.2. The maintenance costs clearly form the biggest share in the life cycle costs. Nevertheless, when looking at the stakeholder group **'workers'**, Figure 20 shows that 'the production of all other components'[19] is the most important life cycle stage in the impact categories 'DALYs due to indoor and outdoor pollution', 'presence of sufficient safety measures', 'non-fatal accidents' and 'fatal accidents', however, in this last impact category, 'maintenance' is equally important.

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[19] All turbine components except for gearbox, blades, pitch mechanism and electrical system.

'Maintenance' is the most important life cycle stage in the impact category 'fair salary'. Lower social risks during the life cycle are observed for CS2 compared to RS2. The main driver is, as in case study 1, the reduced LCOE, which results in lower social risks per functional unit, being 1 kWh of electricity output delivered to the grid. This observation is also valid for the other two stakeholder categories.

For the stakeholder categories '**local communities'** (Figure 21) and for the stakeholder category **'society'** (Figure 22) also maintenance and the production of all other components are hotspots in the life cycle of both the reference case (RS2) and the INNTERESTING solution (CS2). Finally Figure 23 shows the results for the opportunity 'contribution to economic development' and reveals that greater opportunities are created in the reference case (RS2) compared to the INNTERESTING solution (CS2).

Social risks related to the testing of the gearbox are irrelevant for most of the investigated social indicators. For the impact categories 'fair salary' and 'non-fatal accident' the contribution of the BAU testing has a contribution of around 12% to the overall risks generated over the life cycle. As can be seen in Figure 20 a switch to hybrid testing (CS2) clearly reduces the social risks of the testing step.

Figure 20: Comparison of RS2 and CS2 over the life cycle – social risks for 'workers', cost provided as a reference.
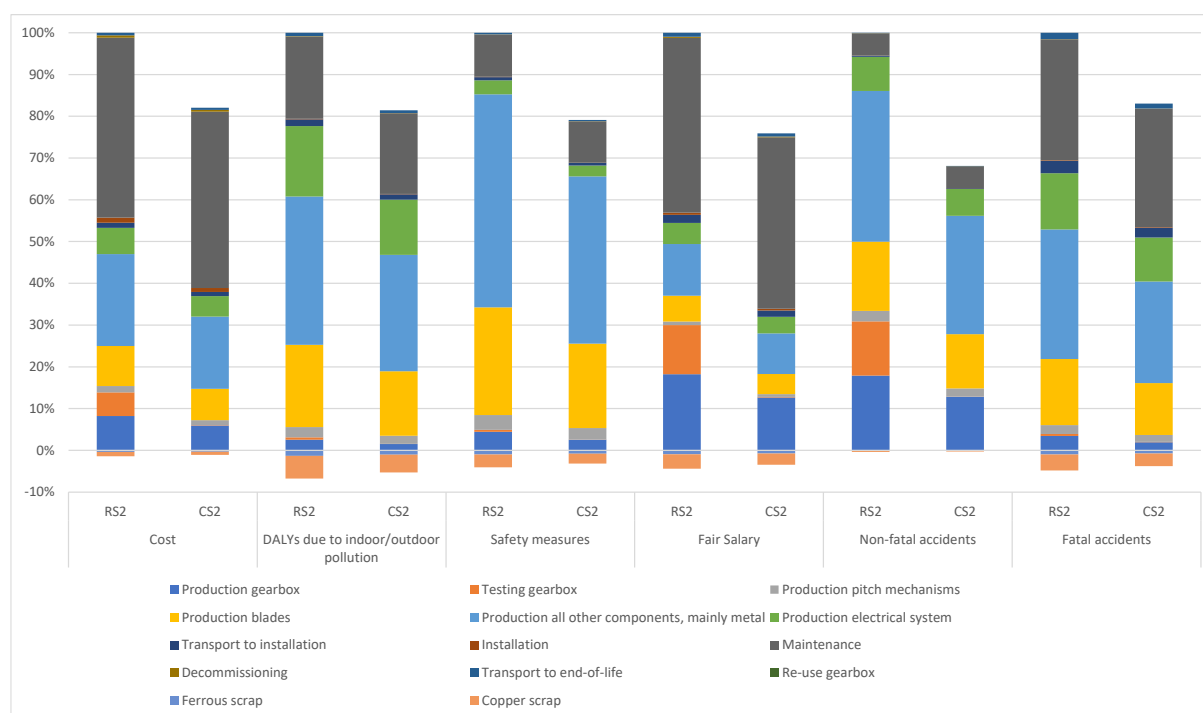
Figure 21: Comparison of RS2 and CS2 over the life cycle – social risks for 'local communities', cost provided as a reference.
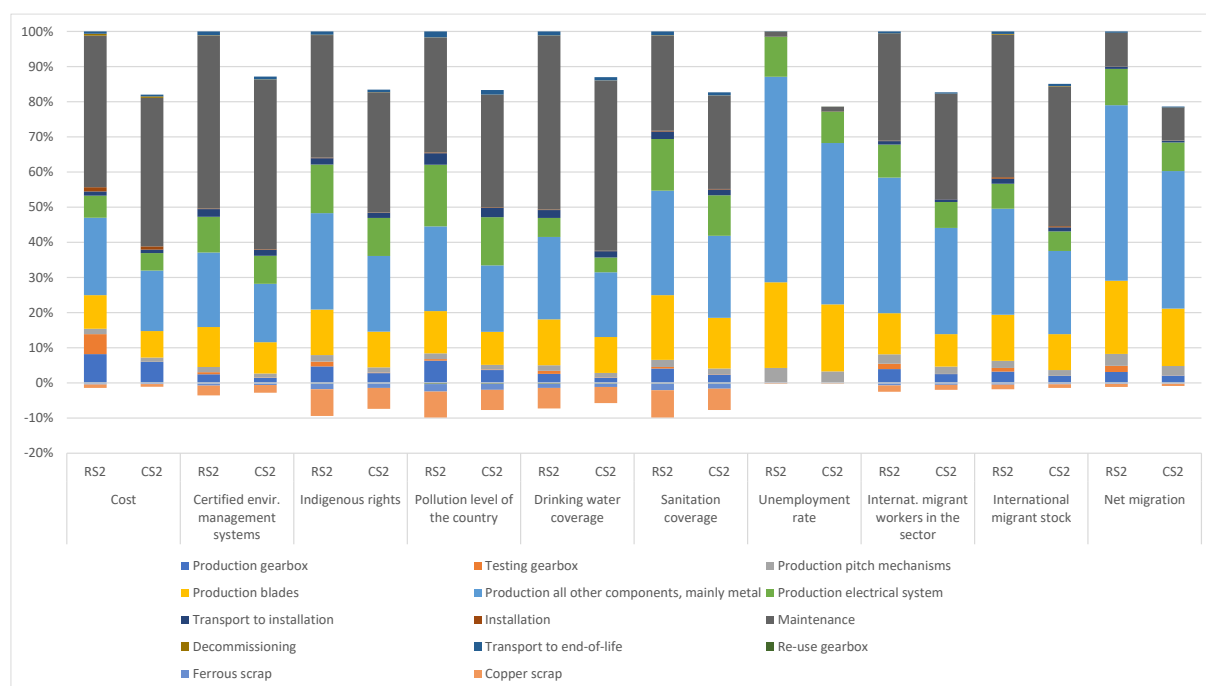
Figure 22: Comparison of RS2 and CS2 over the life cycle – social risks for 'society', cost provided as a reference.
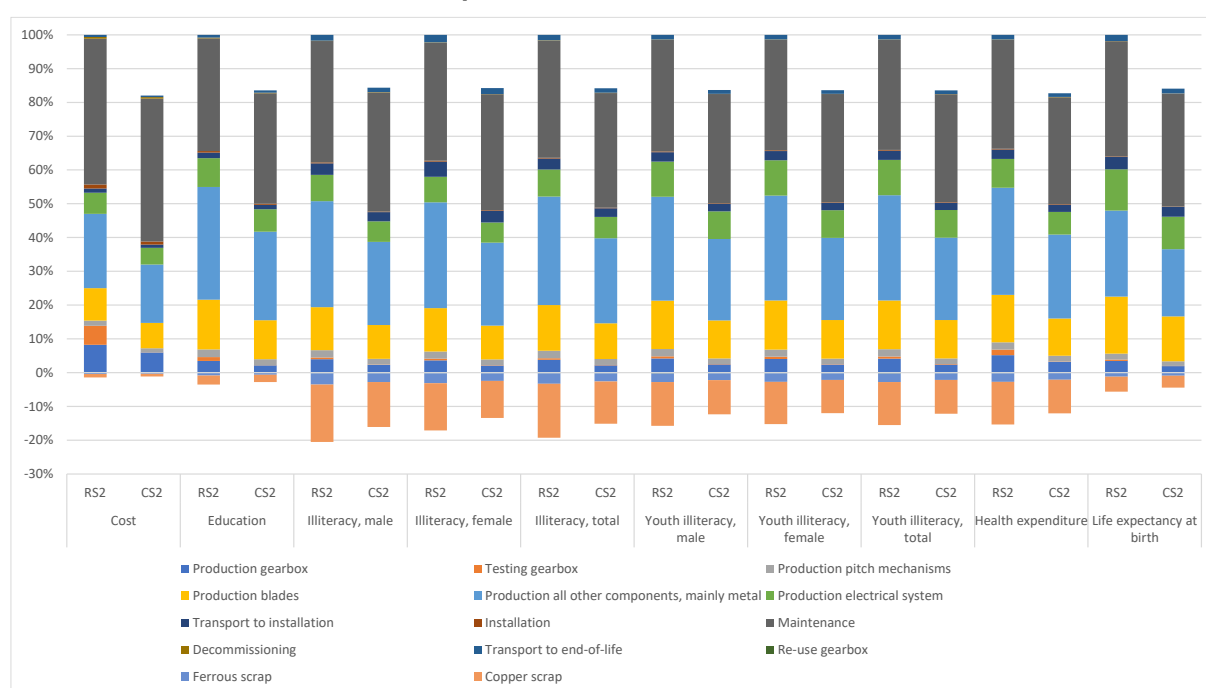
Figure 23: Comparison of RS2 and CS2 over the life cycle – opportunity 'contribution to economic development'.
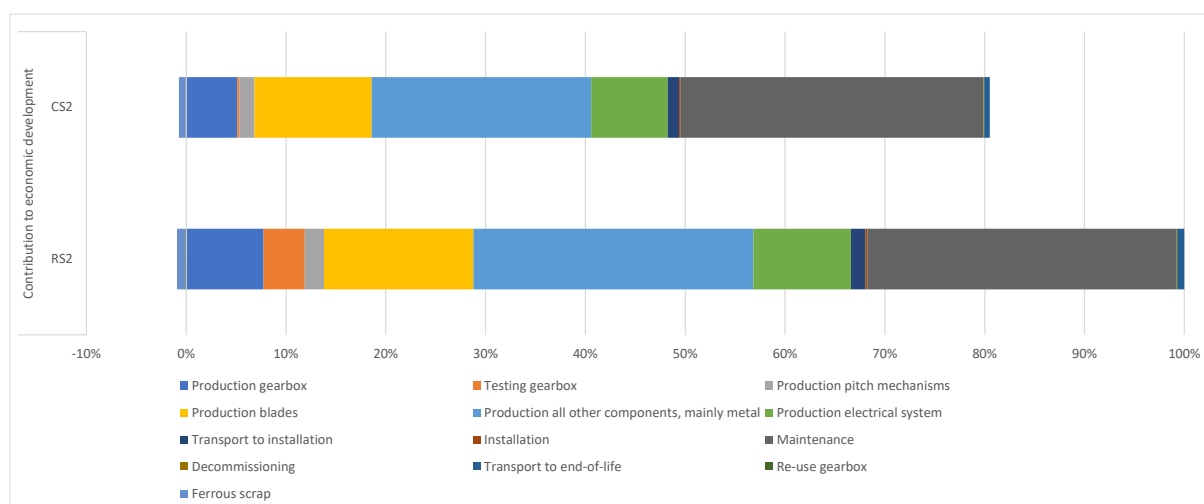
- ### S-LCA findings related to the gearbox

Figure 24 shows the results of the S-LCA for the gearbox production, again for a selected set of impact categories for the stakeholder group '**workers'**. The production of the gear materials is the hotspot in the impact categories, 'DALYs due to indoor and outdoor air pollution', 'safety measures' and 'fatal accidents'. The 'gearbox assembly' is the hotspot in the impact categories 'fair salary' and 'non-fatal accidents'. For the gearbox production primary data have been used for cost, worker hours and risk levels, generic background data on downstream and upstream sectors have been taken from the PSILCA v2 database (Eisfeldt and Ciroth, 2018). When comparing the gearbox production in RS2 with CS2, it becomes clear that social risks are lower for CS2 also for the stakeholder groups '**local communities'** (see Figure 25) and '**society'** (see Figure 26). Figure 27 shows results for the opportunity 'contribution to economic development'.

Figure 24: Results of the social hotspot analysis for RS2 and CS2 gearbox production in Finland for selected impact categories of the stakeholder category 'workers'.
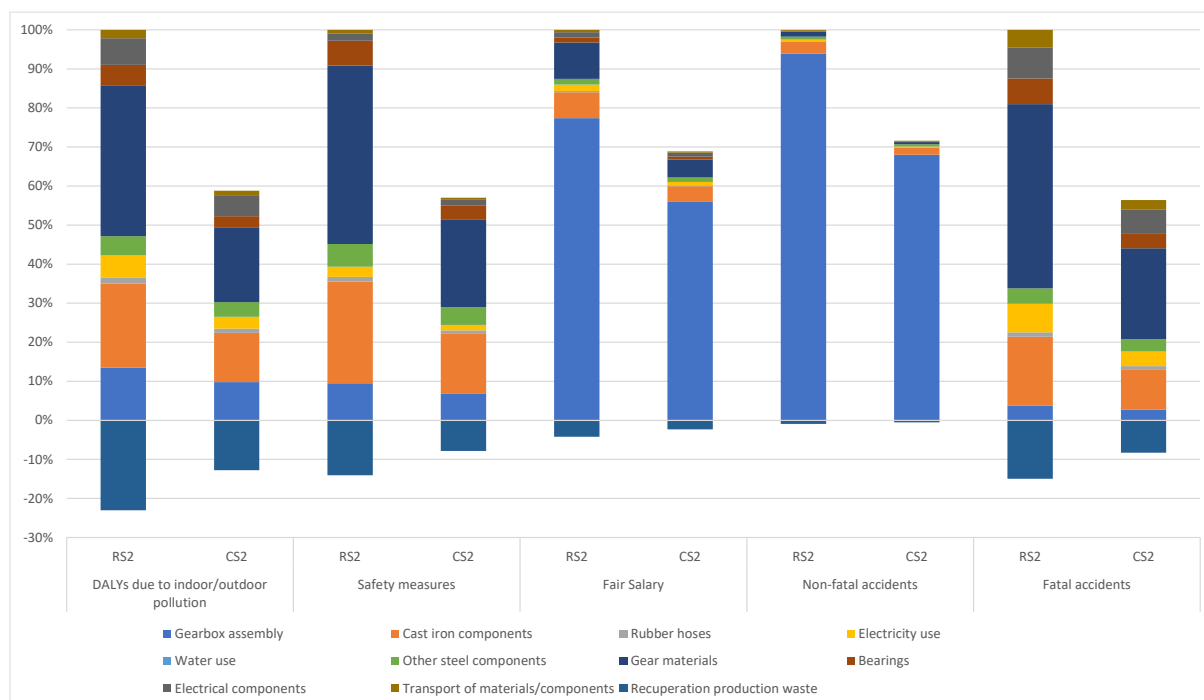
Figure 25: Results of the social hotspot analysis for RS2 and CS2 gearbox production in Finland for stakeholder category 'local communities'.

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

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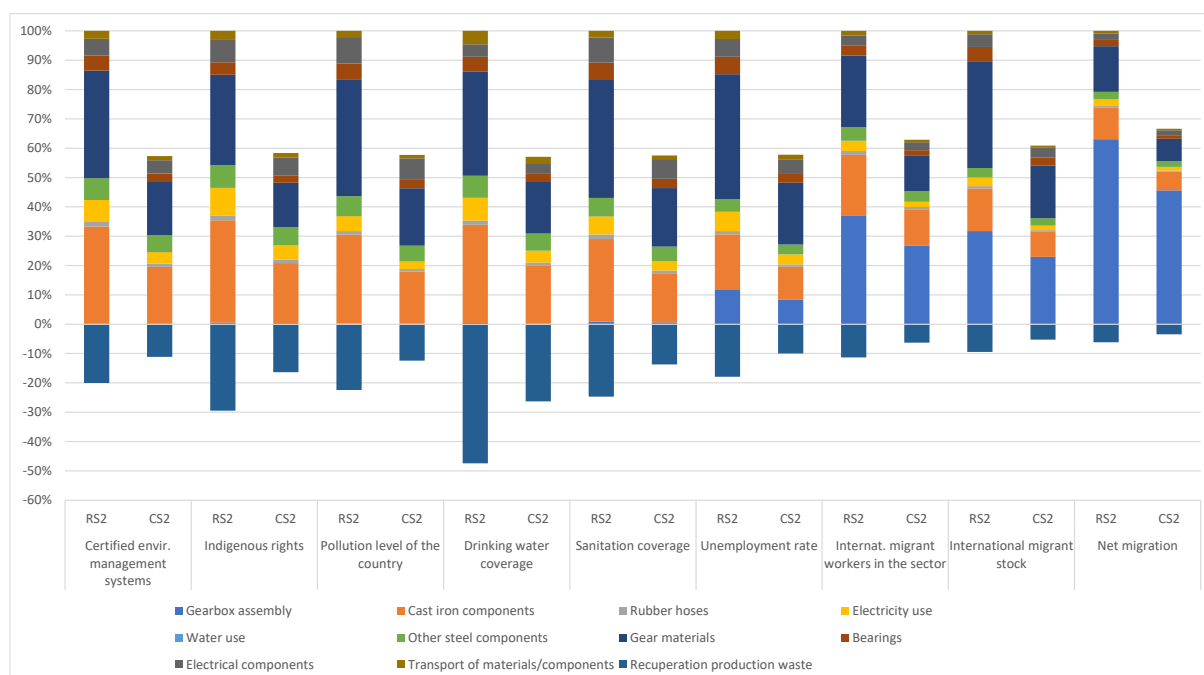
Figure 26: Results of the social hotspot analysis for RS2 and CS2 gearbox production in Finland for stakeholder category 'society'.
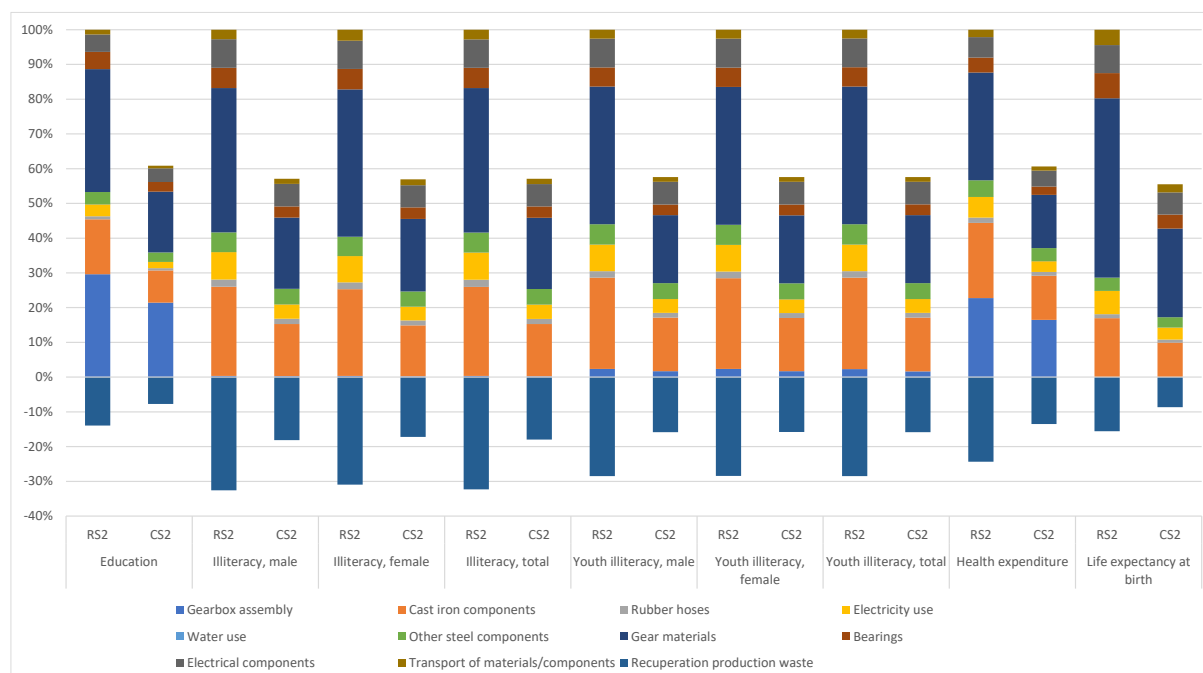
Figure 27: Results of the social hotspot analysis for RS2 and CS2 gearbox production in Finland for stakeholder category 'society', opportunity contribution to economic development
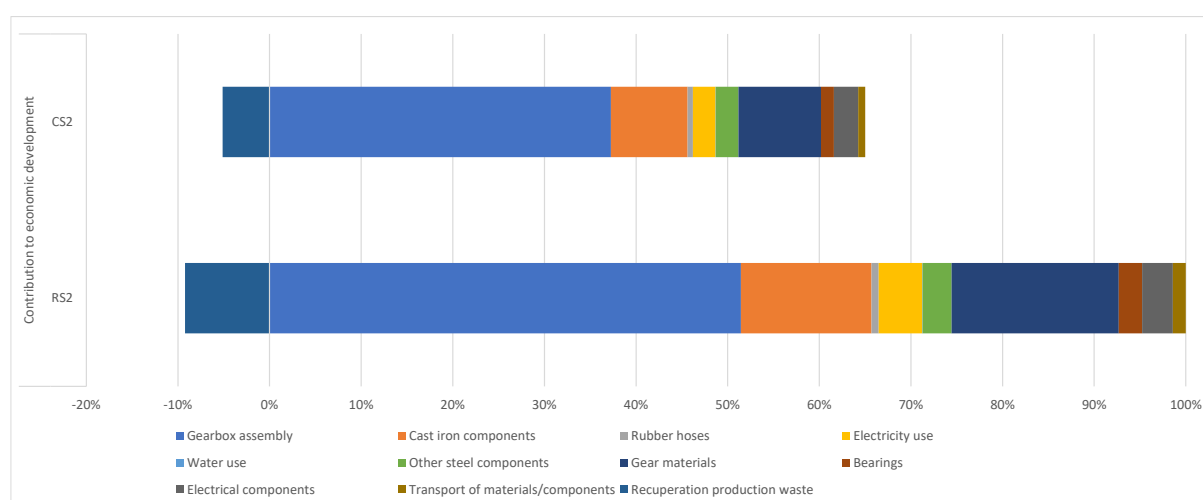
4.4. Conclusions comparative LCSA case 2

On all assessed environmental impact categories, CS2 has a lower environmental impact than RS2 – the reduction ranges between approximately 20 to 55%. This is caused by the increased total energy output of CS2 and the lower environmental impact of the hybrid testing method and innovative gearbox design.

The LCOE estimated for RS2 is 0.032 €/kWh whereas the estimated value for CS2 is 0.027 €/kWh, which is a reduction of 15.2%. This is mainly due to the increased service life of the gearbox resulting in a higher net AEP over the turbine lifespan, relatively less manufacturing cost, and hybrid testing methods. A 10% reduction in the gearbox manufacturing costs is

estimated since less material is used in the innovative design. Using the difference in LCOE (0.004 €/kWh) and multiplying by the additional energy produced, the potential savings are € 1 058 821 for a single wind turbine over 25 years of service life with innovative gearbox and hybrid testing methods. The hybrid testing methods proposed in the INNTERESTING project are significantly cheaper and less time-consuming when compared to BAU RS2 testing methods. The total cost of hybrid testing methods is € 14 449 per wind turbine which is 5000% less than the BAU testing method. However, this large improvement in costs is not reflected in the overall LCOE as these costs are insignificant. Although there is no significant effect of testing costs on LCOE, the time for testing is reduced significantly compared to the BAU testing method resulting in a lower time to market for innovative gearbox designs.

The social risks occurring during the life cycle are lower for the INNTERESTING case (CS2) compared to the BAU (RS2). Hotspots for social risks are the life cycle stages 'maintenance' and 'the production of all other components'. When it comes to social opportunities (contribution to economic development), higher opportunities are identified for RS2 compared to CS2. Social risks related to the testing of the gearbox are irrelevant for most of the investigated social indicators. For the impact categories 'fair salary' and 'non-fatal accident' the contribution of the BAU testing (RS2) is around 12% to the overall risks generated over the life cycle which is reduced to less than 1% contribution when a switch is made to hybrid testing (CS2).

5. LCSA case 3

As last case of the LCSA, the following scenario has been analysed in the comparative assessment between RS3 and CS3. In 2024, (at least) one pitch bearing fails prematurely after 4 years of operation. In the BAU scenario, all three pitch bearings are replaced fully after a redesign resulting in a downtime of 6 months. In case of the CS3 scenario, there is only a downtime of 1.5 months thanks to the innovative repair and stiffening solution. In both scenarios, the wind turbines are decommissioned after a service life of 20 years.

In contrast to the other two cases, no prototype testing processes are included in the assessment. This third cases only focusses on the comparison between a BAU replacement of failed pitch bearings and the developed INNTERESTING repair and stiffening solution.

Figure 28: Scheme of the assessed scenario of the comparison between RS3 and CS3.
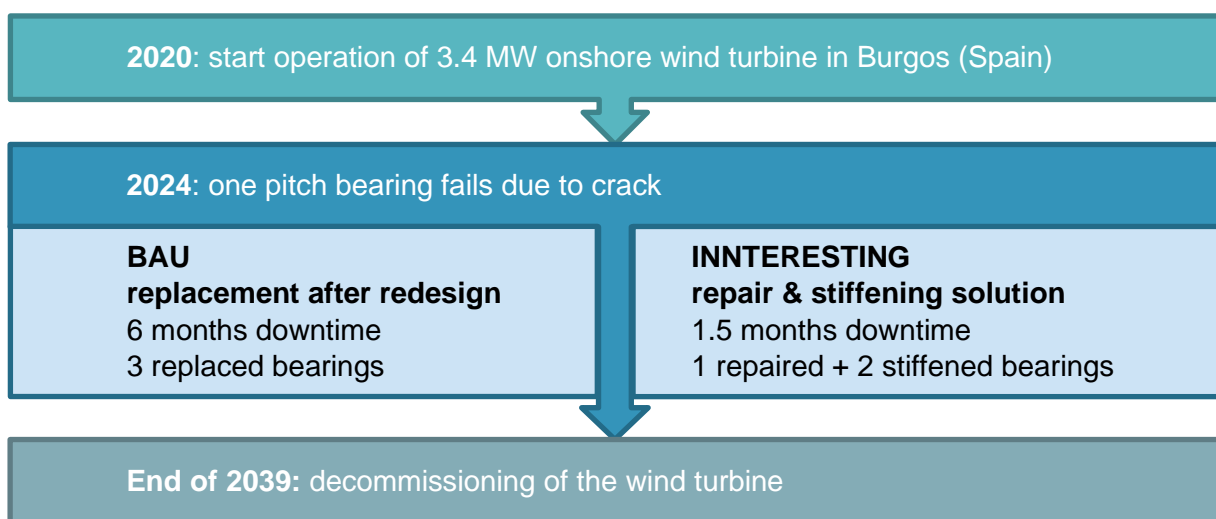
5.1. Scope RS3 and CS3

- **Functional units RS3 and CS3**

The table on the next page gives the specific FU of RS3 and CS3 based on the general FU and the parameters considered to calculate the total electricity output of the two wind turbines.

Table 18: Specific FU and electricity output parameters of RS3 and CS3

	RS3	CS3
Specific FU	1 kWh of the total electricity output delivered to the grid over the service life of **20 years** by a 3.4 MW onshore wind turbine with **(a) prematurely failed pitch bearing(s)** in year 4 **that will be replaced BAU after a redesign of the original pitch bearing**	1 kWh of the total electricity output delivered to the grid over the service life of **20 years** by a 3.4 MW onshore wind turbine with **(a) prematurely failed pitch bearing(s)** in year 4 **to which an innovative reparation and stiffening solution will be applied**
Capacity factor	24% (WindEurope, 2020)	Same as BAU
Annual Energy Production (AEP)	7 148 MWh/y[20]	Same as BAU
AEP in year 4	3 574 MWh	6 255 MWh
Total energy output	139 389 120 kWh	142 069 680 kWh

- **Specifications RS3 and CS3**

The next table and figure present the assumed specifications of the wind turbine and wind farm of case 3.

Table 19: Specifications of the RWT and wind farm of RS3/CS3.

Dimensions wind turbine	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 RS3	Pitch bearing with a diameter of 2.6 m that will fail prematurely and that will be replaced BAU after a redesign of the original pitch bearing Specific data provided by Laulagun Bearings SA
Specific component CS3	Pitch bearing with a diameter of 2.6 m that will fail prematurely and to which an innovative reparation and 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)

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[20] Calculated based on the capacity factor.

**Figure 29: Left – Plot of 3.4 MW land-based wind turbine (Dykes, 2019).
Right – Wind farm location of RS3/CS3: Burgos, Spain.**

5.2. LCI RS3 and CS3

Please refer to the tables in section 3.4 of D6.1 (page 43-46) for the complete overview of the LCI data of RS3. These data has been reused with the following corrections:

Corrections on specific LCI data of RS3 compared to D6.1:

1. Regarding the LCA inventory data, the following changes were made:
   - Addition of 28 800 kg pitch motors, gearing and control system to the rotor. Amount based on the weight of the pitch bearing and the material composition based on RS2.
   - Lowered the amount of drive train brake to 1 187 kg based on RS2 and assumed remaining 10 653 kg as structural components after consultation with IKERLAN.
   - Increased the amount of turbine connection from 7 800 to 8 000 kg.
   - Lowered the amount of monitoring and safety system from 1 700 to 1 500 kg.
   - Lowered the amount of steel of the tower from 553 000 to 470 000 kg based on the ratio between the hub height and tower weight of RS1 and RS2, as the contribution of the weight of the tower to the total weight of the wind turbine was very high.
2. No specific data on maintenance (B2) was included in D6.1. However after the publication of D6.1, specific maintenance data of the pitch bearings were received from Laulagun and are added in this final LCSA. Costs for maintenance of the other components were already included in D6.1 based on a report by Stehly & Beiter (2020). Similar to the previous two cases, the environmental impact of the maintenance of the other components is seen as insignificant and considered as a cut-off that would not affect the results and conclusions of the LCA.
3. For company specific S-LCA data, see section 3.2.1.

To define the specific replacement and repair scenarios of RS3 and CS3 respectively, the following assumptions have been considered:

Assumed RS3 data regarding replacement after redesign solution:

- 100 engineering hours to redesign the pitch bearings for 1 wind farm;
- 5% additional material use compared to original, failed pitch bearing;
- 2 days of crane rent for disassembly and installation with 2 cranes per wind turbine;;
- 2 days of labour by 5 persons per wind turbine;.

Assumed CS3 data regarding innovative repair and stiffening solution:

- 80 engineering hours to define the repair and stiffening solution for 1 wind farm;
- Approximately 4 L of epoxy adhesive for 3 pitch bearings;
- Approximately 170 kg of steel patches for 3 pitch bearings;
- Development of steel tools that can be reused;
- 1 day of crane rent per pitch bearing, thus 3 days per wind turbine;
- 1 day of labour by 2 persons per pitch bearing, thus 3 days per wind turbine by 2 persons.

5.3. LCIA RS3 and CS3

The following subsections present the results and interpretation of the life cycle impact assessment (LCIA) of case 1 comprising of the comparison between RS3 and CS3. First the environmental LCA findings are given, followed by the economic LCC results and the S-LCA results. As already explained in the introduction of section 4 of D6.1 (page 47), the LCIA of the LCSA predicts *potential* environmental, economic or social damages (impacts) related to the system under study; and cannot and is not intended for identifying or predicting *actual* impacts.

5.3.1. Findings LCA

Table 15 and Table 16 (on the next page) provide the environmental impact results in absolute values for 1 kWh of electricity generated to the grid by a 10 MW onshore wind turbine installed in Burgos, Spain with a pitch bearing that fails ins it fourth year of operation. In case of RS3, the pitch bearings are replaced after a redesign and results in a downtime of 6 months. In case of CS3, the pitch bearings are repaired and stiffened and gives a downtime of only 1.5 months.

Based on Table 15 and Table 16 it can be concluded that – similar to the previous two cases – the production stage (A1-A3) is the most relevant life cycle stage, as that stage contributes more than 50% in all assessed impact categories. The repair and stiffening solution in CS3 has an insignificant impact on the total life cycle impact for all assessed impact categories. The BAU replacement also has an insignificant impact, with the exception for the impact category 'human toxicity, cancer' showing a very small contribution to the total life cycle impact.

Table 20: Environmental profile of RS3, in absolute values per FU.

Contribution to impact category	X < 2.5%	2.5% < X < 10%	10% < X < 25%	25% < X < 50%	X > 50%

	Production (A1-A3)	Transport to site (A4)	Assembly (A5)	Maintenance (B2)*	Replacement (B3)	Deconstruction (C1)	(Transport to) EOL (C2-C4)	Total life cycle
Climate change - total [kg CO2 eq]	2,17E-02	2,41E-04	6,00E-04	4,59E-06	5,33E-04	2,57E-04	1,82E-04	2,35E-02
Ozone depletion [kg CFC11 eq]	1,66E-09	5,98E-11	3,66E-11	1,02E-12	3,27E-11	1,57E-11	2,13E-11	1,83E-09
Acidification [mol H+ eq]	1,51E-04	9,55E-07	5,06E-06	1,77E-08	2,90E-06	2,17E-06	4,37E-07	1,63E-04
Eutrophication, freshwater [kg P eq]	1,42E-06	1,70E-09	2,58E-08	1,05E-10	2,22E-08	1,10E-08	1,02E-09	1,49E-06
Eutrophication, marine [kg N eq]	2,26E-05	2,16E-07	7,42E-07	2,76E-09	4,98E-07	3,18E-07	1,33E-07	2,45E-05
Eutrophication, terrestrial [mol N eq]	2,41E-04	2,40E-06	8,31E-06	3,11E-08	5,48E-06	3,56E-06	1,46E-06	2,62E-04
Photochemical ozone formation [kg NMVOC eq]	8,65E-05	8,67E-07	2,23E-06	2,74E-08	1,67E-06	9,57E-07	4,57E-07	9,27E-05
Resource use, minerals and metals [kg Sb eq]	2,30E-06	5,72E-10	1,68E-09	4,12E-11	1,21E-08	7,20E-10	3,06E-10	2,32E-06
Resource use, fossils [MJ]	2,75E-01	3,90E-03	1,38E-02	9,78E-05	6,48E-03	5,93E-03	1,48E-03	3,07E-01
Water use [m³ depriv.]	2,14E-03	3,32E-06	3,80E-04	1,89E-07	4,08E-05	1,63E-04	3,23E-06	2,73E-03
Particulate matter [disease inc.]	1,40E-09	2,73E-11	1,15E-11	1,78E-13	3,67E-11	4,95E-12	1,18E-11	1,49E-09
Ionising radiation [kBq U-235 eq]	1,04E-03	1,69E-05	1,47E-04	3,71E-07	2,53E-05	6,29E-05	6,28E-06	1,30E-03
Ecotoxicity, freshwater [CTUe]	1,03E+00	3,03E-03	9,16E-03	6,67E-05	1,55E-02	3,93E-03	1,87E-03	1,07E+00
Human toxicity, cancer [CTUh]	1,34E-10	8,52E-14	2,16E-13	1,78E-15	9,50E-12	9,27E-14	6,67E-14	1,44E-10
Human toxicity, non-cancer [CTUh]	1,44E-09	3,17E-12	6,58E-12	4,21E-14	1,16E-11	2,82E-12	3,45E-12	1,47E-09
Land use [Pt]	1,22E-01	4,39E-03	2,18E-03	2,06E-05	3,35E-03	9,36E-04	1,67E-03	1,34E-01

* only considering the maintenance of the pitch bearings

Table 21: Environmental profile of CS3, in absolute values per FU.

Contribution to impact category	X < 2.5%	2.5% < X < 10%	10% < X < 25%	25% < X < 50%	X > 50%

	Production (A1-A3)	Transport to site (A4)	Assembly (A5)	Maintenance (B2)*	Repair (B3)	Deconstruction (C1)	(Transport to) EOL (C2-C4)	Total life cycle
Climate change - total [kg CO2 eq]	2,13E-02	2,37E-04	5,89E-04	4,51E-06	1,80E-04	2,52E-04	1,78E-04	2,27E-02
Ozone depletion [kg CFC11 eq]	1,63E-09	5,86E-11	3,59E-11	9,98E-13	2,43E-11	1,54E-11	2,09E-11	1,79E-09
Acidification [mol H+ eq]	1,49E-04	9,36E-07	4,96E-06	1,73E-08	7,19E-07	2,13E-06	4,29E-07	1,58E-04
Eutrophication, freshwater [kg P eq]	1,40E-06	1,67E-09	2,53E-08	1,03E-10	5,31E-09	1,08E-08	1,00E-09	1,44E-06
Eutrophication, marine [kg N eq]	2,22E-05	2,12E-07	7,28E-07	2,71E-09	1,28E-07	3,12E-07	1,31E-07	2,37E-05
Eutrophication, terrestrial [mol N eq]	2,36E-04	2,35E-06	8,16E-06	3,05E-08	1,42E-06	3,50E-06	1,43E-06	2,53E-04
Photochemical ozone formation [kg NMVOC eq]	8,49E-05	8,51E-07	2,19E-06	2,69E-08	5,70E-07	9,39E-07	4,48E-07	8,99E-05
Resource use, minerals and metals [kg Sb eq]	2,26E-06	5,61E-10	1,65E-09	4,04E-11	1,86E-09	7,07E-10	3,00E-10	2,26E-06
Resource use, fossils [MJ]	2,70E-01	3,83E-03	1,36E-02	9,59E-05	3,04E-03	5,82E-03	1,45E-03	2,98E-01
Water use [m³ depriv.]	2,10E-03	3,25E-06	3,72E-04	1,85E-07	8,48E-06	1,60E-04	3,17E-06	2,64E-03
Particulate matter [disease inc.]	1,37E-09	2,68E-11	1,13E-11	1,74E-13	6,70E-12	4,85E-12	1,15E-11	1,43E-09
Ionising radiation [kBq U-235 eq]	1,02E-03	1,66E-05	1,44E-04	3,64E-07	5,62E-06	6,17E-05	6,17E-06	1,25E-03
Ecotoxicity, freshwater [CTUe]	1,01E+00	2,97E-03	8,99E-03	6,55E-05	6,91E-03	3,85E-03	1,83E-03	1,04E+00
Human toxicity, cancer [CTUh]	1,32E-10	8,36E-14	2,12E-13	1,75E-15	2,01E-13	9,10E-14	6,54E-14	1,32E-10
Human toxicity, non-cancer [CTUh]	1,42E-09	3,11E-12	6,45E-12	4,13E-14	2,35E-12	2,77E-12	3,38E-12	1,43E-09
Land use [Pt]	1,19E-01	4,31E-03	2,14E-03	2,02E-05	4,80E-04	9,18E-04	1,63E-03	1,29E-01

* only considering the maintenance of the pitch bearings

Figure 30 below shows the relative comparison between RS3 and CS3 based on the two environmental profiles above. In that figure, the scenario (RS3 or CS3) with the highest total life cycle impact per FU is set to 100% and the remaining scenario is shown relative to the one with the highest impact, per impact category. The graph shows that RS3 has a bigger environmental impact than CS3, but also that the difference between RS3 and CS3 is limited to maximal 8 %.

Figure 30: Comparison between RS3 and CS3 – relative contribution of all life cycle stages of case 3 wind turbines incl. testing based on environmental profiles in Table 15 and Table 16.
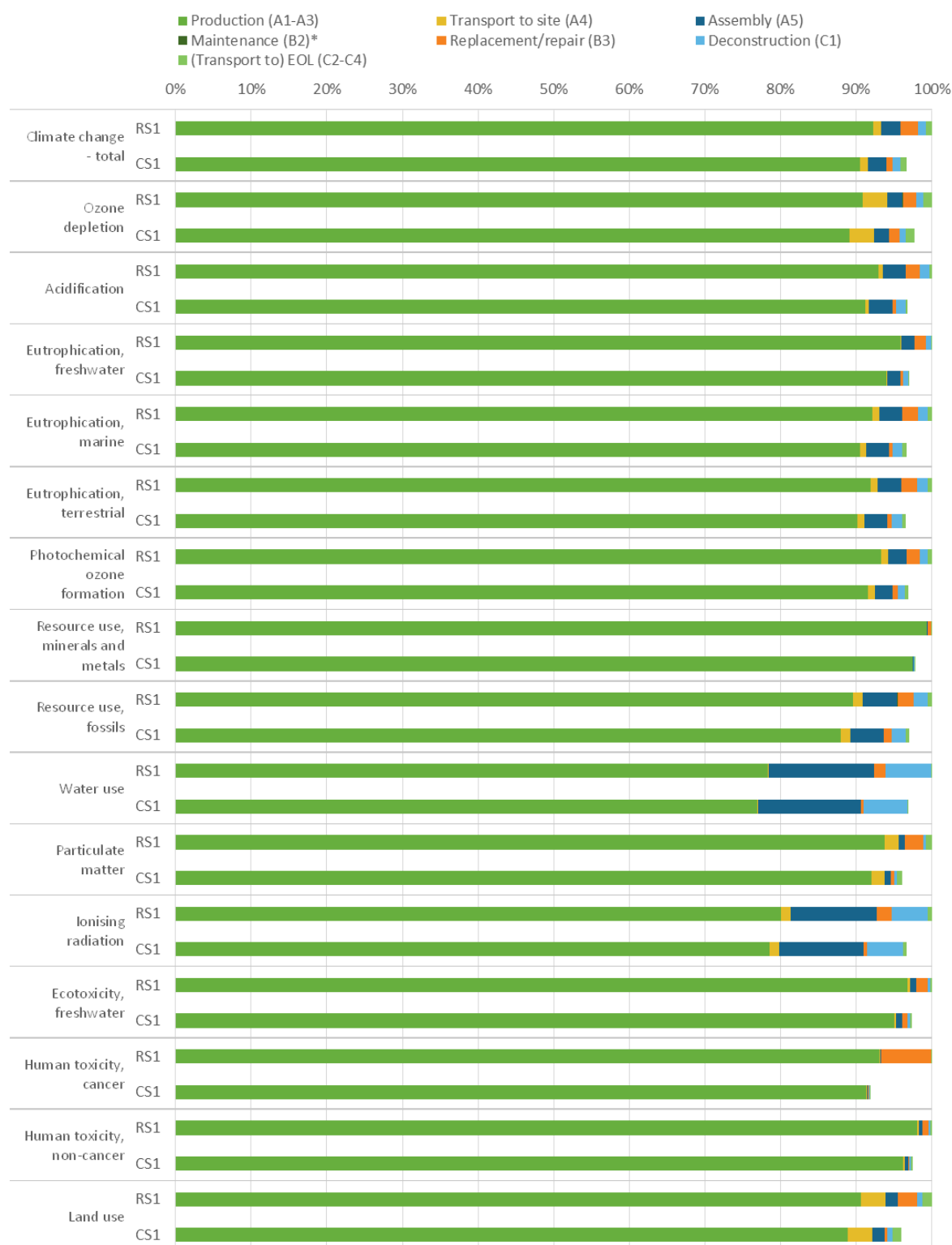
5.3.2.   Findings LCC

Figure 31 shows the detailed life cycle cost breakdown of RS3 and CS3 including DEVEX (development and engineering & management), CAPEX (turbine, transport, balance of plant, assembly & installation and financial), OPEX (O&M) and ABEX (end-of-life). These costs are discounted with the year 2019 as the base year. Both the distribution of the costs and the total costs over the lifetime of the wind turbines are very similar for RS3 and CS3. Behind this small difference of € 380 lies a mix of both increasing and decreasing costs, based on estimates for the year in which the failure of the bearing(s) takes place. The variations between the BAU and CS3 are further clarified in the next table and graph.

Figure 31: Life cycle cost breakdown for (a) RS3 and (b) CS3 – costs in € discounted to 2019
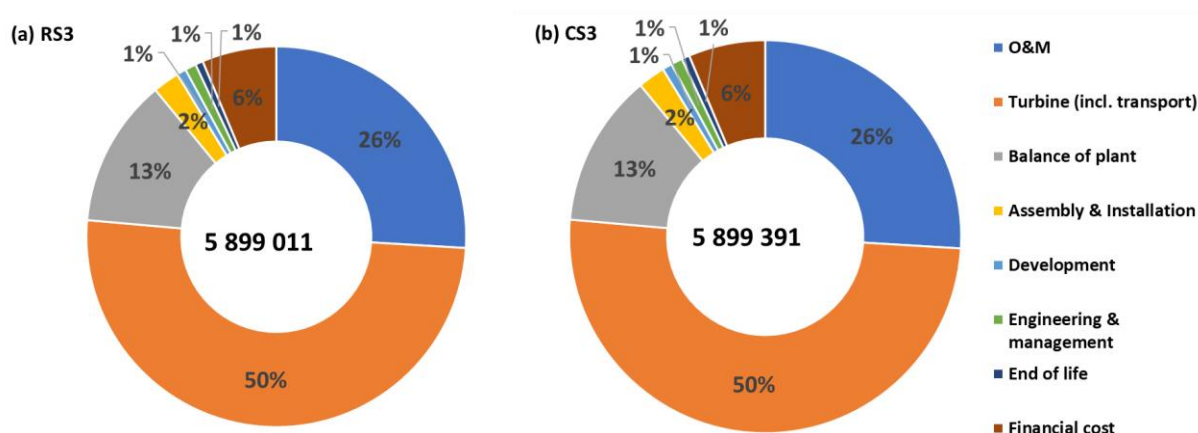
The LCOE estimates in €/kWh of the RS3 (with the BAU replacement) and the CS3 (with the innovative reparation and stiffening solution) are shown in Table 22. For CS3 the LCOE has decreased by 2%. This improvement in costs can mainly be explained by a decrease in material and (dis)assembly costs, which, however, is largely nullified by an increase in variable O&M costs. Therefore, the numerator values, which represent the discounted total sum of costs for the wind turbine, are almost identical for RS3 and CS3 (a difference of € 380). The denominator values represent the discounted total AEP. The shorter reduction in downtime, as a consequence of the innovative reparation and stiffening solution applied in 2024, gives CS3 a 2% higher discounted AEP compared to RS3, which corresponds to an increase in energy production of 2 681 MWh in 2024. For the CS3 scenario no increase in the service lifetime was assumed, therefore the differences in LCOE between the BAU and the INNTERESTING solutions are relatively low compared to the first (RS1-CS1) case and the second (RS2-CS2) case.

Table 22: LCOE comparison between RS3 and CS3

	LCOE [€/kWh]	Numerator [€]	Denominator [kWh]
RS3	0.071	5 899 011	83 444 130
CS3	0.069	5 899 391	85 505 633

Figure 32 shows the detailed LCOE breakdown comparison for RS3 and CS3 in €/MWh. In the CS3 scenario, the turbine cost is reduced by 0.9 €/MWh which is explained by a higher discounted AEP (denominator). The O&M cost decreased by 0.4 €/MWh, while the financial

costs, assembly & installation and BOP decreased by €0.1, €0.1 and €0.2 per MWh, respectively. No substantial changes were observed in end-of-life, engineering & management, and development costs.

Figure 32: Detailed LCOE breakdown [€/MWh] for RS3 and CS3 – cost discounted to 2019.
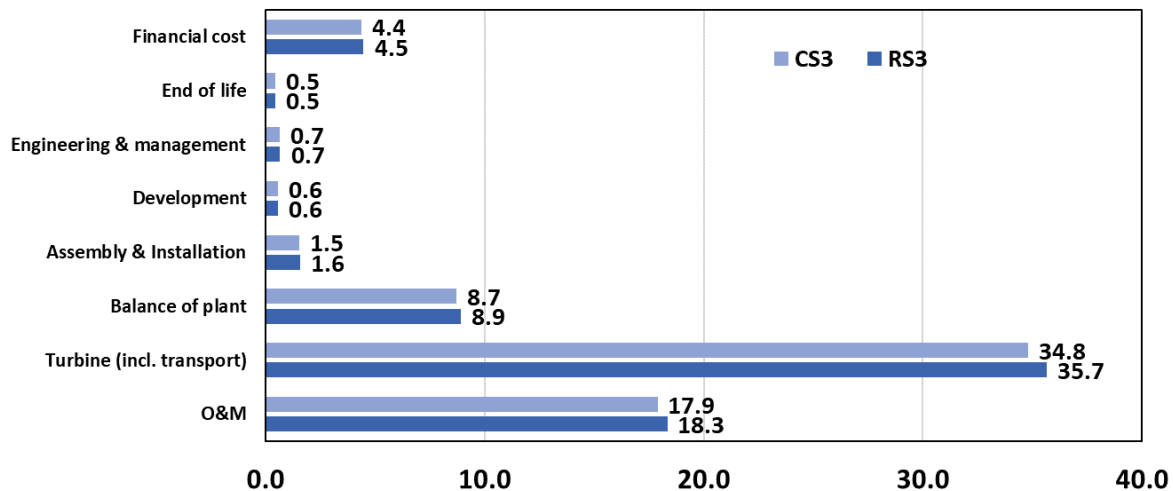
- **LCC findings related to the pitch bearings in RS3 and CS3**

The cost of the pitch bearing remains the same in both RS3 and CS3, as testing was not included in the scenarios. The production cost of the pitch mechanism accounts for 6 % (€179 559) of the total discounted costs of the wind turbine (rotor, nacelle, tower) for both cases. The difference lies in the approach taken for the prematurely failed pitch bearing(s) in year 4. The cost of the innovative reparation and stiffening solution of CS3 is lower than the cost of the BAU replacement for RS3. On the one hand, the CS3 costs of the repair and stiffening solution in 2024 of €11 857 are about 4 times smaller than the RS3 replacement cost of € 48 112. This difference of € 36 255 includes the following cost estimates: engineering, materials, installation, disassembly and transport of failed pitch bearings to end-of-life, as well as the revenues of scrap value of the steel. On the other hand, the variable O&M costs of CS3 increase by € 36 801 compared to RS3, due to a shorter down-time, and therefore almost cancel the cost improvement of the innovative solution. Consequently, the different approach after failure is barely reflected in the overall LCOE.

5.3.3. Findings S-LCA

Also for case study 3, the highest risks for '**workers'** occur during production, with 'the production of all other components' being the most important contributor. The other hotspots are 'maintenance', 'the production of blades' and 'the production of the electrical system' (see Figure 33). 'Replacement/repair of pitch bearings' does not contribute a lot to the social risks for workers over the entire life cycle of the wind turbine. The improvement potential of this case study lies in the reduced down time. The reduction of the downtime is substantial in the year in which the replacement (RS3) or repair/stiffening (CS3) of the pitch bearings takes place, however, when looking at the full life cycle, it has limited relevance. Consequently, little differences in social risks over the life cycle are observed between RS3 and CS3 for the stakeholder category workers. The same observations can be made for the stakeholder categories '**local communities'** (see Figure 34) and for the stakeholder category '**society'** (see Figure 35). Figure 36 shows the results for the opportunity 'contribution to economic development', also here, little differences between the two situations are observed.

Absolute values for all stakeholder categories and social indicators of PSILCA are available in Annex B for both the BAU reference scenario (RS3) and the INNTERESTING case study (CS3).

Figure 33: Comparison of RS3 and CS3 over the life cycle – social risks for 'workers', cost provided as a reference.
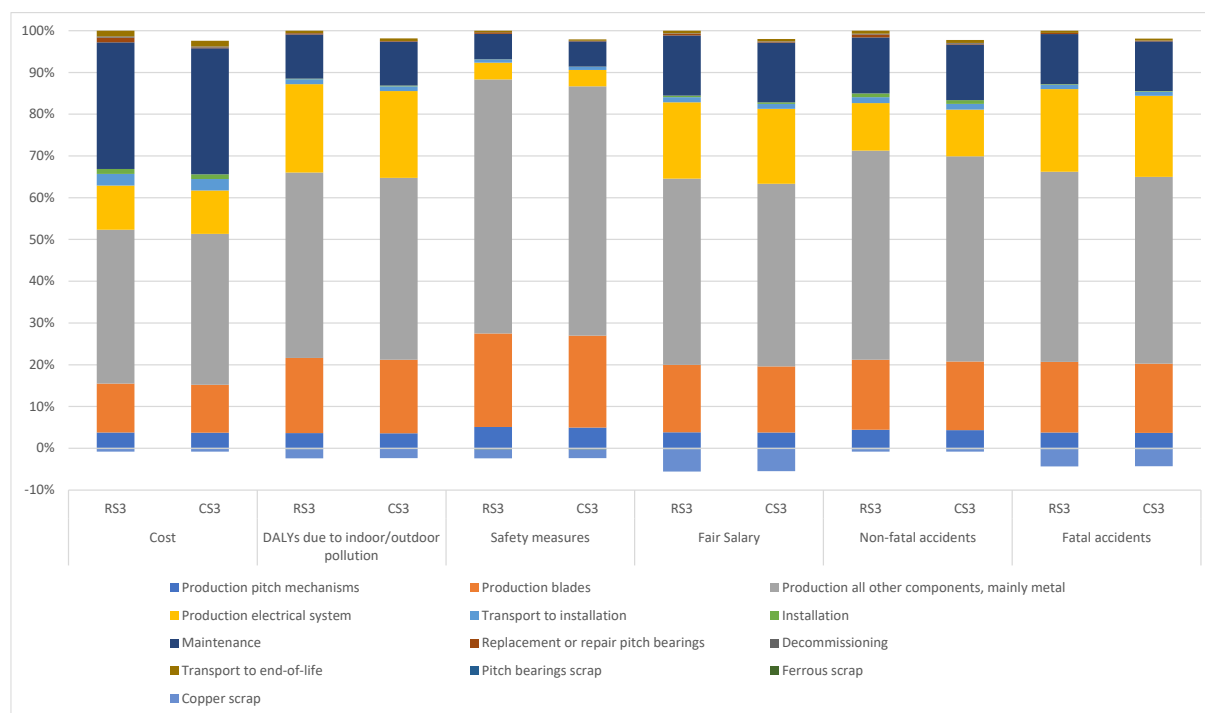
Figure 34: Comparison of RS3 and CS3 over the life cycle – social risks for 'local communities', cost provided as a reference.
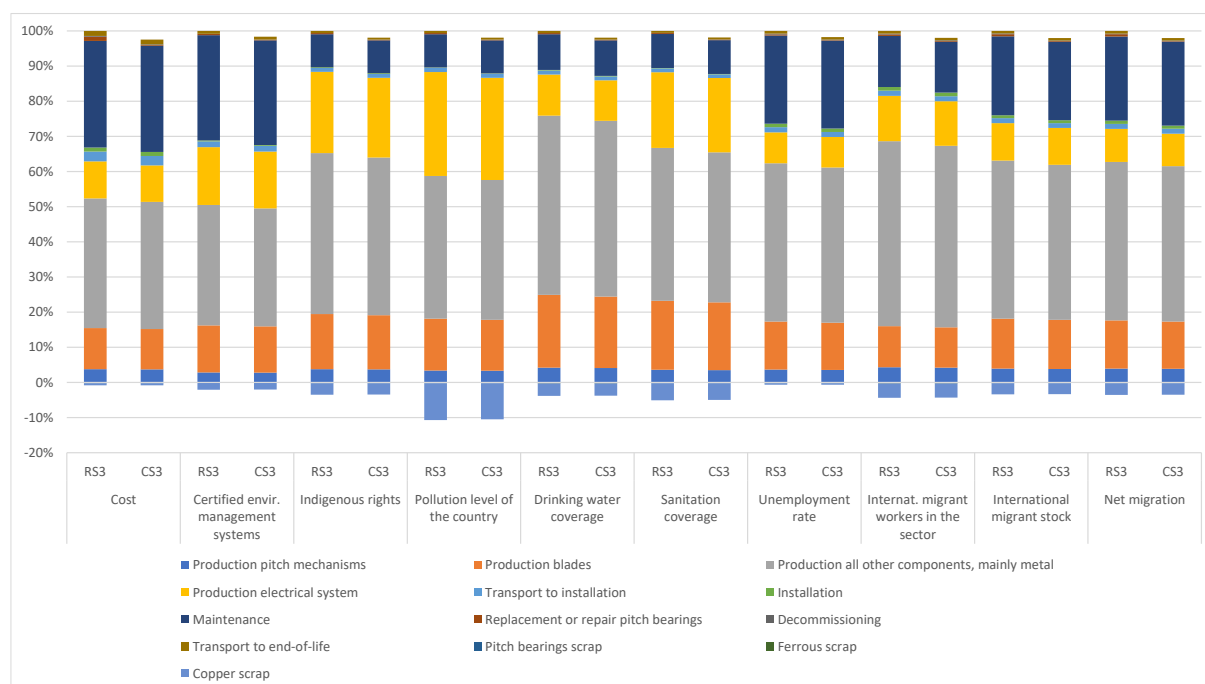
Figure 35: Comparison of RS3 and CS3 over the life cycle – social risks for 'society', cost provided as a reference.
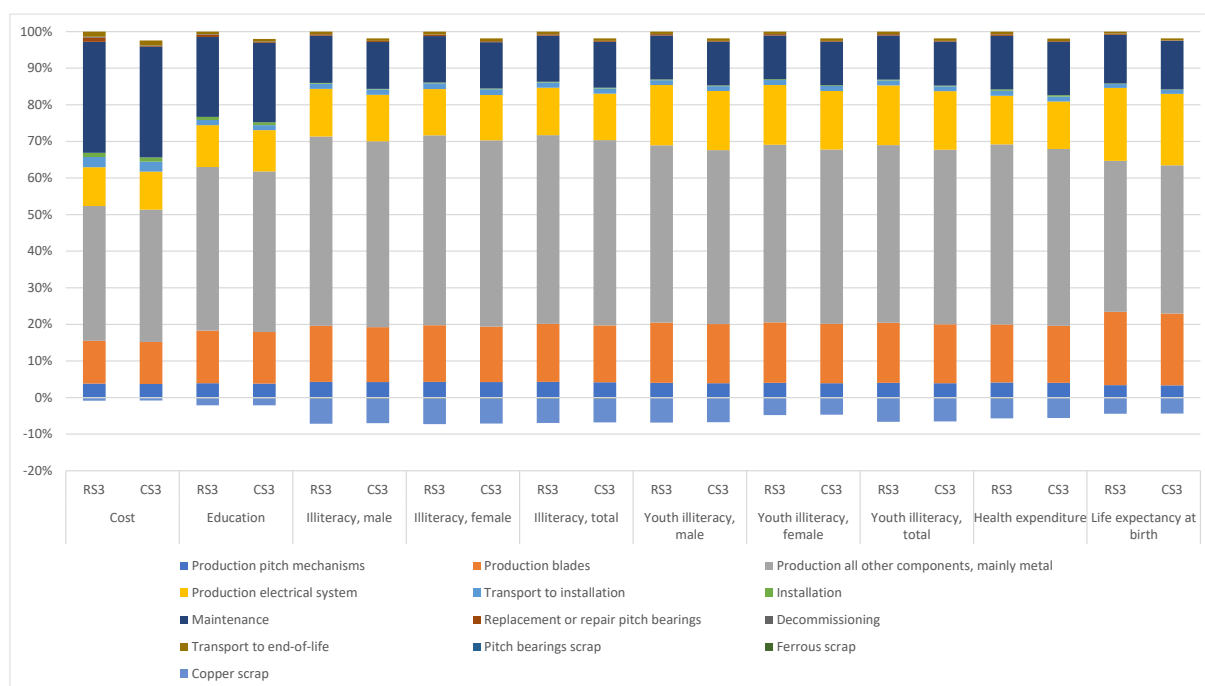
Figure 36: Comparison of RS3 and CS3 over the life cycle – opportunity 'contribution to economic development'.
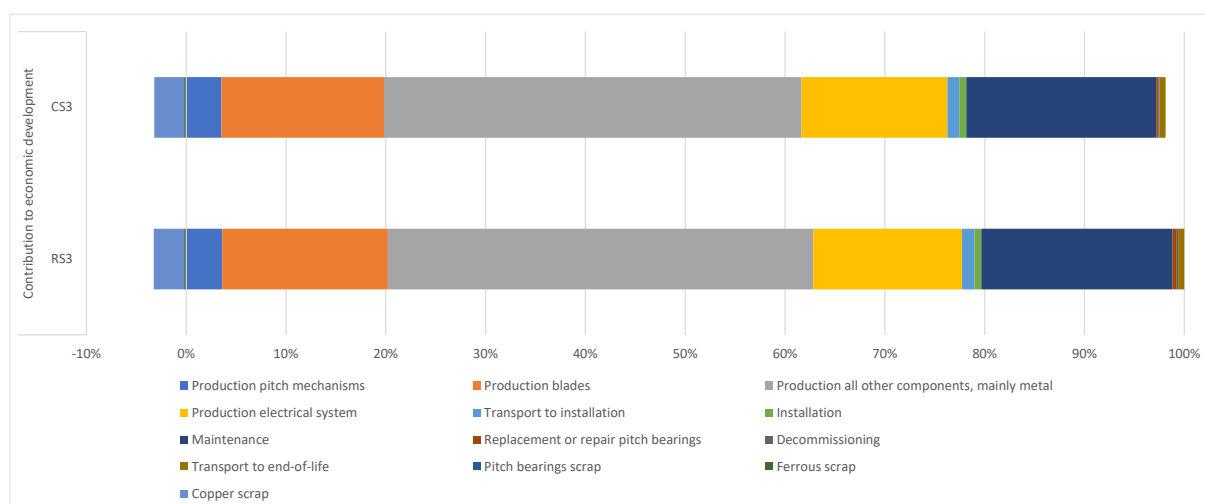
When considering only year 2024, the year in which the pitch bearings are assumed to be replaced or repaired, larger differences are observed between RS3 and CS3. The differences are mainly due to a larger down time in RS3. The results are visualized for the different stakeholder categories in Figure 37, Figure 38, Figure 39 and Figure 40.

Figure 37: Comparison of RS3 and CS3 in year 2024 – social risks for 'workers', cost provided as a reference.
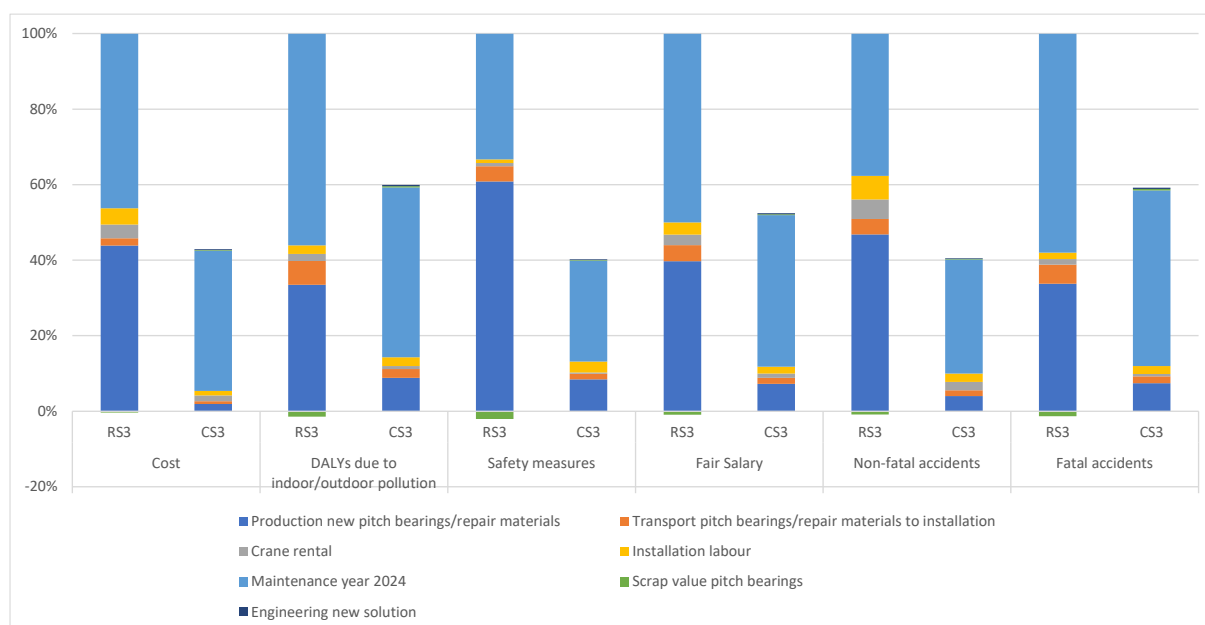
Figure 38: Comparison of RS3 and CS3 in year 2024 – social risks for 'local communities', cost provided as a reference.
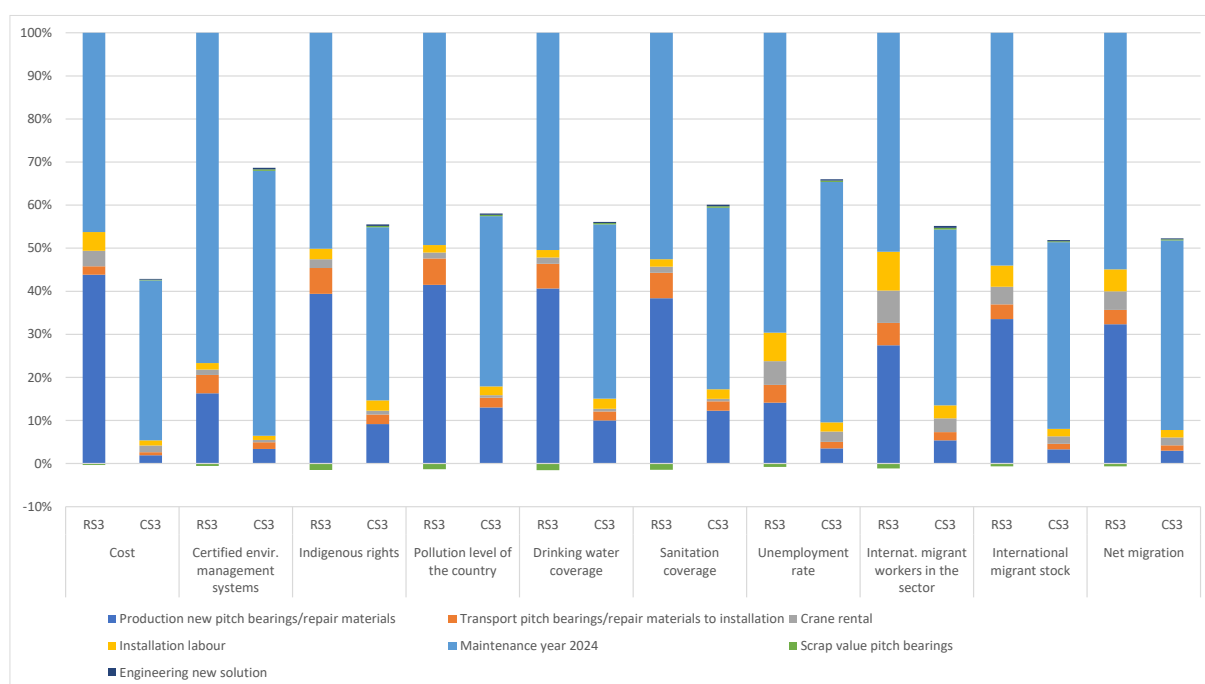
Figure 39: Comparison of RS3 and CS3 in year 2024 – social risks for 'society', cost provided as a reference.
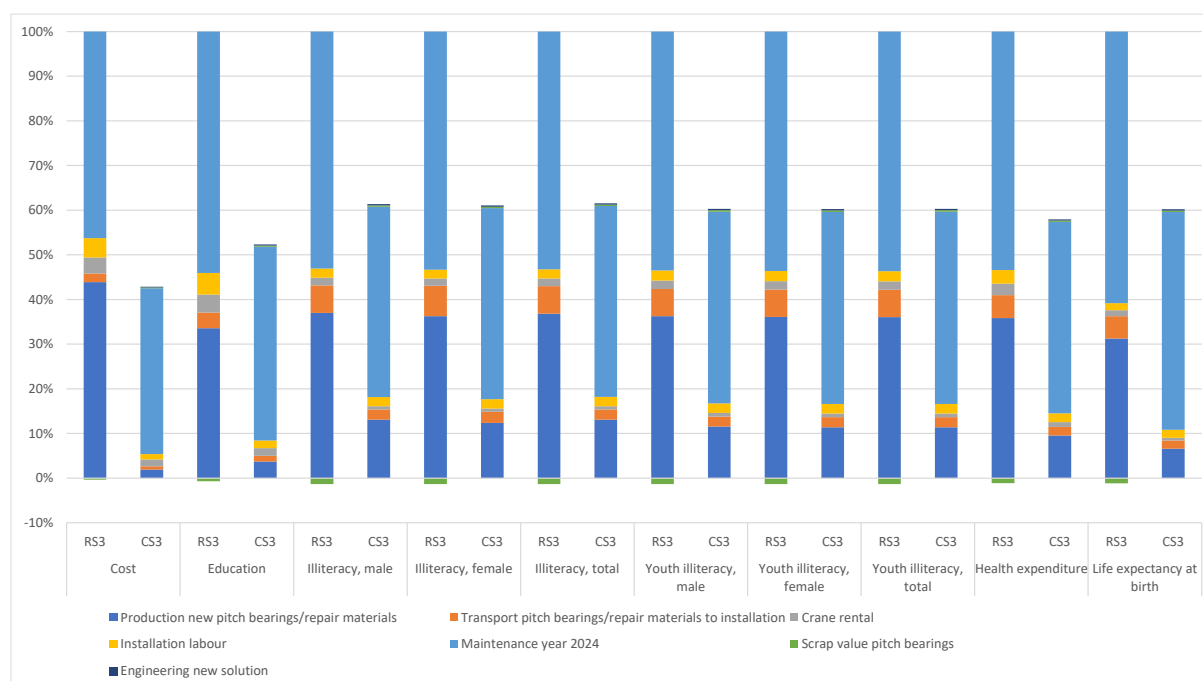
Figure 40: Comparison of RS3 and CS3 in year 2024 – opportunity 'contribution to economic development'.
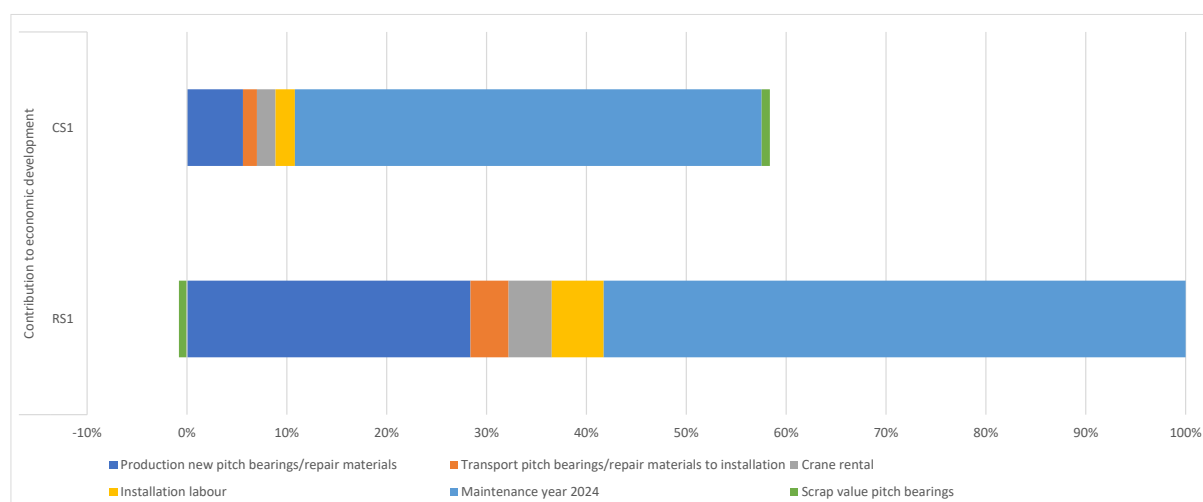
5.4. Conclusions comparative LCSA case 3

Although CS3 has a lower environmental impact compared to RS3, the differences are small, ranging between 2 and 8%. The difference is limited to the small difference in total energy output.

For RS3 the LCOE was estimated at 0.071 €/kWh, whereas a value of 0.069 €/kWh was estimated for CS3, which is a reduction of 2% compared to the BAU. The cost of the pitch bearing remains the same in both RS3 and CS3, as no testing was included in these scenarios. The production cost of the pitch mechanism accounts for 6 % (€179 559) of the total discounted

costs of the wind turbine (rotor, nacelle, tower) for both cases. The difference in approach between RS3 (replacement) and CS3 (repair and stiffening) after the pitch bearing failure is not clearly reflected in the overall LCOE. The cost advantages of the innovative solution are almost entirely nullified by the increase in O&M costs due to a shorter down-time. However, on the long run, the innovative repair and stiffening solution has potential cost advantages that were not taken into account in this economic assessment, such as a lifetime extension, lower risks of failure, and increased knowledge on pitch bearing failures.

Little differences are observed with regard to social risks occurring over the life cycle in the BAU (RS3) versus INNTERESTING case (CS3). The main hotspots for social risks is the production of all other components, but also 'maintenance', 'the production of blades' and 'the production of the electrical system' are relevant contributors. Replacement/repair of pitch bearings' does not contribute a lot to the social risks for workers over the entire life cycle of the wind turbine and also the improvement due to the reduced down time in CS3 is not substantial. The difference between applying a replacement versus repair and stiffening is however relevant in the year in which the failure occurs, with a clear benefit for the repair solution (CS3) which is mainly the consequence of the reduced down time.

6. Conclusions and recommendations

6.1. 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.

When less material is used – as seen in case 2 regarding the gearbox – the environmental impact of the material use will also decrease.

In general, also the social risks over the life cycle, investigated following the methodology described in D6.1, of the innovative solutions will decrease compared to BAU. The drivers are equal to those leading to the reduction in LCOE. An increase in energy production results in lower social risks per functional unit, being 1 kWh of electricity output delivered to the grid. Also, If the CAPEX decreases due to lower material costs, the social impact will also decrease, at least if the material type and location of origin remains the same. Similarly, social impacts will be reduced due to a lower replacement rate of components during operation of the turbines.

The proposed hybrid testing methods are significantly cheaper, less time-consuming, and have much smaller impacts on the environment and social risks when comparing them with the BAU testing methods. Although, when allocating the impacts of the testing to one wind turbine, the impacts are insignificant compared to impacts caused by the initial material use of the whole turbine. Nevertheless, with the proposed hybrid testing methods the reliability of the design of critical components is increased which is a necessity to ensure a longer lifetime of the components and as a result also ensuring a longer service life of the wind turbine. The prolongation of the service life and reduction of the down-time of a wind turbine due to the proposed solutions have a more significant effect. In that case, the energy production will be significantly higher which consequently will reduce the environmental, economic and social impacts per kWh generated with the wind turbine.

The proposed repair and stiffening solution compared to the BAU replacement process is relevant in the year in which the failure occurs, with a clear benefit for CS3 which is mainly the consequence of the reduced down time. However, when the total service life of 20 years is considered the differences between RS3 and CS3 are small.

6.2. Recommendations for further research in the LCSA

Based on the LCSA performed within this project, the following topics are suggested for further research in the field of LCSA:

- How to integrate the 3 types of assessments, i.e. LCA, LCC and S-LCA;
- Possible trade-offs between the three pillars of the LCSA, when optimising mainly one pillar.

Annex A: Company specific data for S-LCA

The tables below give an overview of the indicators which have been adapted or kept equal to the sector average based on information provided by Moventas (Figure 41) and Laulagun (Figure 42) for the BAU and INNTERESTING solution. The risk levels for BAU and INNTERESTING have been calculated using the data provided by the companies and the PSILCA guidelines (version 2, Eisfeldt 2017). Sometimes it was not possible to directly link the available information with the PISLCA calculation methodology, which has been developed for sector data. This was the case for:

- Violations of mandatory health and safety standards: this indicator is to be measured based on the number of violations of safety and health standards. Since both Moventas and Laulagun have a health and safety policy in place, it was decided to reduce the risk level for this category with one category compared to the sector average risk level.
- Local employment: this is to be measured based on the employment ratio of the country. However, as the employees from Moventas and Laulagun come for respectively 95% and 99% from the neighbourhood, it was decided to assign a low risk to this indicator.

Figure 41: Risk levels for sector average (machinery and equipment Finland), Moventas BAU and Moventas INNTERESTING solution
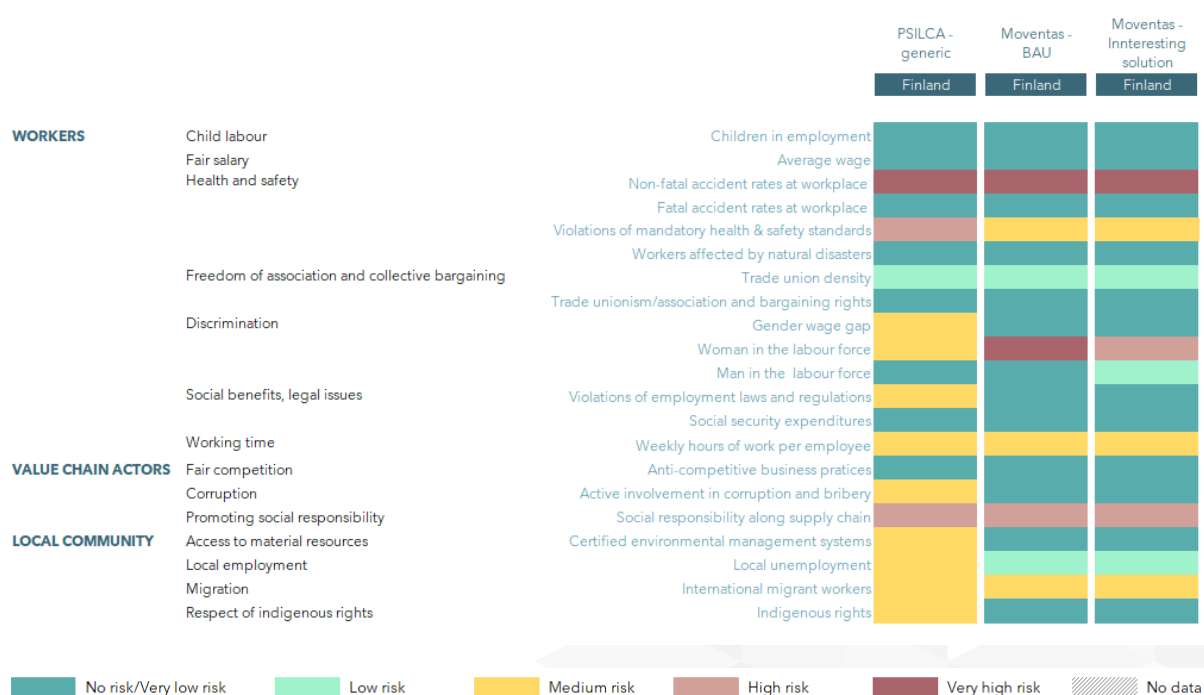
Figure 42: Risk levels for sector average (metal products Spain), Laulagun BAU and Laulagun INNTERESTING solution
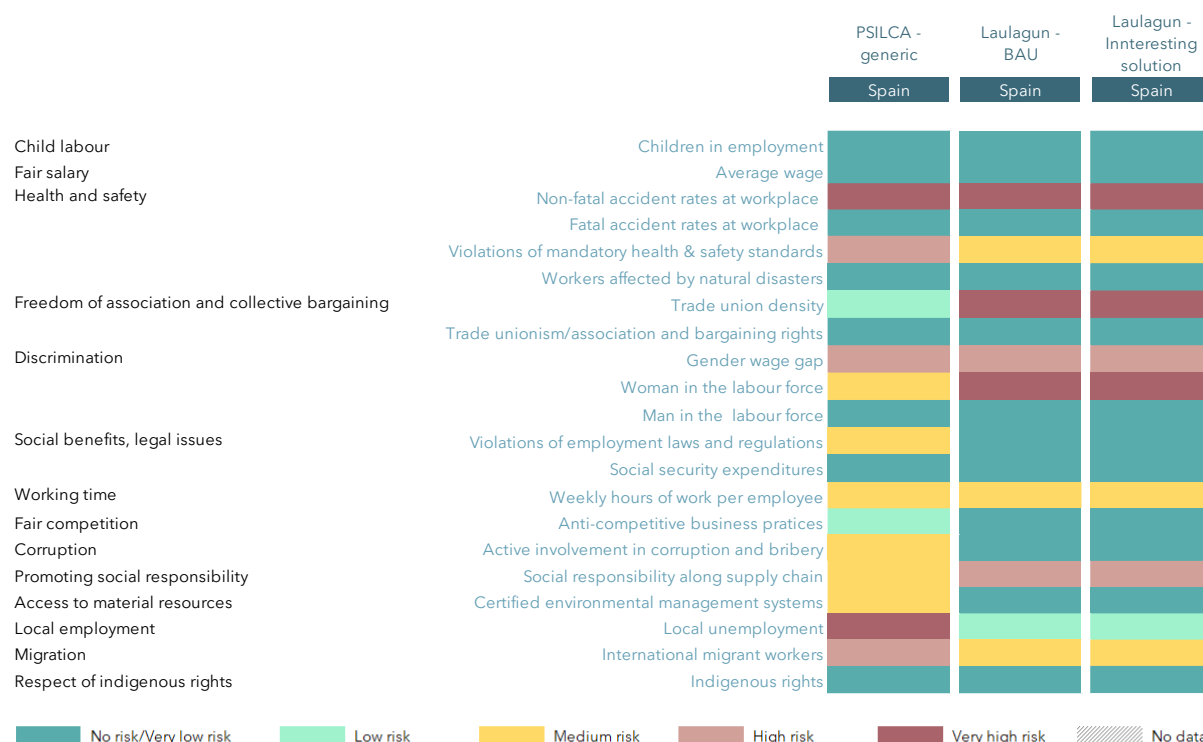
For Moventas, generic sector data (from sector machinery and equipment, Finland) have been retained for:

- Society: all indicators from database
- Consumers: all indicators from database
- Workers – forced labour: all indicators
- Workers - health and safety - DALY's due to indoor/outdoor pollution
- Value chain actors – corruption - public sector corruption
- Local community – access to material resources: industrial water depletion, biomass consumption, minerals consumption, fossil fuel consumption
- Local community – Migration: International migrant stock, net migration
- Local community – safe and healthy living conditions: contribution to environmental load, sanitation coverage, pollution and drinking water coverage

For Laulagun, generic sector data (from sector metal products, Spain) have been retained for:

- Society: all indicators from database
- Consumers: all indicators from database
- Workers – forced labour: all indicators
- Workers - health and safety - DALY's due to indoor/outdoor pollution
- Workers - health and safety – fatal and non-fatal accidents: no company specific data available
- Workers - working time: no company specific data available
- Workers - fair salary: no company specific data available

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- Value chain actors – corruption - public sector corruption
- Local community – access to material resources: industrial water depletion, biomass consumption, minerals consumption, fossil fuel consumption
- Local community – Migration: International migrant stock, net migration
- Local community – safe and healthy living conditions: contribution to environmental load, sanitation coverage, pollution and drinking water coverage

Moventas also provided data which allowed us to change the activity variable, being the 'worker hours', which represents the time needed to produce 1 USD of output product.

The worker hours for the generic sector 'machinery and equipment' in Finland is 0,00562 USD2015/h. For the production of a gearbox, the worker hours per dollar of output are substantially higher (absolute value kept confidential). This will result in a substantially higher contribution of the gearbox in the life cycle compared to what has been reported in deliverable D6.1. The worker hours per dollar of output decrease with 4% when the INNTERESTING solution will be applied.

Annex B: S-LCA results

Table 23: S-LCA results of RS1 for the complete life cycle expressed in medium risk hours

Stakeholder group/Subcategory/Indicator	Impact result	Unit
Consumers		
Transparancy		
Bus. practices deceptive to consumers	5,38E-04	CONS med risk hours
Local Community		
Access to material resources		
Industrial water depletion	6,78E-02	WU med risk hours
Biomass consumption	3,44E-02	BM med risk hours
Certified envir. management systems	5,60E-02	CMS med risk hours
Minerals consumption	4,44E-03	MC med risk hours
Fossil fuel consumption	8,46E-04	FF med risk hours
Local employment		
Unemployment	2,83E-02	U med risk hours
Migration		
International migrant stock	8,78E-03	IMS med risk hours
Internat. migrant workers in the sector	5,56E-03	IMW med risk hours
Net migration	3,73E-04	NM med risk hours
Respect of indigenous rights		
Indigenous rights	2,63E-03	IR med risk hours
Safe and healthy living conditions		
Contribution to environmental load	1,56E-01	CS med risk hours
Sanitation coverage	1,83E-02	SC med risk hours
Pollution	7,12E-03	P med risk hours
Drinking water coverage	5,02E-03	DW med risk hours
Society		
Contribution to economic development		
Education	7,77E-03	E med risk hours
Illiteracy, female	4,97E-03	I med risk hours
Illiteracy, total	4,18E-03	I med risk hours
Illiteracy, male	3,88E-03	I med risk hours
Youth illiteracy, female	6,45E-04	YI med risk hours
Youth illiteracy, total	6,44E-04	YI med risk hours
Youth illiteracy, male	6,30E-04	YI med risk hours
Contribution to economic development	-1,98E-03	CE med risk hours
Health and Safety (Society)		
Health expenditure	6,61E-03	HE med risk hours
Life expectancy at birth	5,66E-04	LE med risk hours
Value Chain Actors		
Corruption		
Active involv. in corruption and bribery	1,26E-02	AI med risk hours
Public sector corruption	2,49E-02	C med risk hours
Fair competition		
Anti-competitive business pratices	7,15E-04	AC med risk hours
Promoting social responsibility		
Social responsibility along supply chain	5,40E-02	SR med risk hours

Stakeholder group/Subcategory/Indicator	Impact result	Unit
Workers		
Child labour		
Child Labour, male	1,28E-03	CL med risk hours
Child Labour, total	1,27E-03	CL med risk hours
Child Labour, female	1,16E-03	CL med risk hours
Discrimination		
Women in the sectoral labour force	8,38E-03	W med risk hours
Gender wage gap	1,13E-02	GW med risk hours
Men in the sectoral labour force	7,26E-05	M med risk hours
Fair Salary		
Fair Salary	5,55E-02	FS med risk hours
Forced labour		
Trafficking in persons	4,96E-03	TP med risk hours
Goods produced by forced labour	4,24E-04	GFL med risk hours
Frequency of forced labour	3,55E-04	FL med risk hours
Freedom of association and collective bargaining		
Trade unionism	7,17E-02	TU med risk hours
Association and bargaining rights	5,98E-03	ACB med risk hours
Health and Safety (Workers)		
Non-fatal accidents	3,39E-02	NFA med risk hours
Fatal accidents	6,03E-04	FA med risk hours
Safety measures	1,61E-02	SM med risk hours
DALYs due to indoor/ outdoor pollution	1,83E-04	DALY med risk hours
Workers affected by natural disasters	1,22E-03	ND med risk hours
Social benefits, legal issues		
Violations of empl. laws and regulations	3,18E-03	VL med risk hours
Social security expenditures	5,73E-03	SS med risk hours
Working time		
Weekly hours of work per employee	7,83E-04	WH med risk hours

Table 24: S-LCA results of CS1 for the complete life cycle expressed in medium risk hours

Stakeholder group/Subcategory/Indicator	Impact result	Unit
Consumers		
Transparancy		
Bus. practices deceptive to consumers	4,81E-04	CONS med risk hours
Local Community		
Access to material resources		
Industrial water depletion	6,78E-02	WU med risk hours
Biomass consumption	3,43E-02	BM med risk hours
Certified envir. management systems	5,23E-02	CMS med risk hours
Minerals consumption	3,82E-03	MC med risk hours
Fossil fuel consumption	8,41E-04	FF med risk hours
Local employment		
Unemployment	2,14E-02	U med risk hours
Migration		
International migrant stock	7,99E-03	IMS med risk hours
Internat. migrant workers in the sector	4,89E-03	IMW med risk hours
Net migration	2,98E-04	NM med risk hours
Respect of indigenous rights		
Indigenous rights	2,38E-03	IR med risk hours
Safe and healthy living conditions		
Contribution to environmental load	1,54E-01	CS med risk hours
Sanitation coverage	1,62E-02	SC med risk hours
Pollution	6,44E-03	P med risk hours
Drinking water coverage	4,72E-03	DW med risk hours
Society		
Contribution to economic development		
Education	6,95E-03	E med risk hours
Illiteracy, female	4,61E-03	I med risk hours
Illiteracy, total	3,89E-03	I med risk hours
Illiteracy, male	3,64E-03	I med risk hours
Youth illiteracy, female	5,91E-04	YI med risk hours
Youth illiteracy, total	5,89E-04	YI med risk hours
Youth illiteracy, male	5,78E-04	YI med risk hours
Contribution to economic development	-1,76E-03	CE med risk hours
Health and Safety (Society)		
Health expenditure	6,06E-03	HE med risk hours
Life expectancy at birth	5,10E-04	LE med risk hours
Value Chain Actors		
Corruption		
Active involv. in corruption and bribery	1,09E-02	AI med risk hours
Public sector corruption	2,21E-02	C med risk hours
Fair competition		
Anti-competitive business pratices	6,46E-04	AC med risk hours
Promoting social responsibility		
Social responsibility along supply chain	5,12E-02	SR med risk hours

Stakeholder group/Subcategory/Indicator	Impact result	Unit
Workers		
Child labour		
Child Labour, male	1,15E-03	CL med risk hours
Child Labour, total	1,13E-03	CL med risk hours
Child Labour, female	1,04E-03	CL med risk hours
Discrimination		
Women in the sectoral labour force	6,63E-03	W med risk hours
Gender wage gap	1,01E-02	GW med risk hours
Men in the sectoral labour force	6,53E-05	M med risk hours
Fair Salary		
Fair Salary	5,31E-02	FS med risk hours
Forced labour		
Trafficking in persons	4,71E-03	TP med risk hours
Goods produced by forced labour	3,78E-04	GFL med risk hours
Frequency of forced labour	3,37E-04	FL med risk hours
Freedom of association and collective bargaining		
Trade unionism	6,38E-02	TU med risk hours
Association and bargaining rights	5,40E-03	ACB med risk hours
Health and Safety (Workers)		
Non-fatal accidents	2,66E-02	NFA med risk hours
Fatal accidents	5,32E-04	FA med risk hours
Safety measures	1,29E-02	SM med risk hours
DALYs due to indoor/ outdoor pollution	1,56E-04	DALY med risk hours
Workers affected by natural disasters	1,13E-03	ND med risk hours
Social benefits, legal issues		
Violations of empl. laws and regulations	2,78E-03	VL med risk hours
Social security expenditures	5,35E-03	SS med risk hours
Working time		
Weekly hours of work per employee	6,98E-04	WH med risk hours

Table 25: S-LCA results of RS2 for the complete life cycle expressed in medium risk hours

Stakeholder group/Subcategory/Indicator	Impact result	Unit
Consumers		
Transparancy		
Bus. practices deceptive to consumers	3,56E-04	CONS med risk hours
Local Community		
Access to material resources		
Industrial water depletion	3,47E-02	WU med risk hours
Biomass consumption	1,81E-02	BM med risk hours
Certified envir. management systems	3,29E-02	CMS med risk hours
Minerals consumption	1,35E-02	MC med risk hours
Fossil fuel consumption	4,14E-04	FF med risk hours
Local employment		
Unemployment	2,37E-02	U med risk hours
Migration		
International migrant stock	5,48E-03	IMS med risk hours
Internat. migrant workers in the sector	3,72E-03	IMW med risk hours
Net migration	2,97E-04	NM med risk hours
Respect of indigenous rights		
Indigenous rights	1,61E-03	IR med risk hours
Safe and healthy living conditions		
Contribution to environmental load	7,59E-02	CS med risk hours
Sanitation coverage	1,23E-02	SC med risk hours
Pollution	4,55E-03	P med risk hours
Drinking water coverage	2,85E-03	DW med risk hours
Society		
Contribution to economic development		
Education	5,09E-03	E med risk hours
Illiteracy, female	2,98E-03	I med risk hours
Illiteracy, total	2,49E-03	I med risk hours
Illiteracy, male	2,27E-03	I med risk hours
Youth illiteracy, female	3,98E-04	YI med risk hours
Youth illiteracy, total	3,97E-04	YI med risk hours
Youth illiteracy, male	3,87E-04	YI med risk hours
Contribution to economic development	-1,38E-03	CE med risk hours
Health and Safety (Society)		
Health expenditure	4,19E-03	HE med risk hours
Life expectancy at birth	3,62E-04	LE med risk hours
Value Chain Actors		
Corruption		
Active involv. in corruption and bribery	9,64E-03	AI med risk hours
Public sector corruption	1,64E-02	C med risk hours
Fair competition		
Anti-competitive business pratices	4,60E-04	AC med risk hours
Promoting social responsibility		
Social responsibility along supply chain	3,21E-02	SR med risk hours

Stakeholder group/Subcategory/Indicator	Impact result	Unit
Workers		
Child labour		
Child Labour, male	8,35E-04	CL med risk hours
Child Labour, total	8,25E-04	CL med risk hours
Child Labour, female	7,52E-04	CL med risk hours
Discrimination		
Women in the sectoral labour force	1,74E-02	W med risk hours
Gender wage gap	7,25E-03	GW med risk hours
Men in the sectoral labour force	4,94E-05	M med risk hours
Fair Salary		
Fair Salary	4,12E-02	FS med risk hours
Forced labour		
Trafficking in persons	2,75E-03	TP med risk hours
Goods produced by forced labour	2,90E-04	GFL med risk hours
Frequency of forced labour	2,03E-04	FL med risk hours
Freedom of association and collective bargaining		
Trade unionism	4,65E-02	TU med risk hours
Association and bargaining rights	3,86E-03	ACB med risk hours
Health and Safety (Workers)		
Non-fatal accidents	3,72E-02	NFA med risk hours
Fatal accidents	4,01E-04	FA med risk hours
Safety measures	1,24E-02	SM med risk hours
DALYs due to indoor/ outdoor pollution	1,33E-04	DALY med risk hours
Workers affected by natural disasters	7,40E-04	ND med risk hours
Social benefits, legal issues		
Violations of empl. laws and regulations	2,22E-03	VL med risk hours
Social security expenditures	3,36E-03	SS med risk hours
Working time		
Weekly hours of work per employee	6,08E-04	WH med risk hours

Table 26: S-LCA results of CS2 for the complete life cycle expressed in medium risk hours

Stakeholder group/Subcategory/Indicator	Impact result	Unit
Consumers		
Transparancy		
Bus. practices deceptive to consumers	3,00E-04	CONS med risk hours
Local Community		
Access to material resources		
Industrial water depletion	3,17E-02	WU med risk hours
Biomass consumption	1,63E-02	BM med risk hours
Certified envir. management systems	2,87E-02	CMS med risk hours
Minerals consumption	6,40E-03	MC med risk hours
Fossil fuel consumption	3,87E-04	FF med risk hours
Local employment		
Unemployment	1,87E-02	U med risk hours
Migration		
International migrant stock	4,67E-03	IMS med risk hours
Internat. migrant workers in the sector	3,08E-03	IMW med risk hours
Net migration	2,34E-04	NM med risk hours
Respect of indigenous rights		
Indigenous rights	1,35E-03	IR med risk hours
Safe and healthy living conditions		
Contribution to environmental load	7,14E-02	CS med risk hours
Sanitation coverage	1,02E-02	SC med risk hours
Pollution	3,82E-03	P med risk hours
Drinking water coverage	2,50E-03	DW med risk hours
Society		
Contribution to economic development		
Education	4,26E-03	E med risk hours
Illiteracy, female	2,55E-03	I med risk hours
Illiteracy, total	2,13E-03	I med risk hours
Illiteracy, male	1,95E-03	I med risk hours
Youth illiteracy, female	3,37E-04	YI med risk hours
Youth illiteracy, total	3,36E-04	YI med risk hours
Youth illiteracy, male	3,28E-04	YI med risk hours
Contribution to economic development	-1,11E-03	CE med risk hours
Health and Safety (Society)		
Health expenditure	3,49E-03	HE med risk hours
Life expectancy at birth	3,05E-04	LE med risk hours
Value Chain Actors		
Corruption		
Active involv. in corruption and bribery	7,50E-03	AI med risk hours
Public sector corruption	1,37E-02	C med risk hours
Fair competition		
Anti-competitive business pratices	3,82E-04	AC med risk hours
Promoting social responsibility		
Social responsibility along supply chain	2,78E-02	SR med risk hours

Stakeholder group/Subcategory/Indicator	Impact result	Unit
Workers		
Child labour		
Child Labour, male	6,99E-04	CL med risk hours
Child Labour, total	6,91E-04	CL med risk hours
Child Labour, female	6,30E-04	CL med risk hours
Discrimination		
Women in the sectoral labour force	5,46E-03	W med risk hours
Gender wage gap	6,11E-03	GW med risk hours
Men in the sectoral labour force	4,41E-05	M med risk hours
Fair Salary		
Fair Salary	3,12E-02	FS med risk hours
Forced labour		
Trafficking in persons	2,43E-03	TP med risk hours
Goods produced by forced labour	2,38E-04	GFL med risk hours
Frequency of forced labour	1,75E-04	FL med risk hours
Freedom of association and collective bargaining		
Trade unionism	3,93E-02	TU med risk hours
Association and bargaining rights	3,23E-03	ACB med risk hours
Health and Safety (Workers)		
Non-fatal accidents	2,53E-02	NFA med risk hours
Fatal accidents	3,34E-04	FA med risk hours
Safety measures	9,78E-03	SM med risk hours
DALYs due to indoor/ outdoor pollution	1,08E-04	DALY med risk hours
Workers affected by natural disasters	6,35E-04	ND med risk hours
Social benefits, legal issues		
Violations of empl. laws and regulations	1,80E-03	VL med risk hours
Social security expenditures	2,89E-03	SS med risk hours
Working time		
Weekly hours of work per employee	4,66E-04	WH med risk hours

Table 27: S-LCA results of RS3 for the complete life cycle expressed in medium risk hours

Stakeholder group/Subcategory/Indicator	Impact result	Unit
Consumers		
Transparancy		
Bus. practices deceptive to consumers	1,04E-03	CONS med risk hours
Local Community		
Access to material resources		
Industrial water depletion	1,66E-02	WU med risk hours
Biomass consumption	1,07E-02	BM med risk hours
Certified envir. management systems	8,16E-02	CMS med risk hours
Minerals consumption	3,96E-03	MC med risk hours
Fossil fuel consumption	2,48E-04	FF med risk hours
Local employment		
Unemployment	1,21E-01	U med risk hours
Migration		
International migrant stock	1,43E-02	IMS med risk hours
Internat. migrant workers in the sector	1,05E-02	IMW med risk hours
Net migration	1,27E-03	NM med risk hours
Respect of indigenous rights		
Indigenous rights	4,06E-03	IR med risk hours
Safe and healthy living conditions		
Contribution to environmental load	6,80E-02	CS med risk hours
Sanitation coverage	3,50E-02	SC med risk hours
Pollution	1,06E-02	P med risk hours
Drinking water coverage	5,38E-03	DW med risk hours
Society		
Contribution to economic development		
Education	1,52E-02	E med risk hours
Illiteracy, female	7,97E-03	I med risk hours
Illiteracy, total	7,07E-03	I med risk hours
Illiteracy, male	6,36E-03	I med risk hours
Youth illiteracy, female	1,13E-03	YI med risk hours
Youth illiteracy, total	1,11E-03	YI med risk hours
Youth illiteracy, male	1,07E-03	YI med risk hours
Contribution to economic development	-3,63E-03	CE med risk hours
Health and Safety (Society)		
Health expenditure	1,19E-02	HE med risk hours
Life expectancy at birth	8,92E-04	LE med risk hours
Value Chain Actors		
Corruption		
Active involv. in corruption and bribery	3,26E-02	AI med risk hours
Public sector corruption	4,81E-02	C med risk hours
Fair competition		
Anti-competitive business pratices	1,16E-03	AC med risk hours
Promoting social responsibility		
Social responsibility along supply chain	6,94E-02	SR med risk hours

Stakeholder group/Subcategory/Indicator	Impact result	Unit
Workers		
Child labour		
Child Labour, male	2,07E-03	CL med risk hours
Child Labour, total	2,05E-03	CL med risk hours
Child Labour, female	1,87E-03	CL med risk hours
Discrimination		
Women in the sectoral labour force	2,74E-02	W med risk hours
Gender wage gap	2,32E-02	GW med risk hours
Men in the sectoral labour force	1,23E-04	M med risk hours
Fair Salary		
Fair Salary	4,47E-02	FS med risk hours
Forced labour		
Trafficking in persons	4,35E-03	TP med risk hours
Goods produced by forced labour	7,95E-04	GFL med risk hours
Frequency of forced labour	5,46E-04	FL med risk hours
Freedom of association and collective bargaining		
Trade unionism	1,48E-01	TU med risk hours
Association and bargaining rights	8,90E-03	ACB med risk hours
Health and Safety (Workers)		
Non-fatal accidents	1,06E-01	NFA med risk hours
Fatal accidents	1,09E-03	FA med risk hours
Safety measures	4,16E-02	SM med risk hours
DALYs due to indoor/ outdoor pollution	4,39E-04	DALY med risk hours
Workers affected by natural disasters	1,46E-03	ND med risk hours
Social benefits, legal issues		
Violations of empl. laws and regulations	8,17E-03	VL med risk hours
Social security expenditures	8,23E-03	SS med risk hours
Working time		
Weekly hours of work per employee	1,49E-03	WH med risk hours

Table 28: S-LCA results of CS3 for the complete life cycle expressed in medium risk hours

Stakeholder group/Subcategory/Indicator	Impact result	Unit
Consumers		
Transparancy		
Bus. practices deceptive to consumers	1,03E-03	CONS med risk hours
Local Community		
Access to material resources		
Industrial water depletion	1,62E-02	WU med risk hours
Biomass consumption	1,05E-02	BM med risk hours
Certified envir. management systems	8,03E-02	CMS med risk hours
Minerals consumption	3,89E-03	MC med risk hours
Fossil fuel consumption	2,43E-04	FF med risk hours
Local employment		
Unemployment	1,19E-01	U med risk hours
Migration		
International migrant stock	1,40E-02	IMS med risk hours
Internat. migrant workers in the sector	1,03E-02	IMW med risk hours
Net migration	1,24E-03	NM med risk hours
Respect of indigenous rights		
Indigenous rights	3,98E-03	IR med risk hours
Safe and healthy living conditions		
Contribution to environmental load	6,69E-02	CS med risk hours
Sanitation coverage	3,43E-02	SC med risk hours
Pollution	1,04E-02	P med risk hours
Drinking water coverage	5,28E-03	DW med risk hours
Society		
Contribution to economic development		
Education	1,49E-02	E med risk hours
Illiteracy, female	7,82E-03	I med risk hours
Illiteracy, total	6,94E-03	I med risk hours
Illiteracy, male	6,24E-03	I med risk hours
Youth illiteracy, female	1,11E-03	YI med risk hours
Youth illiteracy, total	1,09E-03	YI med risk hours
Youth illiteracy, male	1,05E-03	YI med risk hours
Contribution to economic development	-3,56E-03	CE med risk hours
Health and Safety (Society)		
Health expenditure	1,17E-02	HE med risk hours
Life expectancy at birth	8,75E-04	LE med risk hours
Value Chain Actors		
Corruption		
Active involv. in corruption and bribery	3,20E-02	AI med risk hours
Public sector corruption	4,72E-02	C med risk hours
Fair competition		
Anti-competitive business pratices	1,14E-03	AC med risk hours
Promoting social responsibility		
Social responsibility along supply chain	6,83E-02	SR med risk hours

Stakeholder group/Subcategory/Indicator	Impact result	Unit
Workers		
Child labour		
Child Labour, male	2,03E-03	CL med risk hours
Child Labour, total	2,01E-03	CL med risk hours
Child Labour, female	1,83E-03	CL med risk hours
Discrimination		
Women in the sectoral labour force	2,64E-02	W med risk hours
Gender wage gap	2,27E-02	GW med risk hours
Men in the sectoral labour force	1,20E-04	M med risk hours
Fair Salary		
Fair Salary	4,38E-02	FS med risk hours
Forced labour		
Trafficking in persons	4,26E-03	TP med risk hours
Goods produced by forced labour	7,82E-04	GFL med risk hours
Frequency of forced labour	5,36E-04	FL med risk hours
Freedom of association and collective bargaining		
Trade unionism	1,45E-01	TU med risk hours
Association and bargaining rights	8,73E-03	ACB med risk hours
Health and Safety (Workers)		
Non-fatal accidents	1,03E-01	NFA med risk hours
Fatal accidents	1,07E-03	FA med risk hours
Safety measures	4,08E-02	SM med risk hours
DALYs due to indoor/ outdoor pollution	4,30E-04	DALY med risk hours
Workers affected by natural disasters	1,43E-03	ND med risk hours
Social benefits, legal issues		
Violations of empl. laws and regulations	8,04E-03	VL med risk hours
Social security expenditures	8,08E-03	SS med risk hours
Working time		
Weekly hours of work per employee	1,46E-03	WH med risk hours

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