Deliverable 6.1:
Report on sustainability assessment of business-as-usual reference scenarios
WP6, Task 6.1

Date of document

31/08/2020 (M 8)

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[1] PU = Public

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

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

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

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Document History

Project acronym	INNTERESTING	
Project title	Innovative Future-Proof Testing Methods for Reliable Critical Components in Wind Turbines	
Project coordinator	Mireia Olave MOlave@ikerlan.es IKERLAN	
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Work package	WP6 - Environmental, social and economic assessment	
Work package Lead	VITO	
Contributing beneficiaries	IKERLAN, MOVENTAS, LAULAGUN, BEC, VTT	
DoA	Task 6.1 will start with the definition of the intended use (the goal) of the integrated LCA, S-LCA and LCC assessment and the breath and the depth (the scope) of the integrated sustainability assessment throughout the whole project, agreed by all partners. The description of the business-as-usual (BAU) reference scenario will be based on the goal and scope. The environmental, social and economic inventory data of the BAU will be collected under guidance of VITO. IKERLAN and LAULAGUN will be responsible for the data collection for the BAU pitch bearing; and MOVENTAS the data for the BAU gear box. When the necessary data are collected, VITO can start with the integrated LCA, S-LCA and LCC assessment. To conclude the first round of the iterative sustainability assessment, the assessment results will be interpreted including a hotspot analysis to know which life cycle stages and processes within the life cycles of the BAU pitch bearing, gear box and their conventional test	

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		methods generate the main important impacts: environmentally, social and economic. This interpretation will be used to support the developments within CS1, CS2 and CS3 Furthermore, and will serve as a reference scenario (benchmark) for the next rounds of the iterative sustainability assessment.	
Date	**Version**	**Author**	**Comment**
20/07/2020	0.1	VITO	First draft (incl. sections 1, 2, 3.1, 3.3, and 4.2) for internal review
22/07/2020	0.2	SIEMENS	1st Review
24/07/2020	0.3	IKERLAN	1st Review
27/08/2020	0.4	VITO	Final draft for internal review
30/08/2020	0.5	IKERLAN	2nd Review
31/08/2020	1.0	VITO	Final version

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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 expenditure
CS	Case Study
CSR	Corporate Social Responsibility
DALYs	Disability Adjusted Life Years
DEVEX	Development expenditure
EOL	End-of-Life
eq.	equivalent
I/O	Input-Output
ILO	International Labour Organisation
FU	Functional Unit
LCA	(environmental) Life Cycle Assessment
LCC	(economic) Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Cost Of Energy
LCSA	Life Cycle Sustainability Assessment
MRIO	Multi-Regional I/O
NGO	Non-Governmental Organisation
NORCOWE	Norwegian Centre for Offshore Wind Energy
OEM	Original Equipment Manufacturer
OPEX	Operational expenditure
OSHA	Occupational Safety and Health Administration
PSILCA	Product Social Inventory Life Cycle Assessment
RS	Reference Scenario
RWT	Reference Wind Turbine
SDG	Sustainable Development Goal
SETAC	Society of Environmental Toxicology and Chemistry

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Acronym	Description
SHDB	Social Hotspot Database
S-LCA	Social Life Cycle Assessment
S-LCIA	Social Life Cycle Impact Assessment
UNEP	United Nations Environment Program
USDOL	United States Department of Labor
WACC	Weighted Average Cost of Capital
WHO	World Health Organisation

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Executive summary

This deliverable is the first of WP6 of the INNTERESTING project. WP6 revolves around the environmental, social and economic assessment of the three case studies defined within the project. In the three case studies disruptive technologies for new pitch bearings and gearboxes, and a novel lifetime extension concept of existing pitch bearings will be developed. 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) will be performed iteratively in WP6.

This report describes the overall approach and the different methodological frameworks applied for the three parts of the LCSA, i.e. an environmental life cycle assessment (LCA), a social life cycle assessment (S-LCA) and life cycle costing (LCC). For each case study a matching business-as-usual (BAU) reference scenario has been developed and assessed. Section 4 presents the findings per assessment per refence scenario. The purpose of the BAU reference scenarios is to gain insights in the contribution of the different components to the environmental, economic and social impact of wind turbines during their life cycle. In addition, the results of the LCSA of the BAU scenarios can be used for comparing potential improvements of the environmental, economic and social performance of the case studies within the project.

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1. Introduction

The INNTERESTING project aims to accelerate wind energy technology development and increase lifetime extension of wind turbine components. The project revolves around three case studies in which disruptive technologies for new pitch bearings and gearboxes, and a novel lifetime extension concept of existing pitch bearings will be developed. 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) will be performed iteratively throughout the project.

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

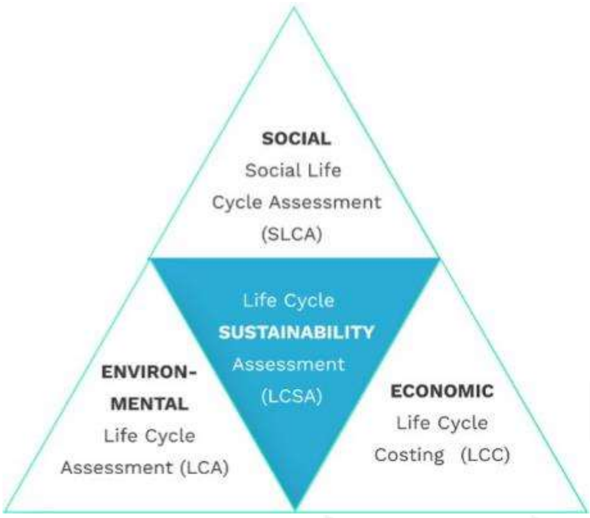

Figure 1: The three pillars of the life cycle sustainability assessment.

Work Package 6 of the INNTERESTING project is fully dedicated to the execution of the LCSA and consist of three tasks corresponding with the three LCSA iterations that will be performed throughout the project:

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

This report (D6.1) describes the results of the Task 6.1 of the INNTERESTING project.

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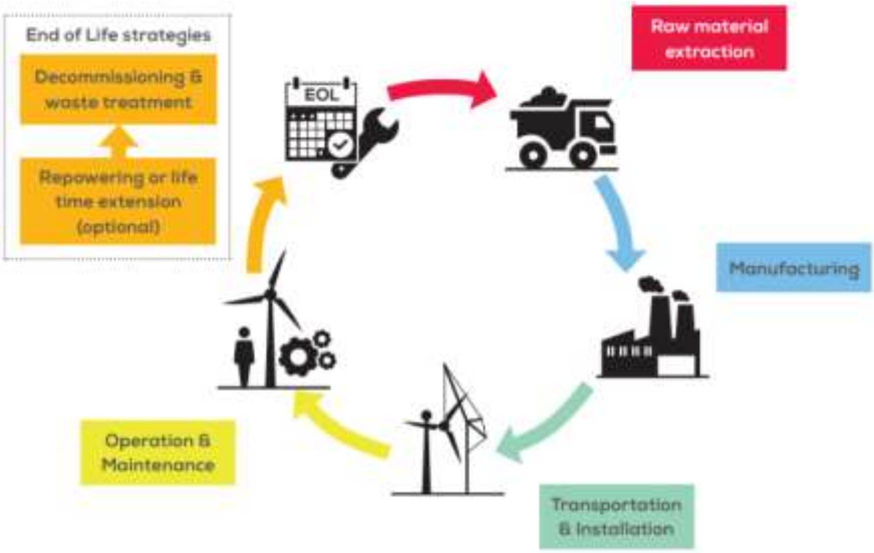
1.1. Purpose and content of this deliverable

As mentioned above, D6.1 presents the results of the first iteration of the LCSA, in which the BAU reference scenarios (RSs) are assessed. The purpose of the assessment of the RSs is to gain insights in the contribution of the different components[2] to the environmental, social and economic impact of wind turbines during their life cycle (see Figure 2).



(image from WindEurope)

Figure 2: The life cycle of a wind turbine

For each case study, a specific BAU reference scenario has been defined in order to have a reference to evaluate the improvement potential of the INNTERESTING solutions per case study (CS). The descriptions of the RSs are given in subsection 2.2. The three case studies are presented in the next figure. For more information on the three case studies, please refer to section 6 of D1.1[3].

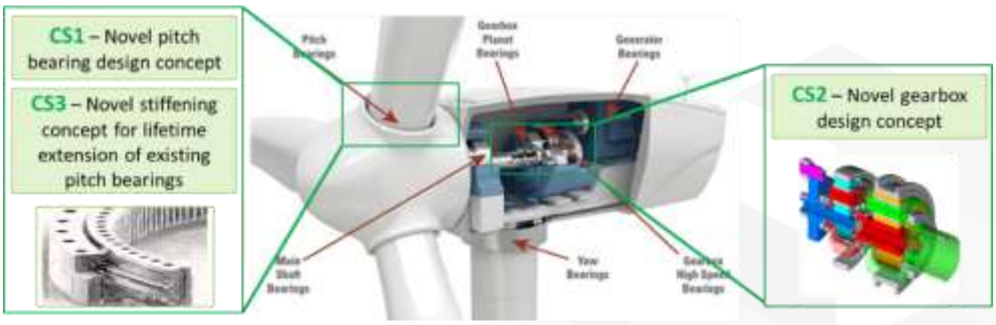


Figure 3: The three case studies of the INNTERESTING project.

After subsection 1.1.1, the content of this deliverable is structured as follows:

[2] The initial plan was also to gain insights in the LCSA impact of testing methods during the BAU product development process of wind turbines. Unfortunately, the necessary data on testing methods needed for the LCSA are not publicly available in literature. Hopefully we will be able to collect these data the upcoming year via our advisory board. See also section 1.1.1 which describes the deviations from the originally planned content of this deliverable.

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

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- Subsection 1.2 gives the overall approach and the different methodological frameworks applied for the three parts of the LCSA, i.e. LCA. LCC, and S-LCA.
- Section 2 describes the goal and the scope of the LCSA: first in general for the LCSA throughout this project, followed by the scope per RS.
- Section 3 presents (restricted) overviews of the data collected during the life cycle inventory (LCI) phase of the LCSA: first starting with the general data assumptions, followed by the data per RS.
- Section 4 shows the findings based on the life cycle impact assessment (LCIA) per RS, including an interpretation of the LCIA.
- Section 5 concludes this deliverable with the conclusions per RS and the outputs for other work packages of the INNTERESTING project.

1.1.1. Deviations from the plan

For the calculation of the potential environmental, economic and social benefits of the to-be-developed INNTERSTING hybrid testing method, it is necessary to have LCI data on BAU testing methods for pitch bearings and gearboxes; also, for a fair comparison between the BAU reference scenarios and the INNTERESTING case studies. From the Basque Energy Cluster (one of the project partners) we have received the LCI data on the WINDBOX, a blade pitch bearing test bench[4]. Unfortunately, we have not been able to collect usable data on gearbox test benches. Therefore, we have decided to leave the impacts of prototype and serial production testing out the LCSA for the time being.

Hopefully, we will be able to collect the missing necessary data via the Technical Advisory Board. This will be done during the first stakeholder consultation meeting held on 9th of September 2020 (initially planned for May but postponed due to the COVID-19 pandemic) This means that there is a deviation from the original plan regarding this deliverable and that a revision of the BAU LCSA RSs will be incorporated in D6.2 [M30] in which the impact of the prototype and serial production testing will be included.

1.2. Overall approach

The ISO standards 14040:2006 and 14044:20016 are applied as the main methodological framework for the LCSA. These ISO standards are specifically developed as a general (conceptual) methodological framework to perform (environmental) LCA studies. However, this framework is so general that it also fits to perform LCC and S-LCA studies, and thus also LCSA studies. The ISO standards prescribe the following four steps:

- Goal and scope definition,
- Life cycle inventory (LCI) analysis,
- Life cycle impact assessment (LCIA),
- Interpretation.

The relation between the different steps is illustrated in Figure 4. The figure shows that the four steps are not independent of each other. It also shows that the scope, the boundaries and the level of detail depend on the intended application of the study. Three separate sections (i.e. 2 – 4) of this deliverable are devoted to the first three steps respectively and each section starts with a short explanation of the content of that respective step. For the interpretation step there is no separate section, as that step occurs in correlation with the other steps.

[4] http://www.clusterenergia.com/windbox-blade-bearing-test-bench

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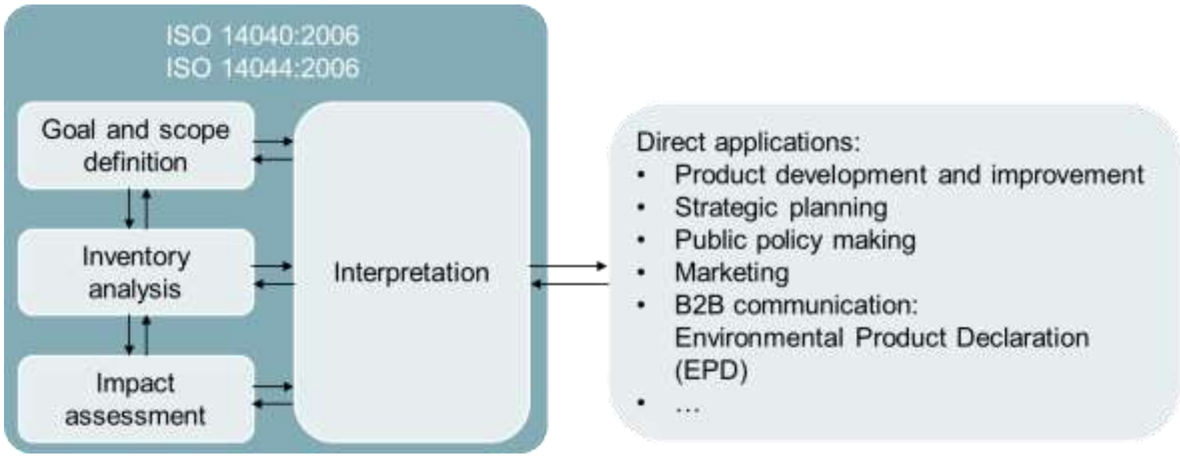

Figure 4: Main methodological framework applied to the LCSA based on ISO 14040 and 14044.

In addition to the general methodology based on ISO 14040/14044, specific methodologies have been applied for each assessment that is a part of the LCSA. The following subsections describe the additional methodological frameworks applied to the LCA, LCC, and S-LCA.

1.2.1. Applied life cycle assessment methodology

ISO 14040/14044:2006 describes LCA as follows: "LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)".

Although the field of LCA is the most mature in comparison with LCC and S-LCA, it is still a relatively young instrument as the LCA methodologies are still evolving. For example, the Environmental Footprint (EF) method for products (PEF) and originations (OEF) of the European Commission[5] and the EN 15804 standard by CEN/TC 350. The latter is applied to perform the LCA within the INNTERESTING project.

1.2.1.1. LCA approach and database

As mentioned above, the EN 15804:2012+A2:2019[6] standard was selected as additional methodologic framework to the ISO 14040/140044 framework specifically for the LCA part of the LCSA. The aim of the EN 15804 standard is to provide core product category rules for all construction products and services and to ensure that all environmental product declarations of construction products, construction services and construction processes are derived, verified and presented in a harmonised way. Although this standard is set up for the building and construction sector by experts from that sector, it can also be applied to assess wind turbines as in a way, wind turbines can also be seen as construction works. In addition, there exists no comprehensive LCA framework for the energy sector comparable as the EN 15804 for the construction sector.

The EN 15804 is organised in information modules: each module covers a specific life cycle stage. The following four groups of information modules are defined in the EN 15804:

- Module A (from A1 to A5) relates to the production and construction stage.

[5] https://ec.europa.eu/environment/eussd/smgp/dev_methods.htm
[6] Full name of the standard is: Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products

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- Module B (from B1 to B7) relates to the use stage of the product.
- Module C (from C1 to C4) covers deconstruction/demolition, transport to waste processing, waste processing (such as sorting of waste before recycling) and disposal (i.e. landfilling and incineration) during the end-of-life of a product.
- Module D covers the net benefits and loads beyond the system boundary related to reuse, recycling and energy recovery of products.

Within the INNTERSTING project, the modules A-D will be assessed (see also Table 8 with an overview with the system boundaries in section 2.2), also known as a *cradle-to-grave with module D* LCA. To model and calculate the environmental impacts of a wind turbine, the LCA software SimaPro (version 9.1.0.7)[7] and generic LCI database ecoinvent 3.6[8] are used. Both are commonly used by environmental LCA practitioners.

For recycling of waste, two ISO-compatible methodological approaches are frequently applied in life cycle assessment studies: the EOL recycling approach[9] or the recycled content approach. This study uses the recycled content approach[10], because this approach serves the strong sustainability concept (where natural capital is not replaceable by man-made capital) and is based on a risk-aversive attitude. The EOL recycling approach serves the weak sustainability concept (losses in natural capital can be compensated by man-made capital) and corresponds to a risk-seeking attitude.

1.2.1.2. Selection of environmental impact categories

In LCA, environmental impacts are expressed with environmental LCIA indicators by using characterisation factors[11]. The standard EN 15804:2012+A2:2019 prescribes thirteen core environmental impact indicators and six additional environmental impact indicators (see Table 1). For all indicators, the characterisation factors from the JRC of the European Commission needs to be applied[12]. In this project, all nineteen environmental indicators will be included.

The EN 15804 also requires declaring so-called *indicators describing resource use and environmental information based on LCI*; for instance the amounts of kg of secondary material used, hazardous waste disposed, materials for energy recovery, and biogenic carbon content. As our focus lies on the environmental impact categories, these additional indicators will be excluded from this project.

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7 https://simapro.com/
8 https://www.ecoinvent.org/
9 Also known as the avoided burdens approach; it is based on the recyclability of the product at the end of his life and considers environmental impacts and credits for the recycling process and the recycled materials at the end of the system.
10 In this approach, recyclable materials are available burden-free to recycling processes, which means that secondary (recycled) materials bear only the impacts of the recycling processes. The model does not give any credit to producers of wastes for the recycling or reuse of products from any waste treatment.
11 E.g. the LCIA indicator 'global warming potential' with the unit kg CO_2 eq. is used to assess the impact category 'climate change'. The characterisation factors of 1 kg carbon dioxide (CO_2) and 1 kg methane (CH_4) emissions are 1 CO_2 eq. and 36.75 CO_2 eq. respectively (based on the factors by JRC, see footnote 12). This can be interpreted as: 1 kg of methane emission equals to 36.75 kg of carbon dioxide emission and that 1 kg of methane leads to 36.75 times bigger environmental impact to climate change than 1 kg of carbon dioxide. If a product would emit 1 kg of carbon dioxide and 1 kg of methane, then the total impact on climate change by that product would be (1+36.75=) 37.75 kg CO_2 eq.
12 http://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml

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Table 1: Core and additional environmental impact indicators, units and models EN 15804+A2.

Impact category	Indicator	Unit	Model
Core environmental impact indicators			
Climate change – total (= fossil + biogenic + luluc)	Global Warming Potential total (GWP-total)	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013
Climate change - fossil	Global Warming Potential fossil fuels (GWP-fossil)	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013
Climate change - biogenic	Global Warming Potential biogenic (GWP-biogenic)	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013
Climate change - land use and land use change	Global Warming Potential land use and land use change (GWP-luluc)	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013
Ozone Depletion	Depletion potential of the stratospheric ozone layer (ODP)	kg CFC 11 eq.	Steady-state ODPs, WMO 2014
Acidification	Acidification potential, Accumulated Exceedance (AP)	mol H+ eq.	Accumulated Exceedance, Seppälä et al. 2006, Posch et al., 2008
Eutrophication aquatic freshwater	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-freshwater)	kg PO_4 eq.	EUTREND model, Struijs et al., 2009b, as implemented in ReCiPe
Eutrophication aquatic marine	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-marine)	kg N eq.	EUTREND model, Struijs et al., 2009b, as implemented in ReCiPe
Eutrophication terrestrial	Eutrophication potential, Accumulated Exceedance (EP-terrestrial)	mol N eq.	Accumulated Exceedance, Seppälä et al. 2006, Posch et al.
Photochemical ozone formation	Formation potential of tropospheric ozone (POCP)	kg NMVOC eq.	LOTOS-EUROS ,Van Zelm et al., 2008, as applied in ReCiPe
Depletion of abiotic resources – minerals and metals	Abiotic depletion potential for non-fossil resources (ADP-minerals&metals)	kg Sb eq.	CML 2002, Guinée et al., 2002, and van Oers et al. 2002.
Depletion of abiotic resources - fossil fuels	Abiotic depletion potential for fossil resources (ADP-fossil)	MJ, net calorific value	CML 2002, Guinée et al., 2002, and van Oers et al. 2002.
Water use	Water (user) deprivation potential, deprivation- weighted water consumption (WDP)	m^3 world eq. deprived	Available WAter REmaining (AWARE) Boulay et al., 2016
Additional environmental impact indicators			
Particulate matter emissions	Potential incidence of disease due to PM emissions (PM)	Disease incidence	SETAC-UNEP, Fantke et al. 2016
Ionising radiation, human health	Potential Human exposure efficiency relative to U235 (IRP)	kBq U235 eq.	Human health effect model as developed by Dreicer et al. 1995 update by Frischknecht et al., 2000
Ecotoxicity (freshwater)	Potential Comparative Toxic Unit for ecosystems (ETP-fw)	CTUe	Usetox version 2 until the modified USEtox model is available from EC-JRC
Human toxicity, cancer effects	Potential Comparative Toxic Unit for humans (HTP-c)	CTUh	Usetox version 2 until the modified USEtox model is available from EC-JRC
Human toxicity, non- cancer effects	Potential Comparative Toxic Unit for humans (HTP-nc)	CTUh	Usetox version 2 until the modified USEtox model is available from EC-JRC
Land use related impacts / soil quality	Potential Soil quality index (SQP)	dimensionless	Soil quality index based on LANCA

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1.2.2. Applied life cycle costing methodology

ISO 15686-5:2008 describes an LCC assessment as a systematic economic evaluation of life cycle costs over a period of analysis, as defined in the agreed scope. The period of analysis either covers the entire life cycle or selected stages or periods of interest thereof.

Life Cycle Costs are all costs associated with the life cycle of a product or technology system that are directly covered by one or more of the actors in the system life cycle. The costs must relate to real money flows and must be internal costs (Swarr et al., 2011). LCC methodological rules are based on SETAC "Environmental Life Cycle Costing: a code of practice" (2011).

According to Myhr et al. (2014), it is advisable to utilize a levelized cost (a similar reference for value of money) in order to increase the significance of the LCC analysis concerning concept comparison. LCC results can be levelled by expected energy production. This allows a better analysis and evaluation of risk and total cost during the life span. This is often referred to as a Levelized Cost of Energy (LCOE) Analysis (Myhr et al, 2014).

In consultation with the Consortium partners, it was decided to calculate the life cycle costs by using the LCOE approach, in which the total life cycle costs of a wind farm are included.

1.2.2.1. LCOE approach

The Levelized Cost of Energy is a measure for estimating the cost of the electricity that is produced over the life of a generating plant. In this assessment, the LCOE expresses the levelized unit cost of 1 kWh over the lifetime of the wind turbine by taking the sum of the discounted lifetime costs relative to the sum of discounted energy production at the time of the financial investment decision.

The following equation is used to calculate the LCOE and is derived from the commonly accepted LCOE model developed by Megavind (2015):

$$\mathrm{LCOE} = \frac{Present\ value\ (Cost)}{Present\ value\ (Production)}$$

The discounted lifetime costs (the numerator) are equal to the present value of all expenditures associated with the wind farm. The sum of discounted lifetime costs can be formulated as:

$$Present\ value\ of\ Costs = \sum_{t=k}^{T} \frac{I_t + O_t + A_t}{(1 + \mathrm{WACC}_n)^t}$$

See Table 2 for the definition of variables. The sum of discounted energy production (the denominator) is equal to the present value of the energy production. The sum of discounted energy production is independent of perspective.

$$Present\ value\ of\ Production = \sum_{t=k}^{T} \frac{E_t}{(1 + \mathrm{WACC}_r)^t}$$

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Table 2: LCOE formula - Definition of variables

Definition of variables	
t	the time period
k	the earliest period with cash flows or energy production; discount is applied to period 0
T	the latest period with cash flow
I_t	the cash flow at time t from investment at time t
O_t	the cash flow at time t from nominal operational expenditures
A_t	the cash flow at time t from nominal abandonment cost
E_t	the energy production at time t
$WACC_r$	the real weighted average cost of capital
$WACC_n$	the nominal weighted average cost of capital

1.2.2.2. Selection of cost components

The total lifetime costs of a wind farm are included in the LCOE model. As shown in Figure 5, costs are defined in four different overall categories (based on the Megavind 2015 LCOE model):

- DEVEX - Development Expenditures, defined as all costs spent in the period from idea and development to design & planning;
- CAPEX - Capital Expenditures, defined as all costs in the period of construction up to the date the wind farm is commissioned;
- OPEX - Operational Expenditures, defined as costs in the operational period;
- ABEX - Abandonment Expenditures, defined as costs related to the abandonment of the wind farm from the wind farm termination date (end-of-life).

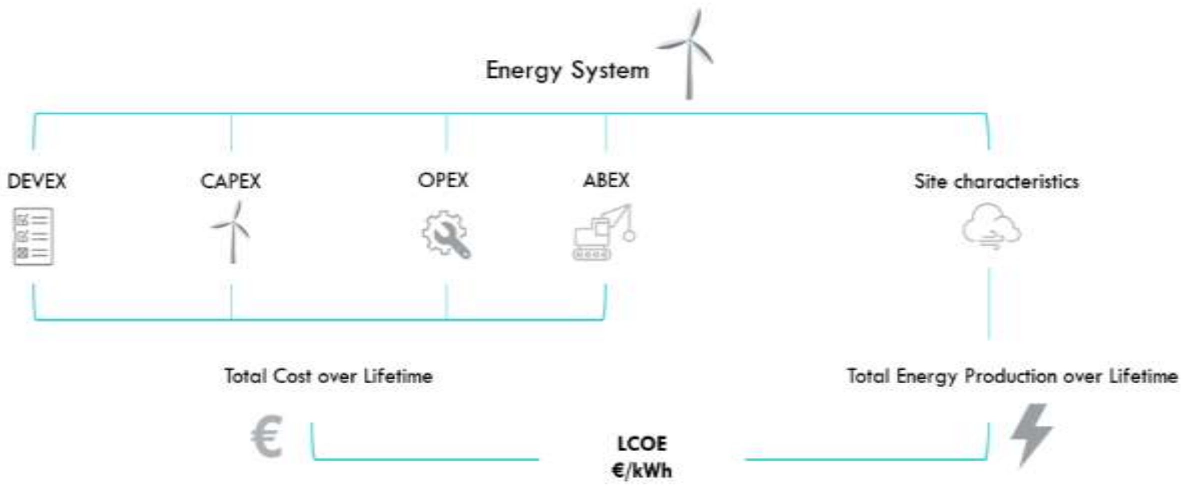

Figure 5: LCOE breakdown

The cost perspective for this assessment is the developer's perspective before tax. The pre-tax developer costs are the sum of the discounted investment I_t (in the form of DEVEX and CAPEX), operational expenditures O_t (OPEX) and abandonment expenditures A_t (ABEX):

$$Present\ value\ of\ Costs = \sum_{t=k}^{T} \frac{DEVEX_t + CAPEX_t + OPEX_t + ABEX_t}{(1 + \mathrm{WACC}_n)^t}$$

1.2.3. Applied social life cycle assessment methodology

S-LCA is a methodology to assess the potential social impacts of products and services across their life cycle. S-LCA provides information on social and socio-economic aspects for decision-making, in the prospect to improve the performance of organisations and ultimately the well-being of stakeholders (Benoît-Norris et al., 2020).

S-LCA is a relatively new field. Guidelines for S-LCA have been developed in 2009 by the UNEP/SETAC Life Cycle Initiative. The work is called *Guidelines for Social Life Cycle Assessment of Products* (UNEP/SETAC, 2009). Currently, those guidelines are being updated. A draft version is available (Benoît-Norris et al., 2020) and the final version is expected in September 2020.

The results of a S-LCA can be used by companies, NGOs and governments. S-LCA can support target-oriented corporate social responsibility (CSR) activities, risk assessment, reporting and labelling, decision support making, establish purchase procedures or specification, and assist in the development of policies, regulations and law (Greendelta, 2020).

In S-LCA, social impacts are assessed in connection to various stakeholder groups, people who may be directly or indirectly affected throughout the life cycle of products or services (Goedkoop et al., 2018). The S-LCA guidelines (Benoît-Norris et al., 2020) consider 6 stakeholder categories: Workers, Local communities, Value chain actors (e.g. suppliers), Consumers, Children and Society, which may be potentially affected by various impacts generated along the life cycle of products. The stakeholder groups are divided into subcategories which are assessed by means of inventory indicators.

1.2.3.1. S-LCA approach and database

This study concerns a ***screening*** S-LCA. Its aim is to **identify social hotspots in the life cycle of the reference wind turbines**. It will also give direction to the work that will happen in this area in a later stage in the INNTERESTING project (the S-LCA of INNTERESTING solutions).

The study uses the Reference Scale Approach[13] for Life Cycle Impact Assessment (LCIA). A Reference scale S-LCIA assesses the behaviour of organisations in the product system based on specific reference points of expected behaviour. It relies on data and provides results that focus on the activities of companies in the product system or their immediate effects (Benoît-Norris et al., 2020). Results of a Reference Scale S-LCA are social performances or risks, organised along impact (sub)categories, stakeholder categories and/or life cycle steps. Typically, databases at risk level are used for this type of S-LCA. There are two major databases available: the SHDB (Social Hotspot Database) of the company *new earth b* and the PSILCA (Product Social Inventory Life Cycle Assessment) database developed by Greendelta (Eisfeldt, 2017).

This study works with version 2 of the PSILCA database (Eisfeldt, 2017). The database combines a global economic input-output (I/O) model with risk-assessed indicators.

The PSILCA database uses a multi-regional I/O (MRIO) database, called Eora, to provide insights into global supply chains. PSILCA v2 makes use of Eora release 2015, which contains

[13] Formerly known as *Type I S-LCA*

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189 individual countries that are represented by a total of 15 909 sectors distinguished by so-called entities: industries, commodities, value added/ final demand (Eora, 2015).

For each sector and country available in Eora, PSILCA provides a risk level per social indicator. PSILCA v2 provides 65 risk-assessed indicators, measured in different units such as single values or percentages, some are also qualitative. The risk levels are 'very low risk', 'low risk', 'medium risk', 'high risk', 'very high risk' and 'no risk'. The assignment of risk levels to the indicator values is based on international conventions and standards, labour laws, expert opinions but also own experience and evaluation of the database providers (Eisfeldt and Ciroth, 2018). A risk scale has been developed for each of the indicators. Table 3 provides, by means of illustration, the risk assessment scale for the indicator 'non-fatal accidents'. This risk assessment scale is based on the mean value of non-fatal accidents per 100 thousand employees worldwide (calculated out of the data available). Besides risk indicators, PSILCA v2 contains also one opportunity indicator, which is related to a positive impact. The opportunity indicator in PSILCA v2 is 'Contribution of the sector to economic development'.

Table 3: Risk assessment scale for non-fatal accidents (Eisfeldt and Ciroth, 2018).

Indicator value y, # per 100,000 employees	Risk level
$0 \leq y < 750$	very low risk
$750 \leq y < 1500$	low risk
$1500 \leq y < 2250$	medium risk
$2250 \leq y < 3000$	high risk
$3000 \leq y$	very high risk
-	no data

The PSILCA database contains an impact assessment method named 'Social Impact Weighting method' (Maister et al., 2020). This impact assessment method assigns numerical values to the levels of the reference scale (very high, high, medium, low, very low risk or opportunity) enabling an aggregation of results (see Table 4). The method expresses all results in medium risk hours.

Table 4: Characterisation factors for the impact assessment method in PSILCA (Maister et al., 2020)

Risk level	Factor
Very low risk	0.01
Low risk	0.1
Medium risk	1
High risk	10
Very high risk	100
No risk/ opportunity	0
Low opportunity	0.1
Medium opportunity	1
High opportunity	10
No data	0.1

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Finally, an activity variable is used to represent the product system process in a way that gives an idea of the relative significance of each unit process in the whole system (Benîot-Norris et al., 2020). Activity variables are used to “reflect the share of a given activity associated with each unit process” (Benoît and Mazijn, 2009). PSILCA uses the activity variable ‘worker hours’, which is the activity variable used in most S-LCA studies. This variable represents the time needed to produce 1 USD of output product.

For each impact category, overall social impacts are calculated by aggregating the social risks of all involved processes along the life cycle. The social risks are scaled by price (inputs), worker hours and characterisation factor (Maister et al., 2020). To further clarify the above described methodology, we apply it to a simple example being a metal component with a cost price of 50 USD. The risk level for the indicator ‘non-fatal accidents’ is ‘very high risk’ (with characterisation factor 100). The worker hours necessary to produce 1 USD of a metal component are 0.0103 hours per USD. The contribution of the production of this component to the life cycle impact is 50 USDx100x0.0103 h/USD = 51.5 medium risk hours. Of course, this example makes abstraction of the risks occurring along the supply chain of the metal component, which are also taken into account in the model in PSILCA.

The calculations were done using the software package SimaPro (version 9.1.0.7)[7].

1.2.3.2. Selection of relevant stakeholders and impact categories

All relevant stakeholders and impact categories should be considered in a S-LCA study (Benoît et al., 2020). For this screening S-LCA, all stakeholder categories and subcategories included in the PSLICA v2 database are considered and the results have been calculated for all the available impact categories. Table 5 lists the available stakeholder categories and subcategories in PSILCA. The full list with stakeholders, subcategories, indicators and units of measurements from the PSILCA database is available in Annex A. For interpretation of the results we focus on a selection of stakeholder subcategories. This is common practice in S-LCA. Benoît-Norris et al. (2020) also concluded that few S-LCA studies manage to cover all stakeholders and impact categories. In practice, the stakeholder groups ‘workers’ and ‘local communities’ are frequently included, while ‘consumers’, ‘value chain actors’ and ‘society’ are often not considered.

Table 5: Stakeholders and subcategories available in the PSILCA database.

Stakeholder category	Subcategories			
Workers	Child labour	Forced labour	Fair salary	Working time
	Discrimination	Health and Safety	Social benefits, legal issues	Workers’ rights
Value chain actors	Fair competition	Corruption	Promoting social responsibility	
Society	Contribution to economic development	Health and Safety	Prevention and mitigation of conflicts	
Local community	Access to material resources	Respect of indigenous rights	Safe and healthy living conditions	Local employment
	Migration			

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Consumers	Health and Safety	Transparency	End of life responsibility	

For this study, we made a selection of relevant impact categories based on materiality assessments and sustainability reports made available by major European wind turbine manufacturers. The UNEP/SETAC draft guidelines (Benoît-Norris et al., 2020) point towards materiality assessment as a possible instrument to prioritise stakeholder groups. In addition, The very high and high risk impact categories in the sectors which are considered important for the life cycle of wind turbines were also included. Table 6 provides the results of the review of sustainability reports and materiality assessments of the three main European wind turbine manufacturers (i.e. Vestas, Siemens Gamesa and Nordex). Figure 3 from the UNEP/SETAC draft guidelines for S-LCA (Benoît-Norris et al., 2020) has been used to make the link between the Sustainable Development Goals (SDGs) and the impact assessment subcategories. More details are available in Annex A.

All three wind turbine producers have selected 'Health and safety' as a material aspect for their company. The SDGs which were mentioned by all three wind turbine producers point towards subcategories in the stakeholder groups 'workers' and 'local community'.

Table 6: Selection of stakeholders and subcategories based on sustainability reports and materiality assessments of the three main European wind turbine manufacturers.

	Topic	Company	Linked subcategories	Stakeholder
SDG	7 – Affordable and clean energy	Vestas, Siemens Gamesa, Nordex	Access to material Resources	Local community
	13 – Climate action	Vestas, Siemens Gamesa, Nordex	Covered by LCA	/
	8 – Decent work and economic growth Promote sustained, inclusive and sustainable economic growth	Vestas, Siemens Gamesa, Nordex	Freedom of association, Child labour, Forced labour, Working time, Social benefits/Security, Local employment, Contributions to economic development, Fair salary, Employment relationship	Workers and Local community
Materiality	Health & safety	Vestas, Siemens Gamesa, Nordex	Health and safety (Workers)	Workers

To make sure no important risks for the sector at hand are overlooked, the indicators with high and very high risk in the PSILCA v2 for important sectors in the life cycle of wind turbines have been checked. The important sectors were selected based on their relevance for the project (developments in gearbox and pitch bearing technologies) and based on their costs they are:

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- ‘Manufacturing of machinery and equipment in Finland’, where the manufacturing of the gearbox takes place;
- ‘Manufacturing of metal products in Spain’, where the manufacturing of all other components takes place;
- ‘Maintenance in Germany’ (for RS1 and RS2) or ‘Maintenance in Spain’ (for RS3), selected because of the high life cycle cost.

For the impact categories within the subcategories ‘Fair salary’ and ‘Health and safety’, all four life cycle steps report high or very high risks. The indicator values are available in Table 7 and the full list with high and very high risks occurring in the abovementioned life cycle stages is available in Annex C.

Table 7: Impact categories with high and very high risk in three important life cycle stages in the life cycle of wind turbines.

Impact category	Stakeholder group/ Subcategory	Machinery and equipment in Finland	Metal products in Spain	Maintenance in Germany	Maintenance in Spain
Living wage per month	Workers/Fair salary	Very high risk	High risk	Very high risk	High risk
Rate of non-fatal accidents at workplace	Workers/Health and safety	Very high risk	Very high risk	High risk	High risk

As mentioned above, results have been calculated for all impact categories available in the PSILCA v2 database. The detailed interpretation focuses on the most important impact categories for the sector and the project. The subcategory ‘Health and safety’ turned out to be the most important subcategory as it is mentioned as a material aspect by the three main wind turbine manufacturers (see Table 6) and very high or high risks are to be expected in sectors important for the project or with high cost (see Table 7). ‘Fair salary’ has also been selected as an important subcategory. It has links to SDG 8 (Decent work and economic growth, promote sustained, inclusive and sustainable economic growth), which was mentioned by all three wind turbine manufacturers as an important SDG and very high or high risks are expected in the important sectors.

1.2.3.3. Fair salary in PSILCA

Fair wage means a wage fairly and reasonably commensurate with the value of a particular service or class of service rendered, and, in establishing a minimum fair wage for such service or class of service (Eisfeldt and Ciroth, 2018).

The results for this subcategory are calculated based on results for the indicators ‘living wage per month’, ‘minimum wage per month’ and ‘sector average wage per month’ and are aggregated in one value for the subcategory ‘Fair salary’. ‘Living wage per month’ is the income needed for a decent living, i.e. the monthly wage needed to cover the necessary living costs of an individual or family (WageIndicator, 2017). PSILCA v2 sources the data for ‘living wage per month’ from WageIndicator (2017). Also, the data for ‘minimum wage’, which is the lowest gross wage a full-time worker can be remunerated in a specific country mainly come from WageIndicator (2017). Risk levels for this impact category are calculated by the ratio of living wage to minimum wage. The last indicator in this subcategory is ‘sector average wage per

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month'. Sector average wage provides information about the mean monthly salaries in different industry sectors and countries and assesses if the salary is enough to afford a decent standard of living (Eisfeldt and Ciroth, 2018).

The three indicators are by the PSILCA v2 characterisation method combined into one result for the subcategory, 'Fair salary'.

1.2.3.4. Health and safety (workers) in PSILCA

In this subcategory, occupational health and safety conditions in different sectors are assessed. Since 1950, ILO and WHO (Agius, 2010) define occupational health as follows:

"Occupational health is the promotion and maintenance of the highest degree of physical, mental and social well-being of workers in all occupations by preventing departures from health, controlling risks and the adaptation of work to people, and people to their jobs."

The subcategory 'Health and safety' in PSILCA v2 consists of the indicators 'Non-fatal accidents at workplace', 'Fatal accidents at workplace', 'DALYs (disability adjusted life years) due to indoor and outdoor air and water pollution', 'Presence of sufficient safety measures' and 'Workers affected by natural disasters'. PSILCA presents the results for each indicator separately, the results are not aggregated into a single number (as is the case for the subcategory 'fair salary').

PSILCA v2 sources values for 'Non-fatal accidents' and 'Fatal-accidents' from ILOSTAT (ILO, 2017), which reports incidence rates statistics on occupational injuries.

'DALYs due to indoor and outdoor air and water pollution' is another indicator available in PSILCA v2 which gives information about 'Health and Safety' of workers. Values for this indicator in PSILCA v2 are sourced from the World Bank. The values are from 2004 and they are available on a country-by-country basis for the whole population, not for workers or specific industry sectors. The data rather give an indication of the health and safety of a society than health and safety of workers in a specific sector. This impact category is not further analysed in detail in the results sections.

'Presence of sufficient safety measures' gives information about the measures taken by an employer to limit occupational health risks. PSILCA sources data for this indicator from the OSHA Violation Statistics (USDOL, 2014), which gives the number of violations per 100 thousand employees per year.

A final indicator of the 'Health and safety' subcategory is 'Workers affected by natural disasters'. The data for natural disasters are provided per country as for DALYs and were not disaggregated per sector. The values in PSILCA represent percentages of affected persons in a country. Countries for which no data were available were assigned 'no data', which is in PSILCA v2 equal to a low risk.

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2. Goal and scope of the LCSA

ISO 14040/14044 specify 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).

Specifically, this first iteration of the LCSA is intended for:

- Gaining insights in the contribution of the different components to the environmental, economic and social impact of wind turbines during their life cycle.
- Assessing BAU reference scenarios per case study of which the results can be used for comparing potential environmental, economic and social performance of product systems (i.e. BAU versus INNTERESTING solutions).

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[14].

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

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2.2. Scope of the LCSA

The product system under study is a wind turbine (excluding balance of plant (BOP) for the LCA and S-LCA and including the BOP for the LCC, see also further below under *System boundaries*) developed, produced, installed, used and decommissioned on the European market. For this first iteration of the LCSA specifically, BAU[15] wind turbines are considered for defining the reference scenarios (RSs). As the three case studies are intended for assembly in differing wind turbines, three different RSs have been defined. The specific functional unit and characteristics of the reference wind turbine (RWT) per RS are given in subsections 2.2.1 – 2.2.3. The general functional unit, system boundaries and other scope related aspects applied throughout all iterations of the LCSA are given hereafter.

- **General functional unit**

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

Figure 6: Illustration of the scope of the LCSA.

- **System boundaries**

Table 8 shows the defined system boundaries. Please note that there are some differences between the LCA, LCC, and S-LCA in what is in-/excluded. The biggest difference in scope is that in the LCA and S-LCA the BOP is excluded from the assessment, whereas in the LCC both the turbine (tower, nacelle and rotor) and BOP (foundations, substation, electrical infrastructure, site access etc.) are included in the scope. All expenditures associated with the wind farm (DEVEX, CAPEX, OPEX and ABEX) are taken into account in the LCC, as described in Figure 5.

Additional smaller differences in one of the assessments could be due to the lack of (generic) data for a certain assessment. These specific differences are reported in section 3 regarding LCI data used.

[15] In case of the reference scenarios for case study 1 and 2 (RS1 and RS2), although the assumed reference wind turbines are not yet available on the current market, the wind turbines are considered BAU in this LCSA with the aim of having the best fitting reference for comparison for the next iteration of the LCSA in which the INNTERESTING solutions will be assessed.

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Table 8: The defined system boundaries of the LCSA.

	Included from scope	Excluded from scope
Components	Tower, nacelle and rotor	Platforms/foundations, the transformers, substation and new roads to/on the wind farm (i.e. balance of plant[16]) for the LCA and S-LCA, but included for in the LCC
Life cycle stages / processes / flows	Production stage (module A1-A3) • extraction/acquisition/ pre-processing of raw materials (A1) • transport of raw materials (A2) • manufacturing and testing process[17] (A3)	Environmental impacts caused by site development and pre-construction of wind farm Environmental impacts caused by personnel
	Construction process stage (modules A4+A5) • transport of components to wind farm, includes intermediary transport to OEM (A4) • (on-site) assembly (A5)	Production and EOL treatment of packaging materials for other components than the specific component per CS/RS
	Use stage (module B) • maintenance (B2) • other B-modules assessed but found not relevant/neglectable, i.e.: ○ other emissions due to use, not covered by B2-B7 (B1) ○ repair of a broken component (B3) ○ replacement of a whole element (B4) ○ refurbishment (B5) ○ operational energy use, such as lighting (B6) ○ operational water use (B7) • the annual energy production (AEP) is taken into account to calculate the functional unit (see subsections 2.2.1-2.2.3)	
	End-of-life (EOL, module C) • deconstruction (C1) • transport to EOL treatment (C2) • EOL treatment (C3+C4)	
	Net benefits and loads outside the system boundaries resulting from recycling, reuse and/or useful energy carriers (module D)	
	Production and maintenance of capital goods, unless specifically noted	

[16] Balance of plant defined as: all infrastructure and facilities of a wind farm with an exception of the wind turbine and all its elements.
[17] As mentioned in subsection 1.1.1, the BAU testing process will be included in a revision of the BAU RSs in D6.2.

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- **Allocation**

Allocation procedures are needed when dealing with systems involving multiple products. In this project, the impact of the testing processes, such as the material and energy flows associated with the construction of a test bench, needs to be allocated to one wind turbine. In D6.2, when the impact of the testing process will be added, the description of the allocation procedure will be included too.

Regarding EOL allocation, for the LCA, the EN 15804 end-of-waste point definition is applied.

- **Databases, impact categories and impact assessment methodology**

Please refer to subsections 1.2.1 – 1.2.3 and their underlying subsections for the selected databases, impact categories and impact assessment methodological frameworks applied to the LCA, LCC, and S-LCA.

- **Data quality requirements and data sources**

The company- and application-specific (foreground) LCI data used in this study relied on the cooperation of different project partners and complies with the quality requirements set out in ISO 14044:2006. In case of data assumptions, these were given by the technical partners or were discussed and verified with at least one relevant partner. For all life cycle stages, an input-output balance is made:

- Input data concerning the consumption of energy, water and raw materials.
- Output data are emissions (to air, water, soil, other), waste and useful (by-)products.

As a measure of data quality, section 3 on the LCI reports whether the data were measured, calculated, averaged, or estimated. In addition, the origin of the data is documented. The data fulfil the requirements of precision, completeness and representativeness. If certain data were missing, this is also mentioned.

The following data requirements were applied to this first LCSA iteration:

- Geographical coverage of the data used:
    - For the production stage of specific components of each RS, company-specific data have been used. The data describing the direct inputs and outputs of the foreground processes are representative for Laulaguns pitch bearing production site for RS1 and RS3 and for Moventas' gearbox production site for RS2.
    - For the product stage of the other components of the RWTs, it is assumed that they are produced in (central) Spain.
- Time period coverage of the data used:
    - The data for the BAU RSs are as much as possible representative for the modern state-of-technology.
- Technological coverage of the data used:
    - The data for the BAU RSs refer to currently available, modern technology and to good standard operating practices
- Precision, completeness and representativeness of the data used:
    - Different data sources are used depending on the type of process: for the specific components, company-specific data is used; for the other components, generic data is used based on literature.
- Consistency and reproducibility of the data used:
    - Section 3 clearly describes the data and data sources used.

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- **Assumptions and limitations**

All assumptions made in and the limitations of the LCSA study are/will be described in D6.1, D6.2 or D6.3 per respective iteration of the LCSA. The results of the LCSA are interpreted in agreement with the goal and scope and therefore also with the ISO 14040/14044 guidelines.

- **Critical review**

Considering that INNTERESTING is a Horizon 2020 project, a critical review by an independent LCA/LCC/S-LCA expert is not necessary.

- **Type and format of report required for the study**

As agreed in the grant agreement of this project and listed in table 2 of D8.1 - Project Management Handbook, a deliverable will be drafted in the form of a public report per iteration of the LCSA, i.e. this D6.1, followed by D6.2 in M30, and D6.3 in M36.

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2.2.1. Scope RS1

- **Functional unit RS1**

Based on the general FU, the specific FU of RS1 is as follows: **1 kWh of the total electricity output delivered to the grid over the service life <u>of 25 years</u> by a <u>20 MW offshore</u> wind turbine**.

To calculate the total electricity output of RS1, the following parameters have been applied:

- AEP: 86 000 MWh/y (Ashuri et al., 2016)
- Capacity factor: 49.1%[18]
- Total energy output: 2 150 000 000 kWh

- **Specifications RS1**

Table 9: Specifications of the RWT and wind farm of RS1.

Dimensions	276 m rotor diameter 160 m hub height 3 blades
Assumptions wind farm	Located in NORCOWE virtual wind farm Total capacity of 100x20 MW
Specific component	Pitch bearing with a diameter of 7 m Specific data provided by Laulagun Bearings SA
RWT / generic data source other components	20 MW common research wind turbine model by T. Ashuri et al. (2016)

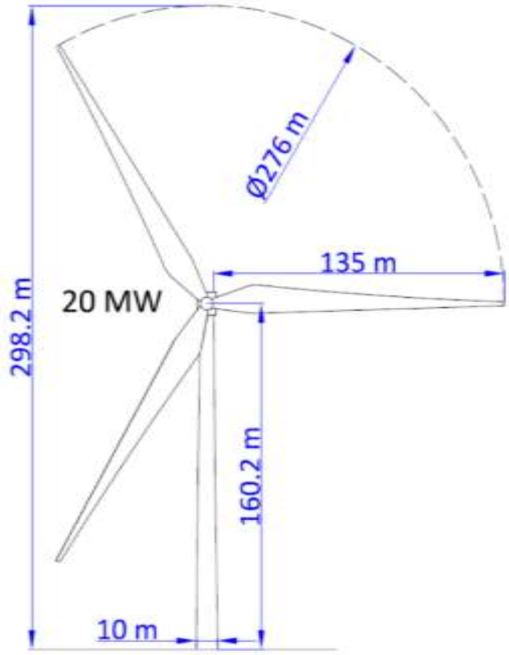

Figure 7: Left – Schematic view of the 20 MW RWT (Ashuri et al., 2016). Right – Location of the NORCOWE virtual wind farm.

18 Calculated based on AEP

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2.2.2. Scope RS2

- **Functional unit RS2**

The specific FU of RS2 is as follows: **1 kWh of the total electricity output delivered to the grid over the service life <u>of 20 years</u> by a <u>10 MW onshore</u> wind turbine <u>with a so-called classical Danish design</u>.**

To calculate the total electricity output of RS2, the following parameters have been applied:

- Availability losses: 6.8%[19]
- Capacity factor: 52.8% (Chaviaropoulos, 2016)
- AEP: 46 211 MWh/y (Chaviaropoulos, 2016)
- Total energy output: 924 224 741 kWh

- **Specifications RS2**

Table 10: Specifications of the RWT and wind farm of RS2.

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

Figure 8: Left – Plot of the DTU 10 MW RWT (Bak et al., 2013).
Right – Wind farm of RS2 is located in north Germany.

[19] Annual average calculated based on bathtub curve by Moventas, with production losses ranging from 6 to 10%.

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2.2.3. Scope RS3

- **Functional unit RS3**

The specific FU of RS3 is as follows: **1 kWh of the total electricity output delivered to the grid over the service life <u>of 20 years</u> by a <u>3.4 MW onshore</u> wind turbine.**

To calculate the total electricity output of RS3, the following parameters have been applied:

- Capacity factor: 24% (WindEurope, 2020)
- AEP: 7 148 MWh/y[20]
- Total energy output: 142 963 200 kWh

- **Specifications RS3**

Table 11: Specifications of the RWT and wind farm of RS3.

Dimensions	130 m rotor diameter 110 m hub height 3 blades
Assumptions wind farm	Located in Burgos, Spain Total capacity of 20x3.4 MW
Specific component	Pitch bearing with a diameter of 2.6 m Specific data provided by Laulagun Bearings SA
RWT / generic data source other components	IEA Wind Task 37 3.4-MW Land-Based Wind Turbine by Bortolotti et al. (2019)

Figure 9: Left – Plot of 3.4 MW land-based wind turbine (Dykes, 2019). Right – Wind farm location of RS3: Burgos, Spain.

[20] Calculated based on the capacity factor.

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3. Life cycle inventory of the LCSA

The life cycle inventory (LCI) phase involves data collection and calculation procedures to quantify the inputs and outputs that are associated with the product system(s) under study. This includes the use of resources, and releases to air, water and soil. Input and output data need to be collected for each process that is included in the system boundaries. The results of the LCI may constitute the input for the LCSA as well as an input for the interpretation phase. This section starts with some general assumptions for all three RSs, followed by (restricted) overviews of the collected LCI data per RS.

3.1. General data assumptions

- **Defined scenarios**

For the production location of the different components we have assumed that for all three RSs the gearbox is produced in Finland and the pitch bearings and other components are made in Spain.

- **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) and the different other wind turbine components (e.g. the tower, blades, etc.). 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 (BVG Associates, 2019; Chaviaropoulos, 2016; IRENA, 2019; Smith et al., 2015; Stehly & Beiter, 2020; Tegen et al., 2012). In one of the deliverables of the ROMEO project[21], a figure on offshore wind LCOE demonstrates that significant variation in economic data can be observed in the available literature based on historical data of installed projects and surveys of project developers. Figure 10 shows the range (blue) and average values (green) of CAPEX (in million GBP per MW) and OPEX (in GBP per MWh) in existing literature compiled and converted to GBP 2015 currency, to illustrate the scattered cost data. This uncertainty needs to be taken into account in the interpretation of the LCOE results.

[21] Horizon 2020 ROMEO Deliverable Report - D8.1: Development of a high-fidelity cost/revenue model for impact assessment - PU-Public (2018) https://www.romeoproject.eu/wp-content/uploads/2018/12/D8.1_ROMEO_Report-reviewing-exsiting-cost-and-OM-support-models.pdf

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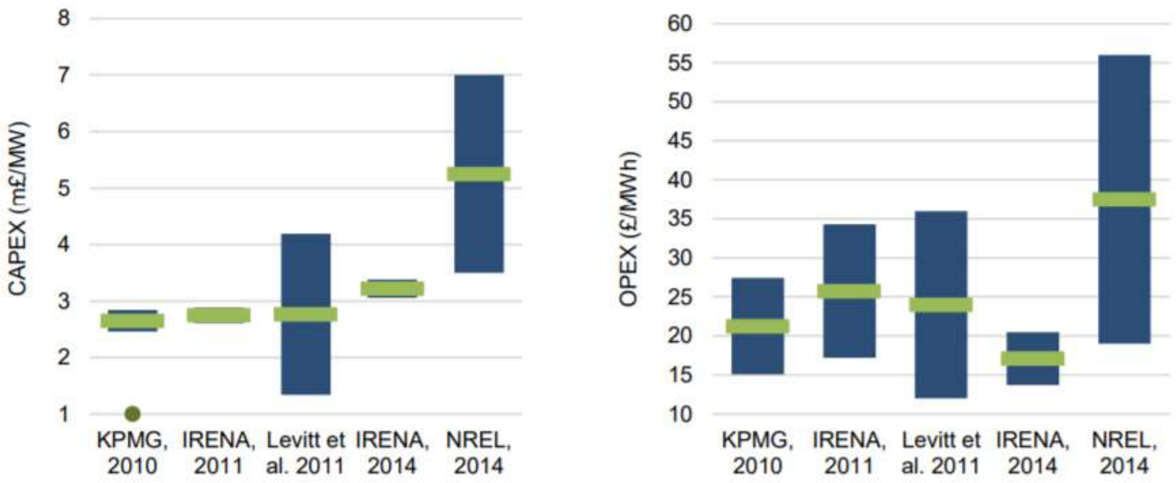

Figure 10: Illustration of high degree of uncertainty for cost data (ROMEO D8.1, 2018)

Regarding the screening S-LCA, no foreground data about risks occurring during the different life cycle steps, for example, on worker conditions have been collected. Instead, 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 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 3.6 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 RS1 or year 2039 (year 20) for RS2 and RS3. 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[22] data. To forecast the residual value of wind turbine components at decommissioning, Worldbank Commodities Prices Forecasts[23] are used.

Regarding the screening 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). The S-LCA study makes use of the same cost data as the LCC study. Costs for the S-LCA are for the

[22] https://www.irs.gov/individuals/international-taxpayers/yearly-average-currency-exchange-rates
[23] http://pubdocs.worldbank.org/en/633541587395091108/CMO-April-2020-Forecasts.pdf

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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 (see Table 8). The costs for installation, transport to installation and maintenance considered in the S-LCA study relate to the turbine only (and not the BOP).

3.2. LCI RS1

Table 12 and Table 13 show the collected data and assumed scenarios for RS1 that could be shared in this public deliverable. Table 12 concerns data on the CAPEX and mass per component. Starting point of the material compositions of the components is the material compositions applied in RS2 and further optimised for RS1 with input from Ikerlan. Table 13 describes the scenarios for the life cycle stages after the raw materials stage (module A1) for all three assessments within the LCSA and if applicable also additional assumptions per pillar of the LCSA (i.e. LCA, LCC, and S-LCA).

Table 12: Specific LCI data (CAPEX and mass) of RS1 for life cycle stage raw materials (A1).

Component	CAPEX [USD 2010]	Mass [kg]	Description	Data source
Rotor				
Blades (3p)	40 517 000	259 000	Glass fibre reinforced fabric	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX
Hub	1 456 900	252 800	Ductile cast iron	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX
Pitch mechanism (incl. pitch bearings)	1 945 300	236 000 (mass pitch bearings 66 000)	Pitch bearings based on specific LCI data Laulagun	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX Partially specific LCI data Laulagun
Hub cone	34 600	4 600	Ductile cast iron	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX
Drive train & nacelle				
Main shaft	1 605 300	159 100	Cast carbon steel	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX
Shaft bearing	1 013 400	42 500	Alloy steel	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX
Gearbox	4 995 500	161 900	Gearings	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX
Drive train brake	44 400	4 000	Steel, rubber	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX
Generator	1 592 000	59 800	Steel, copper wiring	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX
Electronics	1 572 800	180 000	Converter, transformer	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX
Yaw system	1 495 000	176 800	Drive motors, gearings	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX

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Nacelle frame	752 600	280 800	Ductile iron cast	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX
Nacelle railing	414 200	35 100	Steel	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX
Nacelle cover	279 600	23 400	Glass fibre reinforced fabric	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX
Turbine connection (electrical)	1 235 500	35 100	Electronics, cables	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX
Cooling and hydraulic system	309 000	1 600	Oil-based hydraulics, water-cooled system	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX
Tower & controls				
Monitoring and safety system	65 400	7 500	Electronics	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX
Tower	3 971 000	1 588 300	Structural steel	Ashuri et al. (2016) 20 MW common research wind turbine model | Table IX

Table 13: Specific scenarios of RS1 for all other life cycle stages (A2 – A5, B2, B6 and EOL).

	Scenario	Source
Transport of raw materials to factories (A2)		
LCSA	Raw materials of pitch bearing sourced by and transported to Laulagun	Specific data Laulagun
LCA	Transport distance raw materials of all other components based on generic market data	ecoinvent LCI data
LCC	Transportation costs included in the price of the raw materials	Specific data Laulagun
S-LCA	Included in production cost see Table 12	
Production process (A3)		
LCSA	The pitch bearing is produced at factory of Laulagun in Olaberria (Spain); data on ancillary materials, energy and water inputs, emissions and waste flows	Specific data Laulagun
LCA	Assumed generic material processing within Europe of raw materials/production of other components	ecoinvent LCI data
LCC	Specific data on costs of raw materials, ancillary materials and costs of energy for production of pitch bearing. All other cost components based on Ashuri et al.	Specific data Laulagun + Ashuri et al. (2016)
S-LCA	Included in production cost see Table 12	
Transport to wind farm site (A4)		
LCSA	Pitch bearings are transported from factory Laulagun to NORCOWE wind farm via OEM in Denmark Gearbox is transported from Finland and all other components from Spain to NORCOWE wind farm via OEM in Denmark	Assumption
LCA	Pitch bearing: 100 km transport in Spain by truck to Port of Bilboa (ES) + 2350 km per ship to Port of Ringkobing (DK) + 150 km per ship to NORCOWE	Distances based on Google maps + ports.com

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	Gearbox: 250 km transport in Finland by truck to Port of Helsinki (FI) + 1900 km per ship to Port of Ringkobing (DK) + 150 km per ship to NORCOWE All other components: 250 km transport in Spain by truck to Port of Bilboa (ES) + 2350 km per ship to Port of Ringkobing (DK) + 150 km per ship to NORCOWE	
LCC	Specific data for pitch bearing. Other cost components based on Cost of Wind Energy Review report 2020	Stehly & Beiter, 2020
S-LCA	The scope of the S-LCA is limited to the turbine (scope similar to LCA), while the LCC considers a full scope including BOP and DEVEX. Turbine transportation costs are considered 42% of the total transportation costs applied in the LCC.	Calculated based on Stehly & Beiter, 2020
(On-site) assembly by OEM (A5)		
LCSA	Wind farm site in NORCOWE virtual wind farm (see Figure 7)	Assumption
LCA	Medium voltage electricity use: 0.5 kWh/kg material for all components assembly (A5) and deconstruction (C1) Assumed a division of 70% for A5 and 30% for C1.	ecoinvent background report / assumption
LCC	Based on Cost of Wind Energy Review report 2020	Stehly & Beiter, 2020
S-LCA	The scope of the S-LCA is limited to the turbine (scope similar to LCA), while the LCC considers a full scope including BOP and DEVEX. Turbine installation costs are considered 11% of the total installation costs applied in the LCC.	Calculated based on BVG associates (nd)
Maintenance (B2)		
LCSA	No specific data on the maintenance of the pitch bearing included	
LCA	No generic LCA data available on maintenance of other components	/
LCC	No specific data on O&M costs for pitch bearing. Maintenance for all cost components based on *Cost of Wind Energy Review report* (2020)	Stehly & Beiter, 2020
S-LCA	The scope of the S-LCA is limited to the turbine (scope similar to LCA), while the LCC considers a full scope including BOP and DEVEX. Turbine maintenance costs are considered 66% of the total maintenance costs applied in the LCC.	Calculated based on BVG associates (nd)
Deconstruction (C1)		
LCSA	Deconstruction on NORCOWE wind farm site	Assumption
LCA	Medium voltage electricity use: 0.5 kWh/kg material for all components assembly (A5) and deconstruction (C1) Assumed a division of 70% for A5 and 30% for C1.	ecoinvent background report / assumption
LCC	Based on *Guide to an offshore wind farm* (2019)	BVG Associates, 2019
S-LCA	The scope of the S-LCA is limited to the turbine (scope similar to LCA), while the LCC considers a full scope including BOP and DEVEX. Turbine decommissioning costs are considered 14% of the total decommissioning costs applied in the LCC.	Calculated based on BVG associates (nd)

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Transport to EOL treatment (C2)		
LCSA	Transport to waste treatment facilities in Denmark by truck after a trip by ship from NORCOWE	Assumption
LCA	150 km per ship + 250 km to recycling facility, 250 km to incineration, and 125 km to landfill	Assumption
LCC + S-LCA	Transport to EOL: 50% of transportation costs to wind farm	Assumption
EOL treatment (C3+C4)		
LCSA	Waste treatment facilities in Denmark	Assumption
LCA	100% recycling of fibreglass fabric Generic waste scenarios for other waste flows	Windpowermonthly (2020) PEF Annex C (2020)
LCC + S-LCA	Scrap value applied to iron and copper parts in the system, and specifically for the pitch bearing	World Bank Commodities Price Forecast (2020)

3.3. LCI RS2

Table 14 and Table 15 show the collected data and assumed scenarios for RS2 that could be shared in this public deliverable. Table 14 concerns data on the CAPEX and mass per component. Table 15 describes the scenarios for the life cycle stages after the raw materials stage (module A1) for all three assessments within the LCSA and if applicable also additional assumptions per pillar of the LCSA (i.e. LCA, LCC, and S-LCA).

Table 14: Specific LCI data (CAPEX and mass) of RS2 for life cycle stage raw materials (A1).

Component	CAPEX [USD 2002]	Mass [kg]	Description	Data source
Rotor				
Blades (3p)	1 896 925	145 962	Glass fibre reinforced fabric	CAPEX: Costs Model v1.02 (Chaviaropoulos, 2016) | Innwind.EU 10MW RWT Blade - scaled + 17% Blade mass: 198m rotor from IEA Wind TCP Task 37 10MW RWT 47 700kg +2%
Hub	377 254	88 766	Ductile cast iron	Costs Model v1.02 (Chaviaropoulos, 2016) | SF 2,3 + power 10000 kW
Pitch mechanism	299 584	33 287	Bearings, drive motors, gearings, controller	Costs Model v1.02 (Chaviaropoulos, 2016) | SF 2,3 + power 10000 kW
Nose cone	17 916	3 217	Ductile cast iron	Costs Model v1.02 (Chaviaropoulos, 2016) | diameter 202 m
Drive train & nacelle				
Low speed shaft	230 885	76 962	Cast carbon steel	Costs Model v1.02 (Chaviaropoulos, 2016) | SF 3,0 + power 10000 kW
Main bearing	499 626	28 388	Alloy steel	Costs Model v1.02 (Chaviaropoulos, 2016) | diameter 202 m
Gearbox	1 629 919	104 000	Specific LCI data Moventas	Costs Model v1.02 (Chaviaropoulos, 2016) | diameter 202 m Partially specific costs LCI data Moventas

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Mechanical brake & couplings	19 894	2 828	Steel, rubber	Costs Model v1.02 (Chaviaropoulos, 2016) | SF 3,0 + power 10000 kW
Generator	650 000	31 630	Steel, copper wiring	Costs Model v1.02 (Chaviaropoulos, 2016) | Drive train model: Three-stage planetary/helical
Power electronics	790 000	60 000	Converter, transformer	Costs Model v1.02 (Chaviaropoulos, 2016) Mass assumed by Moventas
Bed plate	301 697	70 997	Ductile cast iron	Costs Model v1.02 (Chaviaropoulos, 2016) | Drive train model: Three-stage planetary/helical
Hydraulic & cooling system	120 000	800	Oil-based hydraulics, water-cooled system	Costs Model v1.02 (Chaviaropoulos, 2016) | power 10000 kW
Nacelle cover	104 000	26 000	Glass fibre reinforced fabric	Costs Model v1.02 (Chaviaropoulos, 2016) | SF 2,0 + power 10000 kW
Electrical connections	400 000	11 700	Electronics, cables	Costs Model v1.02 (Chaviaropoulos, 2016) / Mass assumed by Moventas
Yaw system	461 627	62 849	Drive motors, gearings	Costs Model v1.02 (Chaviaropoulos, 2016) | power 10000 kW
Tower & controls				
Control, safety system, CM	55 000	2 500	Electronics	Costs Model v1.02 (Chaviaropoulos, 2016) Mass assumed by Moventas
Tower	1 571 250	628 500	Structural steel	Costs Model v1.02 (Chaviaropoulos, 2016) | Tower model: RWT 10MW Standard – Scaled Material composition provided by Ikerlan

Capital expenses of the Costs Model, expressed in USD 2002, are converted to EUR 2019. Wind turbine price evolutions over time are based on the evolution in the global weighted average of total installed costs of onshore wind projects between 1983 and 2019. Driven by wind turbine price and BOP cost reductions, the global weighted-average total installed cost of onshore wind projects fell by 72% between 1983 and 2019, and by 24% between 2010 and 2019 (IRENA, 2019). These price fluctuations, based on data from the IRENA Renewable Cost Database, are taken into account for the LCOE calculations. Evolutions of costs of transport are based on cost price indices for international road freight transport of the Institute for Road Transport and Logistics Belgium[24].

Table 15: Specific scenarios of RS2 for all other life cycle stages (A2 – A5, B2, B6 and EOL).

	Scenario	Source
Transport of raw materials to factories (A2)		
LCSA	Raw materials of gearbox sourced by and transported to Moventas	Specific data Moventas
LCA	Transport distance raw materials of all other components based on generic market data	ecoinvent LCI data

24 http://94.23.228.57/ITLB/PAGE_Etudes_Permanentes/cAwAAAEpBJ1McGdjWXB6VWxoAAA?A11

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LCC	Specific data for raw materials of gearbox. Included in production costs (CAPEX) of Costs Model for all other components.	Specific data Moventas + Costs Model v1.02 (Chaviaropoulos, 2016)
S-LCA	Included in production cost see Table 14	
Production process (A3)		
LCSA	The gearbox is produced at factory of Moventas in Jyväskylä (Finland); data on ancillary materials, energy and water inputs, emissions and waste flows, packaging of final product for transport	Specific data Moventas
LCA	Assumed generic material processing within Europe of raw materials/production of other components	ecoinvent LCI data
LCC	Specific data on costs of raw materials and costs of energy for production of gearbox. No specific cost data for ancillary materials: costs considered negligible. All other cost components based on Costs Model.	Specific data Moventas + Costs Model v1.02 (Chaviaropoulos, 2016)
S-LCA	Included in production cost see Table 14	
Transport to wind farm site (A4)		
LCSA	Gearbox is transported from factory Moventas to north Germany All other components from Spain to north Germany	Assumption
LCA	Gearbox: 250 km transport in Finland by truck to Port of Helsinki (FI) + 2240 km per ship to Port of Hamburg (DE) + 150 km transport in Germany by truck via OEM to wind farm All other components: 250 km transport in Spain by truck to Port of Bilboa (ES) + 2260 km per ship to Port of Hamburg (DE) + 150 km transport in Germany by truck via OEM to wind farm	Distances based on Google maps + ports.com
LCC	Based on Cost of Wind Energy Review report 2012	Tegen et al., 2012
S-LCA	The scope of the S-LCA is limited to the turbine (scope similar to LCA), while the LCC considers a full scope including BOP and DEVEX. Turbine transportation costs are considered 45% of the total transportation costs applied in the LCC.	Assumption share of turbine transportation equal to share of turbine installation.
(On-site) assembly by OEM (A5)		
LCSA	Wind farm site in north of Germany (see Figure 8)	Assumption
LCA	Gearbox filled with gear oil by OEM Medium voltage electricity use: 0.5 kWh/kg material for all components assembly (A5) and deconstruction (C1) Assumed a division of 70% for A5 and 30% for C1.	Moventas ecoinvent background report / assumption
LCC	Based on Cost of Wind Energy Review report 2020	Stehly & Beiter, 2020
S-LCA	The scope of the S-LCA is limited to the turbine (scope similar to LCA), while the LCC considers a full scope including BOP and DEVEX. Turbine installation costs are considered 45% of the total installation costs applied in the LCC.	Calculated based on BVG associates (nd)
Maintenance (B2)		
LCSA	Specific data on the maintenance of the gearbox included	Moventas

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LCA	No generic LCA data available on maintenance of other components	/
LCC	Specific data on costs of materials and labour hours for maintenance of gearbox. Maintenance for all other cost components based on Costs Model.	Specific data Moventas + Costs Model v1.02 (Chaviaropoulos, 2016)
S-LCA	The scope of the S-LCA is limited to the turbine (scope similar to LCA), while the LCC considers a full scope including BOP and DEVEX. Turbine maintenance costs are considered 66% of the total maintenance costs applied in the LCC.	Calculated based on BVG associates (nd)
Deconstruction (C1)		
LCSA	Deconstruction wind farm site in north Germany	Assumption
LCA	Medium voltage electricity use: 0.5 kWh/kg material for all components assembly (A5) and deconstruction (C1) Assumed a division of 70% for A5 and 30% for C1.	ecoinvent background report / assumption
LCC + S-LCA	Decommissioning costs: 50% of the installation costs	Smith et al., 2015
Transport to EOL treatment (C2)		
LCSA	Transport to waste treatment facilities in Germany by truck	Assumption
LCA	250 km for fibreglass fabric waste flow (assumed to Bremen), for other waste flows 125 km to recycling facility (assumed in Hamburg), 125 km to incineration (assumed in Hamburg), and 100 km to landfill (assumed in Harrislee)	Distances based on Google maps
LCC + S-LCA	Transport to EOL: 50% of transportation costs to wind farm	Assumption
EOL treatment (C3+C4)		
LCSA	Waste treatment facilities in Germany	Assumption
LCA	100% recycling of fibreglass fabric Generic waste scenarios for other waste flows	Windpowermonthly (2020) PEF Annex C (2020)
LCC + S-LCA	Scrap value applied to iron and copper parts in the system, re-use value for the gearbox provided by Moventas	World Bank Commodities Price Forecast (2020)

3.4. LCI RS3

Table 16, Table 17 and Table 18 show the collected data and assumed scenarios for RS3 that could be shared in this public deliverable. Table 16 concerns data on the mass per component and Table 17 on CAPEX. Table 18 describes the scenarios for the life cycle stages after the raw materials stage (module A1) for all three assessments within the LCSA and if applicable also additional assumptions per pillar of the LCSA (i.e. LCA, LCC, and S-LCA).

Table 16: Specific LCI mass data of RS3 for life cycle stage raw materials (A1).

Component	Mass [kg]	Description	Data source
Rotor			
Blades (3p)	11 400	Glass fibre reinforced fabric	Mass: Table 5 D1.1 Material composition based on RS2

Hub (incl. hub cone)	15 000	Cast iron	Table 5 D1.1
Pitch bearings (3p)	9 600	Specific LCI data Laulagun	(Table 5 D1.1) Specific LCI data Laulagun
Pitch plates (3p)	5 700	Structural steel	Table 5 D1.1
Drive train & nacelle			
Low speed shaft	26 550	Cast carbon	Mass: Bortolotti et al. (2019) Table 5 Material composition based on RS2
Shaft bearings	8 160	Alloy steel	Mass: Bortolotti et al. (2019) Table 5 Material composition based on RS2
Gearbox	41 050	Gearings	Mass: Bortolotti et al. (2019) Table 5 Material composition based on RS2
Drive train brake	12 040	Steel, rubber	Mass: calculated as remaining mass of 'overal nacelle' Bortolotti et al. (2019) Table 5 Material composition based on RS2
Generator	16 890	Steel, copper	Mass: Bortolotti et al. (2019) Table 5 Material composition provided by Ikerlan
Power electronics	10 400	Transformer	Bortolotti et al. (2019) Table 5
Bed plate	60 990	Ductile cast iron	Mass: Bortolotti et al. (2019) Table 5 Material composition based on RS2
Cooling and hydraulic system	280	Oil-based hydraulics, water-cooled system	Mass: Bortolotti et al. (2019) Table 5 Material composition based on RS2
Nacelle cover	9 230	Glass fibre reinforced fabric	Mass: Bortolotti et al. (2019) Table 5 Material composition provided by Ikerlan
Yaw system	4 460	Drive motors, gearings	Mass: Bortolotti et al. (2019) Table 5 Material composition based on RS2
Turbine connection (electrical)	7 800	Electronics, cables	Based on RS1 and RS2
Tower			
Monitoring and safety system	1 700	Electronics	Based on RS1 and RS2
Tower	553 000	Structural steel	Mass: Bortolotti et al. (2019) Table 2 Material composition provided by Ikerlan

Table 17: Specific LCI CAPEX data of RS3 for life cycle stage raw materials (A1).

Component	CAPEX [USD 2018]	Description	Data source
Rotor			
Blades (3p)	639 200	Stehly & Beiter, 2020 | Cost of Wind Energy Review report	
Hub assembly	153 000	Stehly & Beiter, 2020 | Cost of Wind Energy Review report	
Pitch assembly	207 400	Specific LCI data Laulagun + Stehly & Beiter, 2020 | Cost of Wind Energy Review report	
Drive train & nacelle			
Nacelle structural assembly	340 000	Stehly & Beiter, 2020 | Cost of Wind Energy Review report	
Drivetrain assembly	663 000		
Nacelle electrical assembly	578 000		
Yaw assembly	112 200		
Tower			
Tower module	744 600	Stehly & Beiter, 2020 | Cost of Wind Energy Review report	

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Table 18: Specific scenarios of RS3 for all other life cycle stages (A2 – A5, B2, B6 and EOL).

	Scenario	Source
Transport of raw materials to factories (A2)		
LCSA	Raw materials of pitch bearing sourced by and transported to Laulagun	Specific data Laulagun
LCA	Transport distance raw materials of all other components based on generic market data	ecoinvent LCI data
LCC	Transportation costs included in the price of the raw materials	Specific data Laulagun
S-LCA	Included in production cost see Table 17	
Production process (A3)		
LCSA	The pitch bearing is produced at factory of Laulagun in Olaberria (Spain); data on ancillary materials, energy and water inputs, emissions and waste flows	Specific data Laulagun
LCA	Assumed generic material processing within Europe of raw materials/production of other components	ecoinvent LCI data
LCC	Specific data on costs of raw materials, ancillary materials and costs of energy for production of pitch bearing. All other cost components based on *Cost of Wind Energy Review report* (2020)	Specific data Laulagun + Stehly & Beiter, 2020
S-LCA	Included in production cost see Table 17	
Transport to wind farm site (A4)		
LCSA	Pitch bearing is transported from factory Laulagun to Burgos via an OEM in Spain Gearbox is transported from Finland and all other components from Spain to Burgos via an OEM in Spain	Assumption
LCA	Pitch bearing: 400 km transport in Spain by truck to Burgos via OEM Gearbox: 250 km transport in Finland by truck to Port of Helsinki (FI) + 2280 km per ship to Port of Bilbao (ES) + 460 km transport in Spain by truck to Burgos via OEM All other components: 500 km transport in Spain by truck to Burgos via OEM	Distances based on Google maps + ports.com
LCC	Specific data for pitch bearing. Other cost components based on *Cost of Wind Energy Review report* (2020)	Stehly & Beiter, 2020
S-LCA	The scope of the S-LCA is limited to the turbine (scope similar to LCA), while the LCC considers a full scope including BOP and DEVEX. Turbine transportation costs are considered 45% of the total transportation costs applied in the LCC.	Assumption share of turbine transportation equal to share of turbine installation.
(On-site) assembly by OEM (A5)		
LCSA	Wind farm site in Burgos (see Figure 9)	Assumption
LCA	Medium voltage electricity use: 0.5 kWh/kg material for all components assembly (A5) and deconstruction (C1) Assumed a division of 70% for A5 and 30% for C1.	ecoinvent background report / assumption
LCC	Based on Cost of Wind Energy Review report 2020	Stehly & Beiter, 2020

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S-LCA	The scope of the S-LCA is limited to the turbine (scope similar to LCA), while the LCC considers a full scope including BOP and DEVEX. Turbine installation costs are considered 45% of the total installation costs applied in the LCC.	Calculated based on BVG associates (nd)
Maintenance (B2)		
LCSA	No specific data on the maintenance of the pitch bearing included	
LCA	No generic LCA data available on maintenance of other components	/
LCC	No specific data on O&M costs for pitch bearing. Maintenance for all cost components based on *Cost of Wind Energy Review report* (2020)	Stehly & Beiter, 2020
S-LCA	The scope of the S-LCA is limited to the turbine (scope similar to LCA), while the LCC considers a full scope including BOP and DEVEX. Turbine maintenance costs are considered 66% of the total maintenance costs applied in the LCC.	Calculated based on BVG associates (nd)
Deconstruction (C1)		
LCSA	Deconstruction wind farm site in Burgos (ES)	Assumption
LCA	Medium voltage electricity use: 0.5 kWh/kg material for all components assembly (A5) and deconstruction (C1) Assumed a division of 70% for A5 and 30% for C1.	ecoinvent background report / assumption
LCC	Based on *Guide to an offshore wind farm* (2019)	BVG Associates, 2019
S-LCA	The scope of the S-LCA is limited to the turbine (scope similar to LCA), while the LCC considers a full scope including BOP and DEVEX. Turbine decommissioning costs are considered 14% of the total decommissioning costs applied in the LCC.	Calculated based on BVG associates (nd)
Transport to EOL treatment (C2)		
LCSA	Transport to waste treatment facilities in Spain by truck	Assumption
LCA	150 km to recycling facility, 250 km to incineration, and 125 km to landfill	Assumption
LCC + S-LCA	Transport to EOL: 50% of transportation costs to wind farm	Assumption
EOL treatment (C3+C4)		
LCSA	Waste treatment facilities in Spain	Assumption
LCA	100% recycling of fibreglass fabric Generic waste scenarios for other waste flows	Windpowermonthly (2020) PEF Annex C (2020)
LCC + S-LCA	Scrap value applied to iron and copper parts in the system, and specifically for the pitch bearing	World Bank Commodities Price Forecast (2020)

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4. Life cycle impact assessment of the LCSA

In the life cycle impact assessment (LCIA), the results of the LCI are linked to specific environmental damage categories (e.g. CO_2 emissions are related to damages to human health caused by climate change, SO_2 emissions are related to damages to the ecosystem caused by acidification, etc.) in case of an environmental LCA. It is important to note that the inventory results generally do not include spatial, temporal, dose-response or threshold information. Therefore, LCIA cannot and is not intended for identifying or predicting *actual* environmental impacts. Instead, LCIA predicts *potential* environmental, economic or social damages (impacts) related to the system under study. For an LCC analysis, the term 'impact assessment' relates to the interpretation of economic results. The Life Cycle Cost of a product is a number expressed in monetary units. Because it is comparative, there is also no threshold and a lower cost is always better (Swarr et al. 2011).

This section consists of three subsections, one per RS, in which the LCIA results are presented and interpreted.

4.1. LCIA RS1

4.1.1. Findings LCA

Table 19 provides the environmental impact results in absolute values for 1 kWh generated to the grid by a 20 MW offshore wind turbine installed in NORCOWE with a service life of 25 years. Figure 11 is a graphical representation of the same results. The calculations are done according to the EN 15804+A2:2019 method and based on the collected LCI data for RS1 as presented in section 3.2.

The results show that the production stage (A1-A3) can be seen as the most relevant life cycle stage, as for all impact categories the production stage contributes more than 82% of the total life cycle impact[25].

Table 19: Environmental profile of RS1 in absolute values per FU.

	Production (A1-A3)	Transport to site (A4)	Assembly (A5)	Deconstruction (C1)	EOL treatment (C2-C4)	Total life cycle
Climate change - total [kg CO2 eq]	7,00E-03	9,26E-05	1,92E-04	8,24E-05	6,89E-05	**7,43E-03**
Ozone depletion [kg CFC11 eq]	5,66E-10	2,10E-11	6,09E-12	2,61E-12	9,92E-12	**6,06E-10**
Acidification [mol H+ eq]	6,31E-05	1,40E-06	6,81E-07	2,92E-07	2,61E-07	**6,57E-05**
Eutrophication, freshwater [kg P eq]	6,31E-07	5,92E-10	1,47E-08	6,31E-09	4,43E-10	**6,53E-07**
Eutrophication, marine [kg N eq]	8,18E-06	3,39E-07	1,21E-07	5,19E-08	7,48E-08	**8,77E-06**
Eutrophication, terrestrial [mol N eq]	8,87E-05	3,78E-06	1,74E-06	7,44E-07	8,26E-07	**9,58E-05**
Photochemical ozone formation [kg NMVOC eq]	3,07E-05	1,04E-06	3,64E-07	1,56E-07	2,49E-07	**3,25E-05**
Resource use, minerals and metals [kg Sb eq]	6,09E-07	1,26E-09	7,58E-10	3,25E-10	7,62E-10	**6,12E-07**
Resource use, fossils [MJ]	8,98E-02	1,37E-03	2,39E-03	1,02E-03	6,80E-04	**9,53E-02**
Water use [m³ depriv.]	2,39E-03	3,60E-06	2,64E-05	1,13E-05	1,04E-07	**2,43E-03**
Particulate matter [disease inc.]	4,64E-10	5,97E-12	3,27E-12	1,40E-12	4,10E-12	**4,78E-10**
Ionising radiation [kBq U-235 eq]	2,94E-04	5,96E-06	1,17E-05	5,04E-06	2,93E-06	**3,20E-04**
Ecotoxicity, freshwater [CTUe]	5,05E-01	1,02E-03	3,64E-03	1,56E-03	7,49E-04	**5,12E-01**
Human toxicity, cancer [CTUh]	3,24E-11	3,86E-14	5,35E-14	2,29E-14	2,33E-14	**3,26E-11**
Human toxicity, non-cancer [CTUh]	6,52E-10	1,03E-12	1,83E-12	7,86E-13	1,24E-12	**6,57E-10**
Land use [Pt]	3,48E-02	1,09E-03	3,97E-03	1,70E-03	7,37E-04	**4,23E-02**
Contribution to impact category	X > 50%	25% < X < 50%	10% < X < 25%	2,5% < X < 10%	X < 2,5%	

[25] Please note that the life cycle stage Maintenance (B2) is excluded in the LCA of RS1 due a lack of environmental LCI data on the maintenance of the wind turbine.

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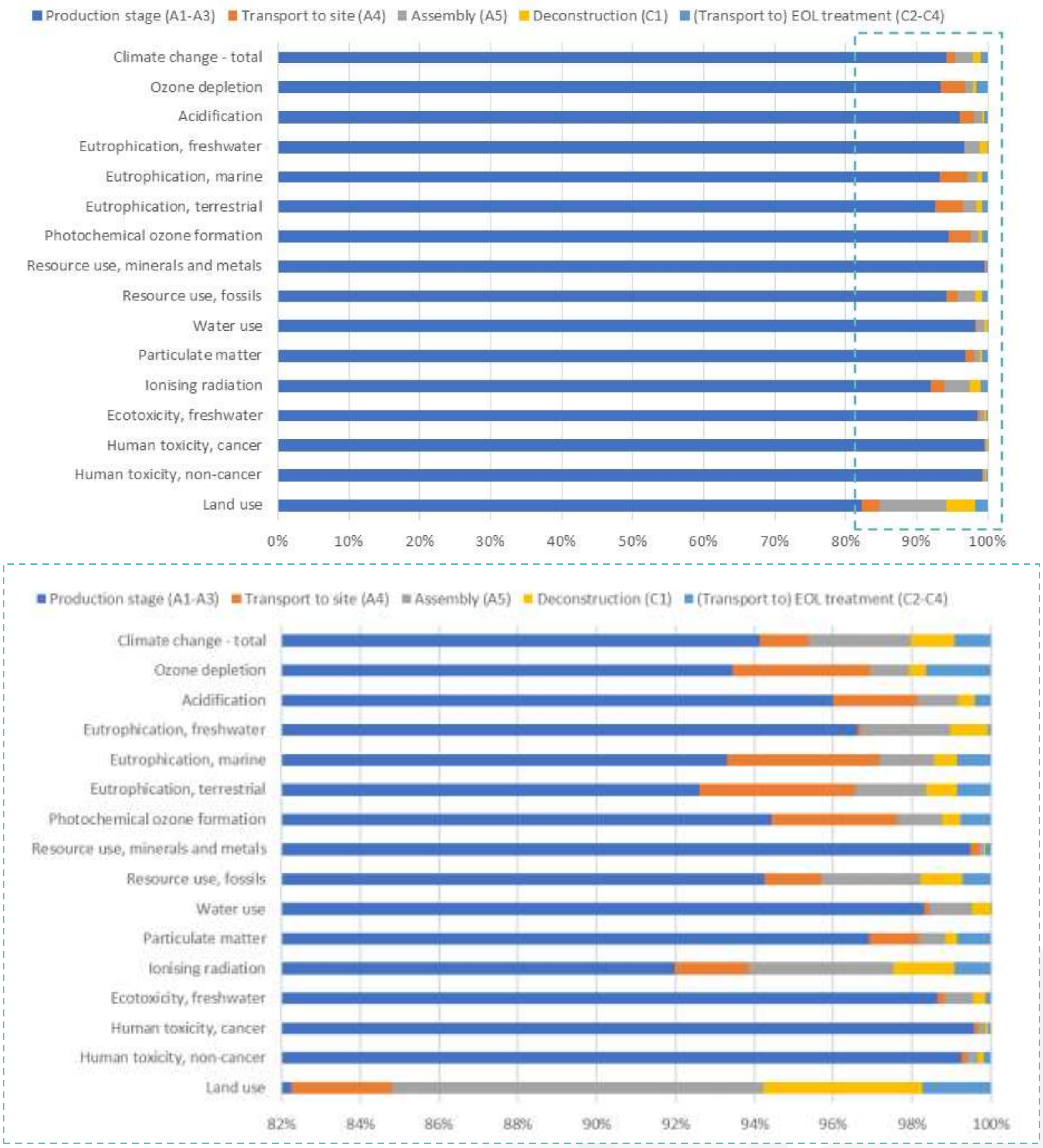

Figure 11: Relative contribution of all life cycle stages of RS1 based on the environmental profile, with below a more detailed view of the last 18%.

When analysing only the production stage of RS1 in more detail (see Figure 12), it shows that the main contributing component of the RS1 wind turbine is the tower. This can be explained by the mass of the tower (1 588 300 kg, which is 45,3% of the total mass of the wind turbine). Other components that have a relatively decisive contributing impact on all impact categories are: the pitch mechanism, electronics and yaw system.

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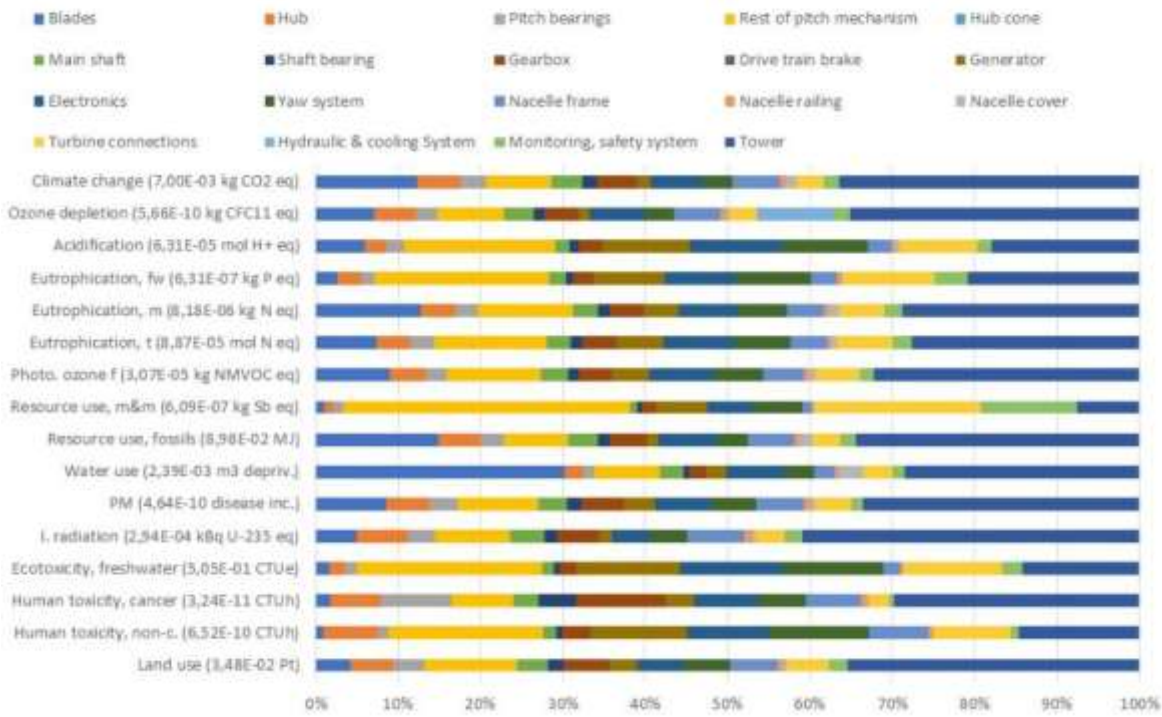

Figure 12: Relative contribution of all components of RS1 to the production stage (A1-A3). The absolute values mentioned between brackets in the vertical axis are per FU.

- ## LCA findings related to the pitch bearing RS1

Table 20 and Figure 13 present the results of the environmental LCIA of the specific component of RS1, i.e. a pitch bearing for a 20 MW offshore wind turbine with a service lifetime of 25 years. Based on the results it can be concluded that the raw materials of the pitch bearing contribute the most to the environmental impact of its complete life cycle. In all impact categories, the contribution of the raw materials is at least 83%. More detailed results and findings of this LCA will be shared with Laulagun.

Table 20: Environmental profile of a pitch bearing in RS1 in absolute values per FU.

	(Transport of) raw materials (A1+A2)	Manufacturing process (A3)	Transport to site (A4)	Assembly (A5)	Deconstruction (C1)	(Transport to) EOL treatment (C2-C4)	Total life cycle
Climate change - total [kg CO2 eq]	7,28E-05	2,13E-06	4,12E-07	1,22E-06	5,23E-07	1,70E-07	**7,72E-05**
Ozone depletion [kg CFC11 eq]	4,63E-12	3,60E-13	8,71E-14	3,87E-14	1,66E-14	3,96E-14	**5,18E-12**
Acidification [mol H+ eq]	4,24E-07	1,87E-08	8,53E-09	4,32E-09	1,85E-09	7,44E-10	**4,58E-07**
Eutrophication, freshwater [kg P eq]	3,11E-09	7,67E-11	2,33E-12	9,35E-11	4,01E-11	1,50E-12	**3,32E-09**
Eutrophication, marine [kg N eq]	7,37E-08	4,15E-09	2,13E-09	7,69E-10	3,30E-10	2,25E-10	**8,13E-08**
Eutrophication, terrestrial [mol N eq]	8,15E-07	4,55E-08	2,37E-08	1,10E-08	4,72E-09	2,49E-09	**9,02E-07**
Photochemical ozone formation [kg NMVOC eq]	2,51E-07	1,26E-08	6,24E-09	2,31E-09	9,91E-10	8,01E-10	**2,74E-07**
Resource use, minerals and metals [kg Sb eq]	2,60E-09	7,86E-12	6,41E-12	4,82E-12	2,06E-12	2,94E-12	**2,62E-09**
Resource use, fossils [MJ]	8,33E-04	4,48E-05	5,65E-06	1,52E-05	6,50E-06	2,67E-06	**9,07E-04**
Water use [m³ depriv.]	1,05E-05	1,11E-06	1,17E-08	1,67E-07	7,17E-08	-1,15E-08	**1,18E-05**
Particulate matter [disease inc.]	5,30E-12	1,55E-13	1,93E-14	2,08E-14	8,90E-15	1,78E-14	**5,52E-12**
Ionising radiation [kBq U-235 eq]	2,86E-06	4,26E-07	2,45E-08	7,46E-08	3,20E-08	1,15E-08	**3,43E-06**
Ecotoxicity, freshwater [CTUe]	2,34E-03	3,13E-05	4,04E-06	2,31E-05	9,91E-06	2,68E-06	**2,41E-03**
Human toxicity, cancer [CTUh]	9,40E-13	7,55E-16	1,94E-16	3,40E-16	1,46E-16	9,55E-17	**9,42E-13**
Human toxicity, non-cancer [CTUh]	2,83E-12	2,30E-14	3,83E-15	1,16E-14	4,99E-15	2,69E-15	**2,88E-12**
Land use [Pt]	4,34E-04	8,38E-06	2,19E-06	2,52E-05	1,08E-05	3,13E-06	**4,84E-04**

Contribution to impact category	X > 50%	25% < X < 50%	10% < X < 25%	2,5% < X < 10%	X < 2,5%

For clarification: a negative value means a negative load, i.e. a benefit.

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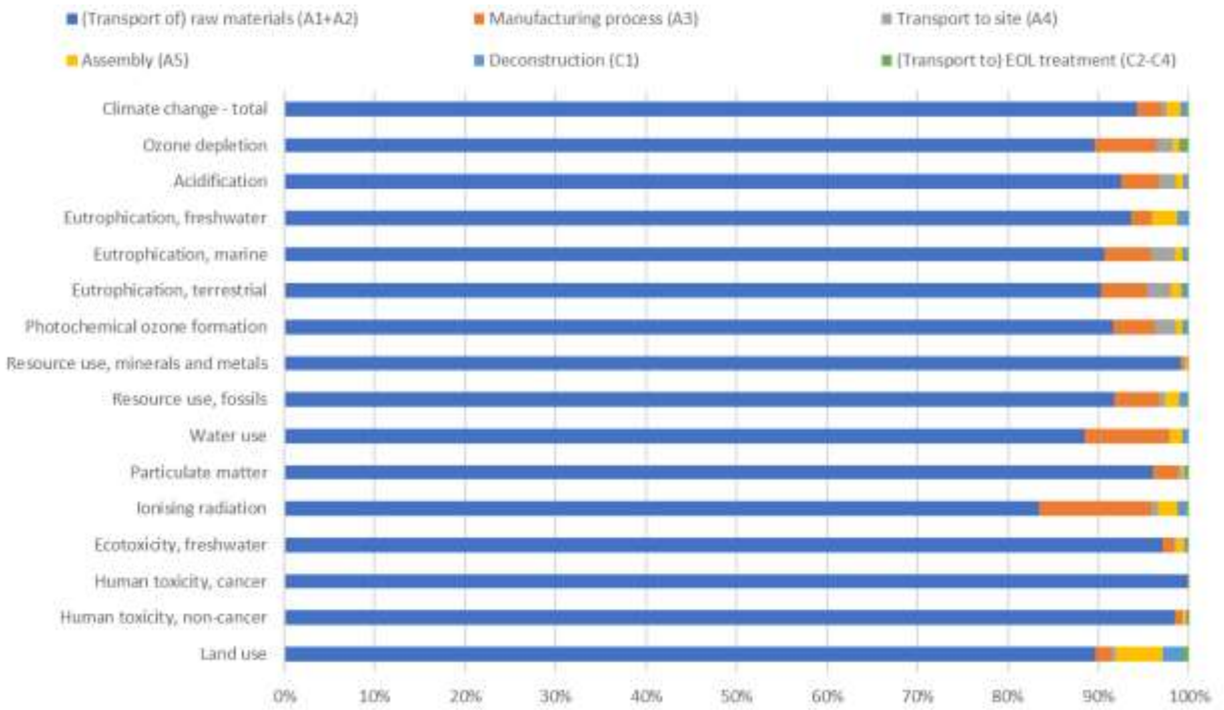

Figure 13: Relative contribution of all life cycle stages of a pitch bearing in RS1.

4.1.2. Findings LCC

Table 21 presents the LCOE estimate (0,066 €/kWh or 66 €/MWh) for the complete life cycle for RS1. The results are expressed in EUR 2019 and are calculated using the LCOE method (as described in section 1.2.2) together with the economic parameters (as described in section 3.1) and the specific cost estimates and scenarios (as described in 3.2). All expenditures associated with the wind farm (DEVEX, CAPEX, OPEX and ABEX) are taken into account. In contrary to the LCA and S-LCA, costs related to the balance of plant are within the scope of the LCC assessment.

The LCOE figure is the discounted total sum of the costs in connection with the total discounted energy production, for the complete life cycle of the wind turbine. The numerator gives the discounted total sum of costs for the wind turbine. The denominator gives the total discounted energy production (which should not be confused with the total energy production of 2 150 580 000 kWh over the lifetime of the turbine).

Table 21: LCOE result for RS1

	LCOE [EUR/kWh]	Numerator [EUR]	Denominator [kWh]
LCOE	0,066 or 6,59 %	76 798 688	1 166 153 131

Table 22 presents the LCOE result for the different cost components:

- The CAPEX LCOE figure of 0,037 EUR/kWh shows the discounted total sum of capital expenditures over the annual energy production of the wind farm. This represents 57% of the LCOE for the complete life cycle for RS1 and includes costs of turbine, balance of plant, transport, assembly and installation. Financial costs were not included in the data source.

- The OPEX LCOE figure of 0,025 EUR/kWh shows the discounted total sum of operational expenditures over the annual energy production of the wind farm. This represents 38% of the LCOE for the complete life cycle for RS1.
- The sum of DEVEX and ABEX LCOE figures only represent 5% of the LCOE for the complete life cycle for RS1. DEVEX includes costs of site development, design engineering and management costs. ABEX represents the end-of-life (EOL) stage and includes costs of decommissioning, transport to EOL, waste processing and disposal on the one hand and revenues from scrap value of wind turbine components on the other hand (mostly steel, iron and copper).

Table 22: LCOE breakdown for RS1

	LCOE [EUR/kWh]	Denominator [EUR]	Numerator [kWh]	Share of total LCOE
DEVEX	0,002	2 340 480	1 166 153 131	3%
CAPEX	0,037	43 589 115	1 166 153 131	57%
OPEX	0,025	29 077 387	1 166 153 131	38%
ABEX	0,002	1 791 707	1 166 153 131	2%

Figure 14 shows a more detailed breakdown of the costs for RS1 over 25 years, discounted to the date of comparison (year 0). For the CAPEX, the biggest cost components are the costs of the turbine (31%), followed by the BOP costs (17%). Transport, assembly and installation account for 8%. Financial costs are not declared as a separate cost in these figures.

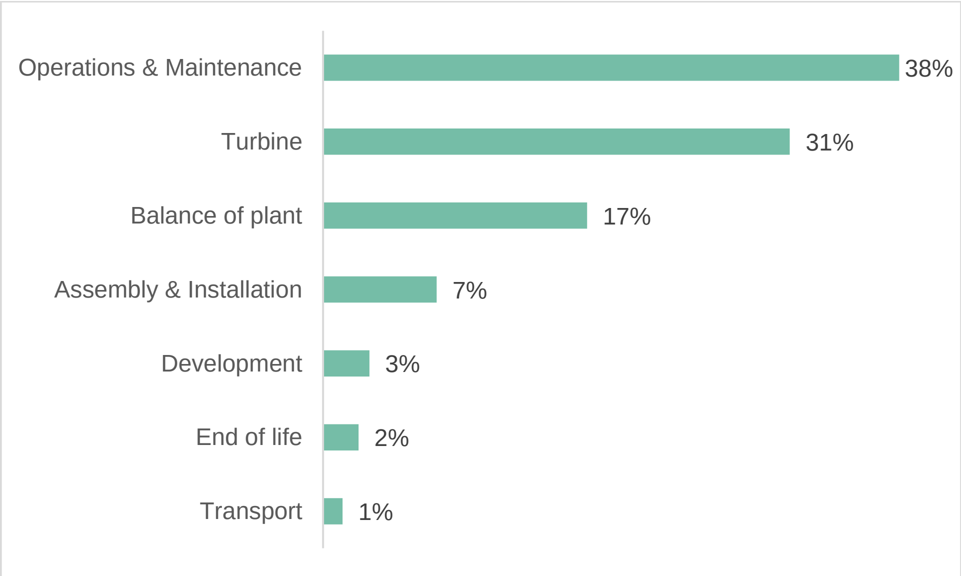

Figure 14: Detailed LCOE breakdown for RS1 - costs discounted to 2019

The goal of this LCC assessment is to assess the BAU reference scenario of which the results can be used for comparing the economic performance of the INNTERESTING solutions. Results depend on the scope, input parameters and assumptions. Therefore one-to-one comparisons to LCOE results of other projects are not possible. For a straightforward comparison of wind farms, the same boundary conditions need to be taken into account. As

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shown in Figure 10, the available literature contains significant variation and high uncertainty in cost data. Therefore, the choice of the cost data source greatly influences the LCOE results.

- **LCC findings related to the pitch bearing RS1**

For the pitch bearing of RS1, specific cost data were provided by Laulagun on the cost of raw materials and energy use in the production process. The production cost (CAPEX) of the pitch mechanism accounts for 6 % of the total production costs of the wind turbine (rotor, nacelle, tower). Specific data on the operational expenditure of pitch bearings were not available.

4.1.3. Findings S-LCA

Table 23 presents the results for the complete life cycle per indicator for RS1. The results are expressed in medium risk hours and are calculated using the PSILCA impact assessment method (see Table 4).

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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	7,24E-04	CONS med risk hours
Local Community		
Access to material resources		
Industrial water depletion	9,39E-02	WU med risk hours
Biomass consumption	4,77E-02	BM med risk hours
Certified envir. management systems	7,64E-02	CMS med risk hours
Minerals consumption	6,16E-03	MC med risk hours
Fossil fuel consumption	1,16E-03	FF med risk hours
Local employment		
Unemployment	3,84E-02	U med risk hours
Migration		
International migrant stock	1,20E-02	IMS med risk hours
Internat. migrant workers in the sector	7,63E-03	IMW med risk hours
Net migration	5,04E-04	NM med risk hours
Respect of indigenous rights		
Indigenous rights	3,36E-03	IR med risk hours
Safe and healthy living conditions		
Contribution to environmental load	2,11E-01	CS med risk hours
Sanitation coverage	2,53E-02	SC med risk hours
Pollution	9,91E-03	P med risk hours
Drinking water coverage	6,87E-03	DW med risk hours
Society		
Contribution to economic development		
Education	1,07E-02	E med risk hours
Illiteracy, female	7,00E-03	I med risk hours
Illiteracy, total	5,92E-03	I med risk hours
Illiteracy, male	5,51E-03	I med risk hours
Youth illiteracy, female	9,02E-04	YI med risk hours
Youth illiteracy, total	9,01E-04	YI med risk hours
Youth illiteracy, male	8,82E-04	YI med risk hours
Contribution to economic development	-2,70E-03	CE med risk hours
Health and Safety (Society)		
Health expenditure	9,28E-03	HE med risk hours
Life expectancy at birth	7,69E-04	LE med risk hours
Value Chain Actors		
Corruption		
Active involv. in corruption and bribery	1,80E-02	AI med risk hours
Public sector corruption	3,42E-02	C med risk hours
Fair competition		
Anti-competitive business pratices	9,87E-04	AC med risk hours
Promoting social responsibility		
Social responsibility along supply chain	7,40E-02	SR med risk hours

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

Stakeholder group/Subcategory/Indicator	Impact result	Unit
Workers		
Child labour		
Child Labour, male	1,76E-03	CL med risk hours
Child Labour, total	1,74E-03	CL med risk hours
Child Labour, female	1,59E-03	CL med risk hours
Discrimination		
Women in the sectoral labour force	1,13E-02	W med risk hours
Gender wage gap	1,54E-02	GW med risk hours
Men in the sectoral labour force	9,96E-05	M med risk hours
Fair Salary		
Fair Salary	7,69E-02	FS med risk hours
Forced labour		
Trafficking in persons	6,82E-03	TP med risk hours
Goods produced by forced labour	5,79E-04	GFL med risk hours
Frequency of forced labour	5,06E-04	FL med risk hours
Freedom of association and collective bargaining		
Trade unionism	9,81E-02	TU med risk hours
Association and bargaining rights	8,35E-03	ACB med risk hours
Health and Safety (Workers)		
Non-fatal accidents	4,58E-02	NFA med risk hours
Fatal accidents	8,22E-04	FA med risk hours
Safety measures	2,20E-02	SM med risk hours
DALYs due to indoor/ outdoor pollution	2,51E-04	DALY med risk hours
Workers affected by natural disasters	1,69E-03	ND med risk hours
Social benefits, legal issues		
Violations of empl. laws and regulations	4,42E-03	VL med risk hours
Social security expenditures	8,06E-03	SS med risk hours
Working time		
Weekly hours of work per employee	1,07E-03	WH med risk hours

The results are analysed in more detail for a selected set of impact categories (‘Fair Salary’ and ‘Health and Safety workers’). Justification for this selection is provided in section 1.2.3.2. Figure 21 shows the results of the S-LCA study for the selected impact categories. All results have been scaled to to 100%. The upper bar in the graph contains the distribution of costs across the life cycle, as social risks are calculated by multiplying the risk characterisation factor with price and worker hours. Maintenance over 25 years and the production of all other components (which are mainly metals e.g. the tower) clearly have the biggest share in the life cycle costs. The maintenance costs are the costs occurring in the year 2015 multiplied with the life span. They have not been discounted as the objective of this exercise was to calculate the social risks along the life cycle which might occur in the maintenance sector.

Maintenance is the most important life cycle stage in the impact categories ‘Workers affected by natural disasters’, ‘Fair salary’ and ‘Fatal accidents’. The ‘production of all other components’ is the most important life cycle stage in the impact categories ‘DALYs due to indoor and outdoor pollution’, ‘Presence of sufficient safety measures’ and ‘Non-fatal accidents’. The results are analysed in more detail in the next paragraphs.

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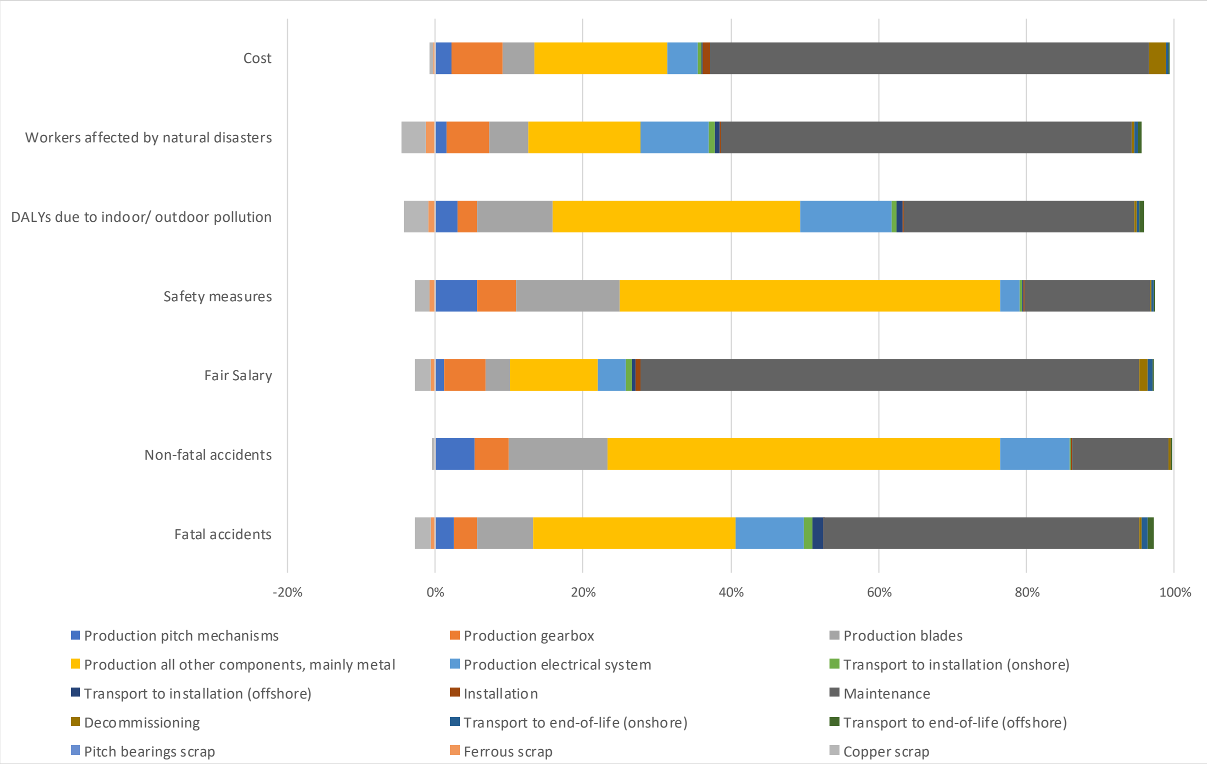

Figure 15: Life cycle results of the social hotspot analysis for RS1 for selected impact categories.

- ### Subcategory Fair salary

More information about the impact category ‘Fair salary’ is available in section 1.2.3.3.

The most important life cycle stage in this subcategory is maintenance with a contribution of 70%. Table 24 summarises the raw values for the life cycle stages ‘Maintenance’ and ‘Production of all other components’. The table reveals that it is mainly the living wage per month which drives the results as it is the impact category where very high risks occur for maintenance. In fact, independently, values for living wages are of only limited informative value. In PSILCA the indicator living wage is risk assessed to stick to the structure of PSILCA However, to stick to the structure of the indicators in PSILCA, also living wages are risk assessed (Eisfeldt, 2018). The idea behind the risk scale for this indicator is that the higher the living wage, the higher minimum and sector average wages have to be and as such it triggers risks especially for workers in low-paid sectors. If living wage per month would not be risk assessed (following the reasoning that it is of limited value on its own), the hotspot in the impact category fair salary would still be maintenance with a 53% contribution and the production of all other components would contribute for 22%.

Table 24 only shows the values for the sector at hand and not the supply chain of these specific sectors which are also taken into account in the calculations in PSILCA. For example, for the life cycle stage ‘Maintenance in Germany’, only 37% of the medium risk hours are generated by the maintenance in Germany, the remaining part is generated in the supply chain.

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Table 24: Raw values and risk levels of RS1 for the three indicators of the subcategory Fair salary.

Life cycle stage	Maintenance in Germany		Production of all other components (mainly metals)	
	worker hours/USD output	USD/month	worker hours/USD output	USD/month
Living wage per month	0,01195	1026	0,01029	708
Minimum wage per month		1968		701
Sector average wage per month		4590		2733

very high risk
high risk
medium risk
low risk
very low risk

- **Subcategory Health and safety (workers)**

More information about the impact category ‘Health and safety (workers)’ is available in section 1.2.3.4. In the following paragraphs some raw values are provided for interpretation purposes. The values are always valid for the sector at hand and do not take into account the supply chain of the specific sector.

‘The production of all other components, mainly metal’ in Spain, generates the most medium risk hours in the impact category ‘Non-fatal accidents’. There is a big cost related the production of ‘All other components’, which of course has its share in the high contribution. However, also the raw values for the sector ‘Metal products’ in Spain are higher compared to for example the raw values for the sector ‘Maintenance’ in Germany (respectively 4 531 and 2 371 non-fatal accidents per year and per 100 thousand employees). The contribution of ‘the production of blades’ to the impact category ‘Non-fatal accidents’ cycle is around 13%. The production of the blades occurs in Spain and the raw value for the sector in Spain is 4531 non-fatal accidents per year and per 100 thousand employees.

In the impact category ‘Fatal accidents’, most medium risk hours are generated in the maintenance life cycle stage (44%) and during the production of all other components (28%). The raw values for maintenance occurring in Germany and the production of all other components occurring in Spain are respectively 1.770 and 2.633 fatal accidents per year and 100 thousand employees.

The most important life cycle stage in the impact category ‘Presence of sufficient safety measures’ is the production of all other components with a contribution of 53%. The raw value is 138 violations which is high compared to the violations reported for the maintenance sector in Germany, being 3.4 violations per 100 thousand employees per year.

The largest contribution to the impact category ‘Workers affected by natural disasters’ comes from the maintenance occurring in Germany (58%). The raw value for Germany is 0.0079%. The raw value for Spain is 0.0027%.

- **S-LCA findings related to the pitch bearing RS1**

Figure 16 shows the results of the S-LCA for the production of the pitch bearings, again for a selected set of impact categories.

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The production of the rings is the hotspot in the impact categories ‘DALYs due to indoor and outdoor air pollution’ and ‘Fatal accidents’. The production of the balls is the hotspot in the impact categories ‘Workers affected by natural disasters’ and ‘Fair salary’. The production of the pitch bearings itself is the hotspot in the impact categories ‘Safety measures’ and ‘Non-fatal accidents’. It is important to note that for the pitch bearing production primary data have been used for cost, while for worker hours and risk levels, generic background data have been taken from the PSILCA v2 database.

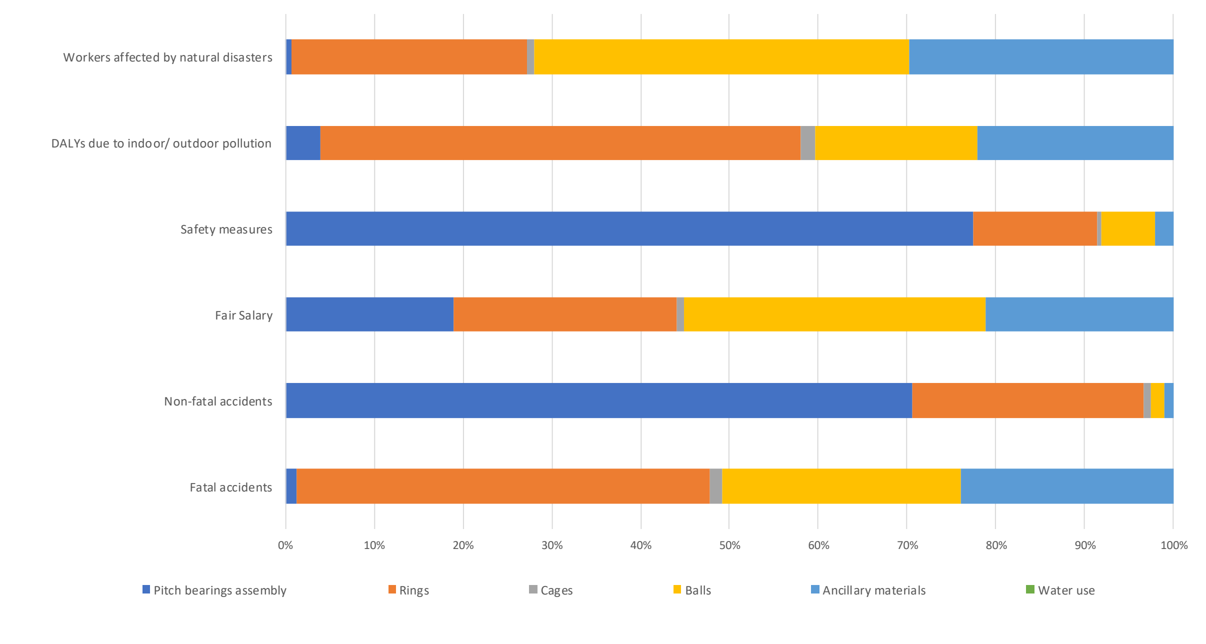

Figure 16: Results of the social hotspot analysis for RS1 pitch bearings production in Spain for selected impact categories

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4.2. LCIA RS2

4.2.1. Findings LCA

Table 25 provides the environmental impact results in absolute values for 1 kWh generated to the grid by a 10 MW onshore wind turbine installed in north Germany with a service life of 20 years. Figure 17 is a graphical representation of the same results. The calculations are done according to the EN 15804+A2:2019 method and based on the collected LCI data for RS2 as presented in section 3.3.

The results show that the production stage (A1-A3) can be seen as the most relevant life cycle stage, as for all impact categories the production stage contributes more than 88% of the total life cycle impact[26].

Table 25: Environmental profile of RS2 in absolute values per FU.

	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]	6,62E-03	8,38E-05	3,49E-04	3,17E-05	1,49E-04	4,46E-05	**7,27E-03**
Ozone depletion [kg CFC11 eq]	5,35E-10	1,91E-11	1,32E-11	7,14E-12	5,19E-12	5,01E-12	**5,85E-10**
Acidification [mol H+ eq]	5,63E-05	1,20E-06	8,59E-07	1,35E-07	3,63E-07	1,05E-07	**5,89E-05**
Eutrophication, freshwater [kg P eq]	5,28E-07	5,44E-10	4,88E-08	8,85E-10	2,09E-08	2,62E-10	**5,99E-07**
Eutrophication, marine [kg N eq]	7,67E-06	2,91E-07	1,39E-07	2,03E-08	5,87E-08	3,17E-08	**8,21E-06**
Eutrophication, terrestrial [mol N eq]	8,03E-05	3,23E-06	2,23E-06	2,33E-07	9,47E-07	3,48E-07	**8,73E-05**
Photochemical ozone formation [kg NMVOC eq]	2,82E-05	8,92E-07	4,41E-07	2,09E-07	1,73E-07	1,09E-07	**3,01E-05**
Resource use, minerals and metals [kg Sb eq]	4,51E-07	1,16E-09	1,26E-09	4,06E-09	4,84E-10	4,08E-10	**4,58E-07**
Resource use, fossils [MJ]	8,84E-02	1,25E-03	4,45E-03	7,01E-04	1,87E-03	3,51E-04	**9,70E-02**
Water use [m³ depriv.]	2,52E-03	3,33E-06	1,12E-05	9,47E-06	4,60E-06	-7,36E-07	**2,55E-03**
Particulate matter [disease inc.]	4,29E-10	5,53E-12	3,06E-12	1,21E-12	1,28E-12	2,26E-12	**4,42E-10**
Ionising radiation [kBq U-235 eq]	3,44E-04	5,43E-06	1,41E-05	2,65E-06	5,90E-06	1,50E-06	**3,74E-04**
Ecotoxicity, freshwater [CTUe]	4,27E-01	9,34E-04	2,90E-03	5,41E-04	1,22E-03	4,54E-04	**4,33E-01**
Human toxicity, cancer [CTUh]	3,06E-11	3,43E-14	5,46E-14	4,18E-14	2,29E-14	1,47E-14	**3,08E-11**
Human toxicity, non-cancer [CTUh]	5,56E-10	9,46E-13	2,40E-12	3,72E-13	1,02E-12	8,00E-13	**5,61E-10**
Land use [Pt]	3,37E-02	1,02E-03	7,95E-04	1,52E-04	3,36E-04	3,94E-04	**3,64E-02**

Contribution to impact category	X > 50%	25% < X < 50%	10% < X < 25%	2,5% < X < 10%	X < 2,5%

For clarification: a negative value means a negative load, i.e. a benefit.

[26] Please note that only the maintenance of the gearbox is included in the life cycle stage Maintenance (B2) due a lack of generic environmental LCI data on the maintenance of the other components.

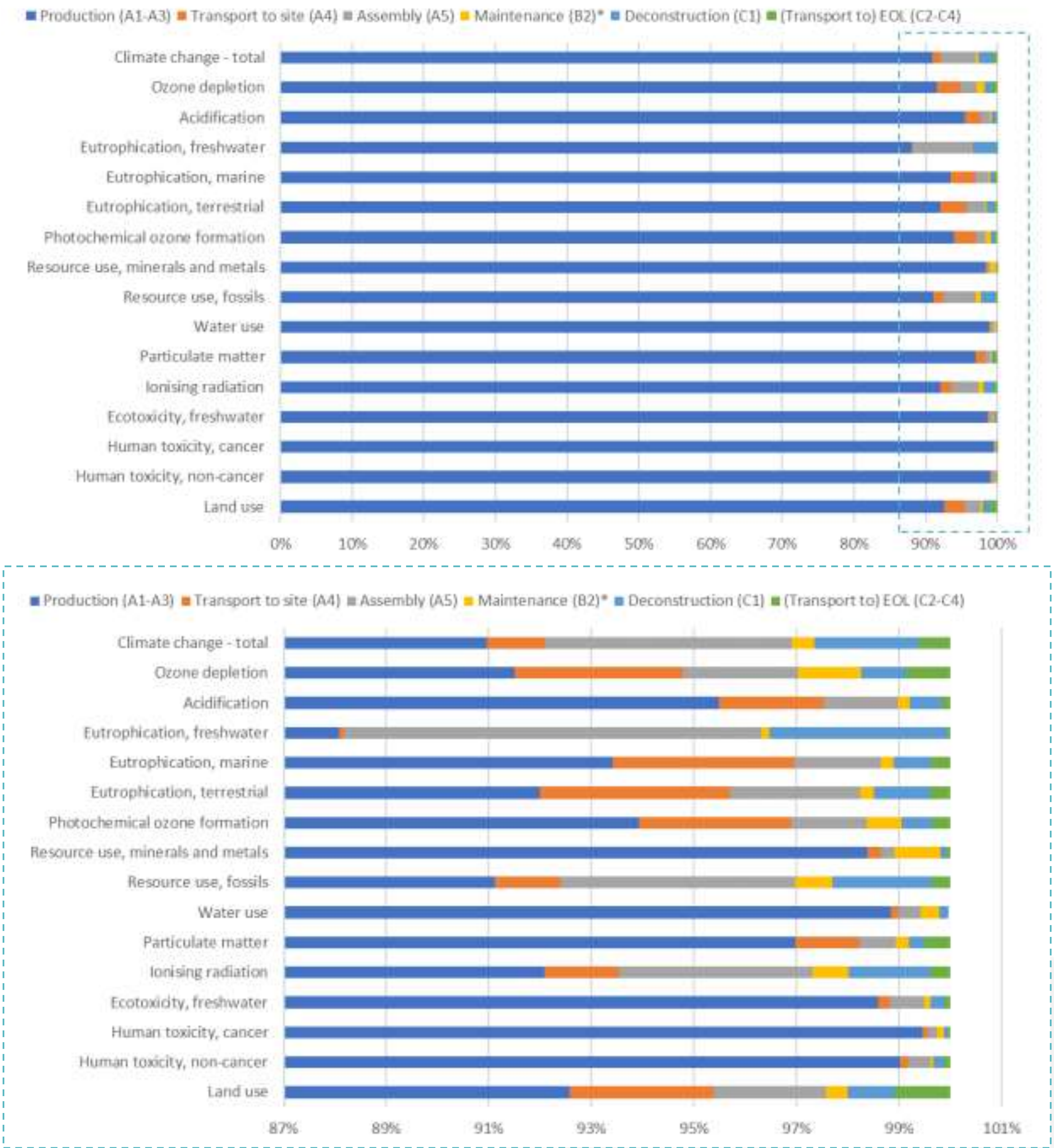

Figure 17: Relative contribution of all life cycle stages of RS2 based on the environmental profile, with below a more detailed view of the last 13%.

When analysing only the production stage of RS2 in more detail (see Figure 18), it shows that the main contributing component of the RS2 wind turbine is the tower. This can be explained by the mass of the tower (628 500 kg, which is 45,6% of the total mass of the wind turbine). Other components that have a relatively decisive contributing impact on all impact categories are: the gearbox, yaw system and pitch mechanism.

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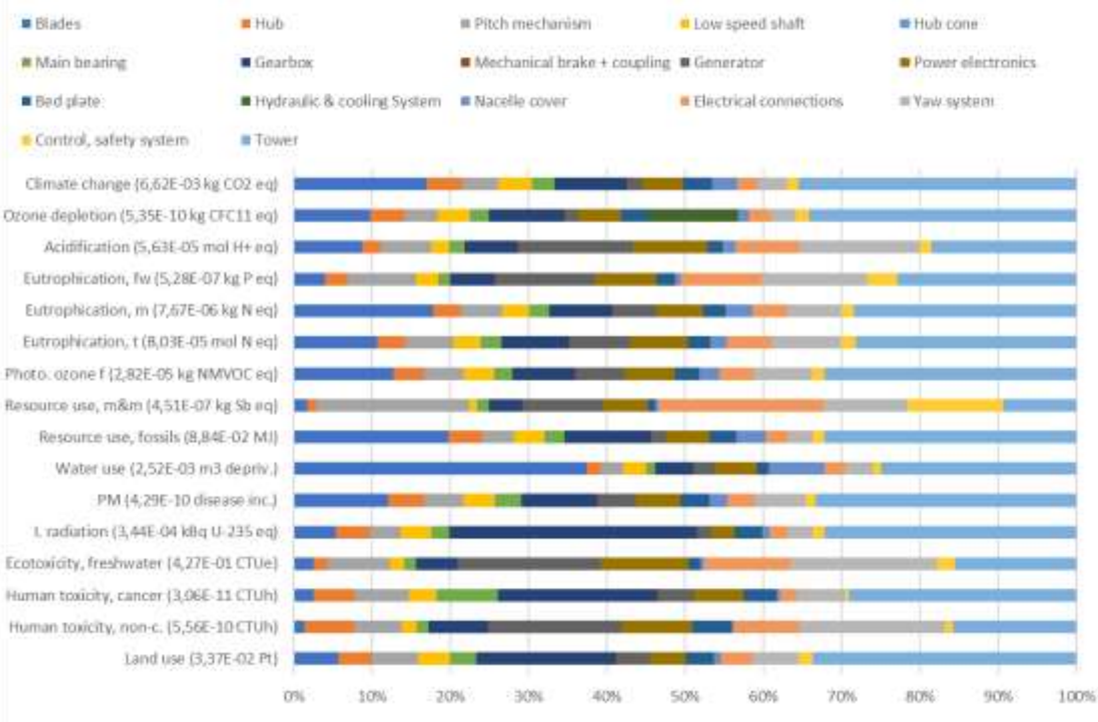

Figure 18: Relative contribution of all components of RS2 to the production stage (A1-A3).

The absolute values mentioned between brackets in the vertical axis are per FU

- ## LCA findings related to the gearbox

Table 26 and Figure 19 present the results of the environmental LCIA of the specific component of RS2, i.e. a gearbox for a 10 MW wind turbine with a service lifetime of 20 years. Based on the results it can be concluded that the raw materials of the gearbox contribute the most to the environmental impact of its complete life cycle. The high relative contribution of the manufacturing process (A3) to the impact category ionising radiation is due to the part nuclear energy of the Finish electricity mix. More detailed results and findings of this LCA will be shared with Moventas.

Table 26: Environmental profile of the gearbox in RS2 in absolute values per FU.

	(Transport of) raw materials (A1+A2)	Manufacturing process (A3)	Transport to site (A4)	Assembly (A5)	Maintenance (B2)	Deconstruction (C1)	(Transport to) EOL treatment (C2-C4)	Total life cycle
Climate change - total [kg CO2 eq]	4,78E-04	1,29E-04	6,41E-06	2,84E-05	3,17E-05	1,12E-05	5,70E-06	**6,90E-04**
Ozone depletion [kg CFC11 eq]	3,13E-11	2,04E-11	1,46E-12	2,00E-12	7,14E-12	3,92E-13	3,54E-13	**6,30E-11**
Acidification [mol H+ eq]	3,31E-06	5,14E-07	9,15E-08	7,68E-08	1,35E-07	2,74E-08	7,51E-09	**4,16E-06**
Eutrophication, freshwater [kg P eq]	2,53E-08	4,99E-09	4,16E-11	3,74E-09	8,85E-10	1,58E-09	1,74E-11	**3,66E-08**
Eutrophication, marine [kg N eq]	5,23E-07	8,64E-08	2,21E-08	1,21E-08	2,03E-08	4,43E-09	2,31E-09	**6,71E-07**
Eutrophication, terrestrial [mol N eq]	5,90E-06	1,07E-06	2,46E-07	1,87E-07	2,33E-07	7,14E-08	2,55E-08	**7,73E-06**
Photochemical ozone formation [kg NMVOC eq]	1,94E-06	3,30E-07	6,80E-08	6,77E-08	2,09E-07	1,30E-08	7,92E-09	**2,64E-06**
Resource use, minerals and metals [kg Sb eq]	1,86E-08	4,25E-10	8,89E-11	2,10E-10	4,06E-09	3,65E-11	2,79E-11	**2,35E-08**
Resource use, fossils [MJ]	5,69E-03	4,08E-03	9,56E-05	4,16E-04	7,01E-04	1,41E-04	2,45E-05	**1,11E-02**
Water use [m³ depriv.]	7,76E-05	4,45E-05	2,55E-07	1,31E-06	9,47E-06	3,47E-07	-7,98E-08	**1,33E-04**
Particulate matter [disease inc.]	3,94E-11	2,37E-12	4,23E-13	3,06E-13	1,21E-12	9,65E-14	1,65E-13	**4,40E-11**
Ionising radiation [kBq U-235 eq]	1,82E-05	9,07E-05	4,16E-07	1,38E-06	2,65E-06	4,45E-07	1,04E-07	**1,14E-04**
Ecotoxicity, freshwater [CTUe]	2,04E-02	2,18E-03	7,14E-05	2,68E-04	5,41E-04	9,20E-05	3,46E-05	**2,36E-02**
Human toxicity, cancer [CTUh]	6,19E-12	4,03E-14	2,62E-15	5,17E-15	4,18E-14	1,73E-15	1,08E-15	**6,29E-12**
Human toxicity, non-cancer [CTUh]	4,15E-11	9,87E-13	7,24E-14	2,11E-13	3,72E-13	7,66E-14	4,59E-14	**4,33E-11**
Land use [Pt]	3,65E-03	2,36E-03	7,82E-05	7,15E-05	1,52E-04	2,53E-05	2,78E-05	**6,37E-03**

Contribution to impact category **X > 50%** **25% < X < 50%** **10% < X < 25%** **2,5% < X < 10%** **X < 2,5%**

For clarification: a negative value means a negative load, i.e. a benefit.

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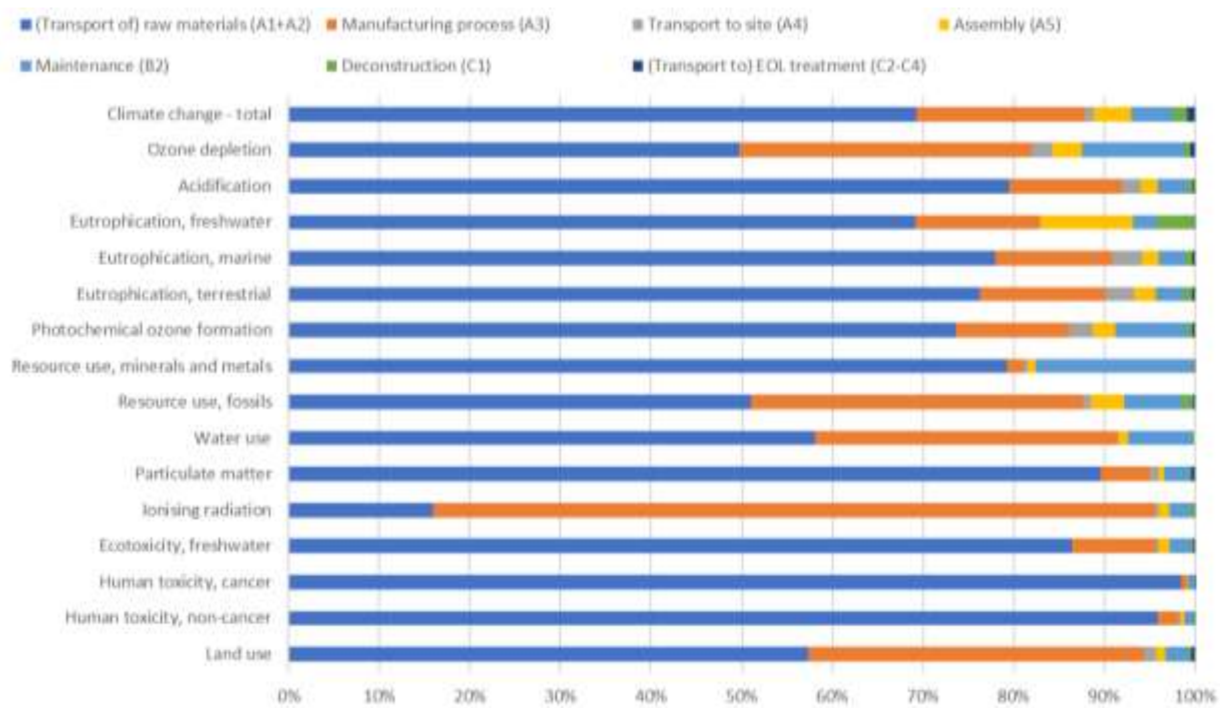

Figure 19: Relative contribution of all life cycle stages of the gearbox in RS2.

4.2.2. Findings LCC

Table 27 presents the LCOE estimate (0,030 €/kWh or 30 €/MWh) for the complete life cycle for RS2. The results are expressed in EUR 2019 and are calculated using the LCOE method (as described in section 1.2.2) together with the economic parameters (as described in section 3.1) and the specific cost estimates and scenarios (as described in 3.3).

All expenditures associated with the wind farm (DEVEX, CAPEX, OPEX and ABEX) are taken into account. In contrary to the LCA and S-LCA, costs related to the balance of plant are within the scope of the LCC assessment.

The LCOE figure is the discounted total sum of the costs in connection with the total discounted energy production, for the complete life cycle of the wind turbine. The numerator gives the discounted total sum of costs for the wind turbine. The denominator gives the total discounted energy production (which should not be confused with the total energy production of 924 224 741 kWh over the lifetime of the turbine).

Table 27: LCOE result for RS2

	LCOE [EUR/kWh]	Numerator [EUR]	Denominator [kWh]
LCOE	0,030 or 3,03 %	16 885 758	577 216 957

Table 28 presents the LCOE result for the different cost components:

- The CAPEX LCOE figure of 0,019 EUR/kWh shows the discounted total sum of capital expenditures over the annual energy production of the wind farm. This represents 61% of the LCOE for the complete life cycle for RS2 and includes costs of turbine, balance of plant, transport, assembly, installation and financial costs.

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- The OPEX LCOE figure of 0,011 EUR/kWh shows the discounted total sum of operational expenditures over the annual energy production of the wind farm. This represents 36% of the LCOE for the complete life cycle for RS2.
- The sum of DEVEX and ABEX LCOE figures only represent 3% of the LCOE for the complete life cycle for RS2. DEVEX includes costs of site development, design engineering and management costs. ABEX represents the end-of-life (EOL) stage and includes costs of decommissioning, transport to EOL, waste processing and disposal on the one hand and revenues from scrap value of wind turbine components on the other hand (mostly steel, iron and copper).

Table 28: LCOE breakdown for RS2

	LCOE [EUR/kWh]	Denominator [EUR]	Numerator [kWh]	Share of total LCOE
DEVEX	0,001	302 736	577 216 957	2%
CAPEX	0,019	10 489 703	577 216 957	61%
OPEX	0,011	6 153 536	577 216 957	36%
ABEX	0,000	104 125	577 216 957	1%

Figure 20 shows a more detailed breakdown of the costs for RS2 over 20 years, discounted to the date of comparison (year 0). For the CAPEX, the biggest cost components are the costs of the turbine (37%), followed by the BOP costs (13%) and financial costs (7%). Transport, assembly and installation account for 5%.

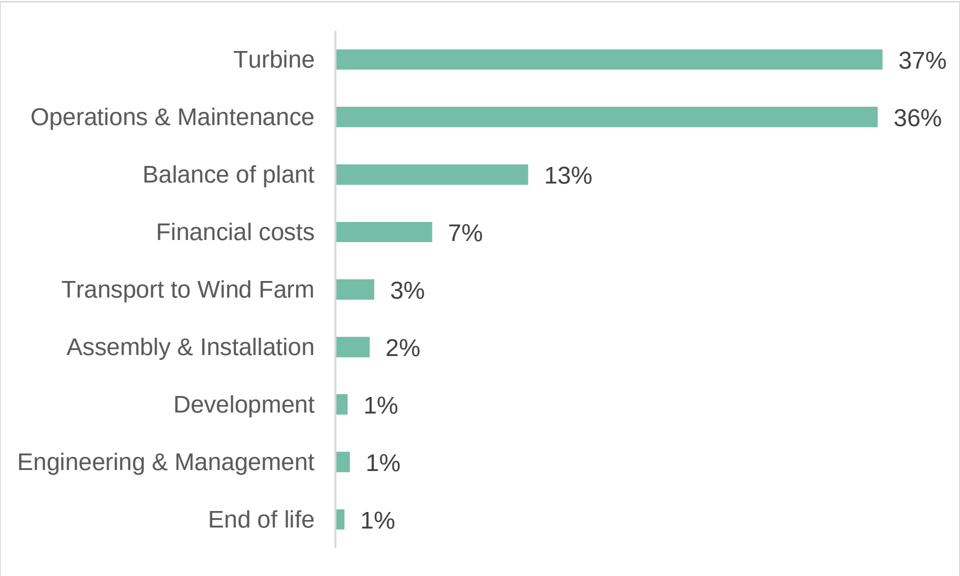

Figure 20: Detailed LCOE breakdown for RS2 - costs discounted to 2019

The goal of this LCC assessment is to assess the BAU reference scenario of which the results can be used for comparing the economic performance of the INNTERESTING solutions. Results depend on the scope, input parameters and assumptions. Therefore one-to-one comparisons to LCOE results of other projects are not possible. For a straightforward comparison of wind farms, the same boundary conditions need to be taken into account.

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- **LCC findings related to the gearbox**

For the gearbox of RS2, specific cost data were provided by Moventas on the cost of raw materials, energy use in the production process, recuperation of production waste, maintenance processes and residual value after decommissioning. The gearbox production cost accounts for 17% of the total production costs (CAPEX) of the wind turbine (rotor, nacelle and tower). The gearbox operational costs account for 6% of the total maintenance costs of the wind turbine.

4.2.3. Findings S-LCA

Table 29 presents the results for the complete life cycle per indicator for RS2. The results are expressed in medium risk hours and are calculated using the PSILCA impact assessment method (see Table 4).

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Table 29: 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	3,67E-04	CONS med risk hours
Local Community		
Access to material resources		
Industrial water depletion	3,39E-02	WU med risk hours
Biomass consumption	1,73E-02	BM med risk hours
Certified envir. management systems	3,36E-02	CMS med risk hours
Minerals consumption	3,07E-03	MC med risk hours
Fossil fuel consumption	4,16E-04	FF med risk hours
Local employment		
Unemployment	2,50E-02	U med risk hours
Migration		
International migrant stock	5,54E-03	IMS med risk hours
Internat. migrant workers in the sector	3,74E-03	IMW med risk hours
Net migration	3,01E-04	NM med risk hours
Respect of indigenous rights		
Indigenous rights	1,55E-03	IR med risk hours
Safe and healthy living conditions		
Contribution to environmental load	7,63E-02	CS med risk hours
Sanitation coverage	1,29E-02	SC med risk hours
Pollution	4,76E-03	P med risk hours
Drinking water coverage	2,96E-03	DW med risk hours
Society		
Contribution to economic development		
Education	5,17E-03	E med risk hours
Illiteracy, female	3,12E-03	I med risk hours
Illiteracy, total	2,62E-03	I med risk hours
Illiteracy, male	2,39E-03	I med risk hours
Youth illiteracy, female	4,16E-04	YI med risk hours
Youth illiteracy, total	4,15E-04	YI med risk hours
Youth illiteracy, male	4,04E-04	YI med risk hours
Contribution to economic development	-1,32E-03	CE med risk hours
Health and Safety (Society)		
Health expenditure	4,26E-03	HE med risk hours
Life expectancy at birth	3,73E-04	LE med risk hours
Value Chain Actors		
Corruption		
Active involv. in corruption and bribery	9,55E-03	AI med risk hours
Public sector corruption	1,71E-02	C med risk hours
Fair competition		
Anti-competitive business pratices	4,66E-04	AC med risk hours
Promoting social responsibility		
Social responsibility along supply chain	3,17E-02	SR med risk hours

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Continuation of Table 29: S-LCA results of RS2 for the complete life cycle expressed in medium risk hours

Stakeholder group/Subcategory/Indicator	Impact result	Unit
Workers		
Child labour		
Child Labour, male	8,69E-04	CL med risk hours
Child Labour, total	8,59E-04	CL med risk hours
Child Labour, female	7,83E-04	CL med risk hours
Discrimination		
Women in the sectoral labour force	6,61E-03	W med risk hours
Gender wage gap	7,52E-03	GW med risk hours
Men in the sectoral labour force	4,83E-05	M med risk hours
Fair Salary		
Fair Salary	3,14E-02	FS med risk hours
Forced labour		
Trafficking in persons	2,84E-03	TP med risk hours
Goods produced by forced labour	2,91E-04	GFL med risk hours
Frequency of forced labour	2,12E-04	FL med risk hours
Freedom of association and collective bargaining		
Trade unionism	4,81E-02	TU med risk hours
Association and bargaining rights	4,05E-03	ACB med risk hours
Health and Safety (Workers)		
Non-fatal accidents	2,82E-02	NFA med risk hours
Fatal accidents	4,14E-04	FA med risk hours
Safety measures	1,30E-02	SM med risk hours
DALYs due to indoor/ outdoor pollution	1,38E-04	DALY med risk hours
Workers affected by natural disasters	7,67E-04	ND med risk hours
Social benefits, legal issues		
Violations of empl. laws and regulations	2,27E-03	VL med risk hours
Social security expenditures	3,52E-03	SS med risk hours
Working time		
Weekly hours of work per employee	5,20E-04	WH med risk hours

The results are analysed in more detail for a selected set of impact categories (‘Fair Salary’ and ‘Health and Safety workers’). Justification for this selection is provided in section 1.2.3.2. Figure 21 shows the results of the S-LCA study for the selected impact categories. All results have been scaled to 100%. The upper bar in the graph contains the distribution of costs across the life cycle, as social risks are calculated by multiplying the risk characterisation factor with price and worker hours. The maintenance costs for 20 years clearly form the biggest share in the life cycle costs. The maintenance costs are the costs occurring in the year 2015 multiplied with the life span. They have not been discounted as the objective of this exercise was to calculate the social risks along the life cycle which might occur in the maintenance sector.

The production of all other components (which are all turbine components except for gearbox, blades, pitch mechanism and electrical system) 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. Maintenance is the most important life cycle stage in the impact categories ‘Workers affected by natural disasters’ and ‘Fair salary’. The results are analysed in more detail in the next paragraphs.

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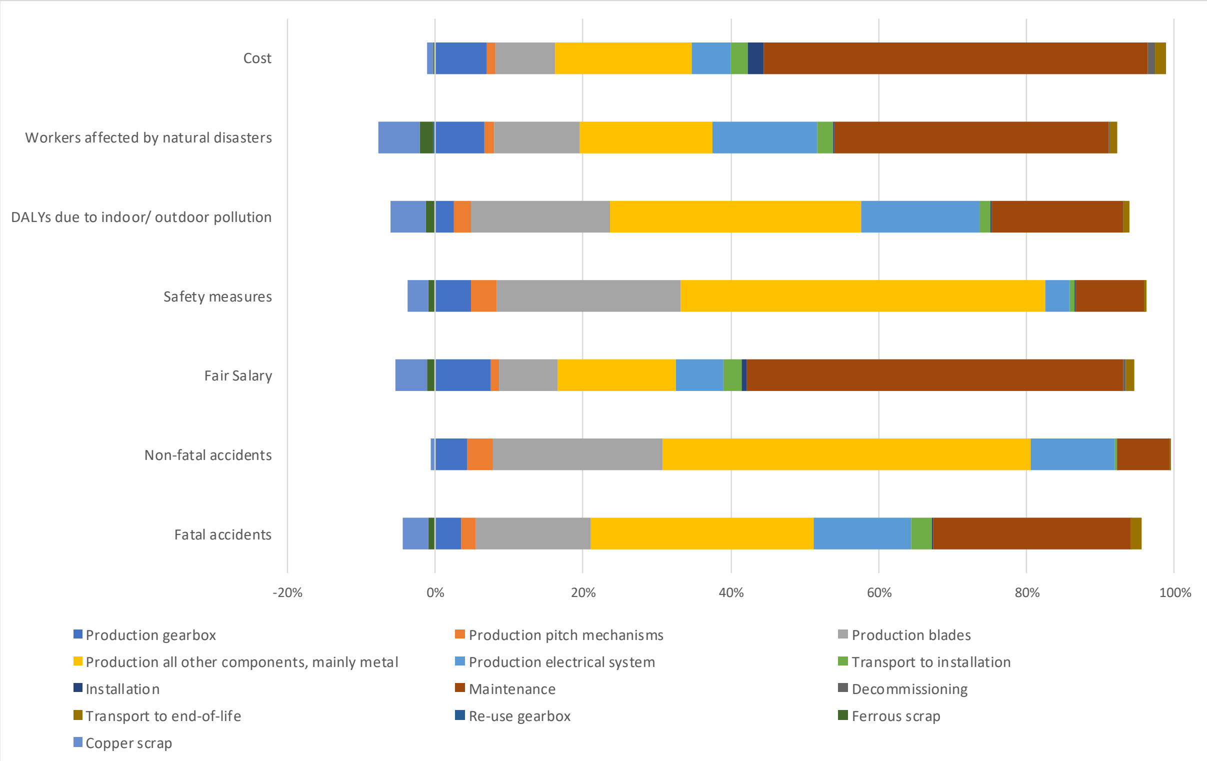

Figure 21: Life cycle results of the social hotspot analysis for RS2 for selected impact categories.

- ## Subcategory Fair salary

More information about the impact category 'Fair salary' is available in section 1.2.3.3.

The most important life cycle stage in this subcategory is maintenance with a contribution of 53%. Table 30 summarises the raw values for the life cycle stages 'Gearbox production in Finland', 'Production of all other components in Spain' and 'Maintenance in Germany'. The table reveals that it is mainly the living wage per month which drives the results in this impact category as very high risks are reported for 'production of the gearbox' in Finland and for maintenance in Germany. As discussed in section 4.1.3 living wages are independently of limited informative value. If living wage per month would not be risk assessed (following the reasoning that it is of limited value on its own), the hotspot in the impact category fair salary would still be maintenance with a 36% contribution and the production of all other components would contribute for 26%. Table 30 only shows the values for the sector at hand and not the supply chain of these specific sectors which are also taken into account in the calculations in PSILCA. For example, for the life cycle stage 'Maintenance in Germany', only 37% of the medium risk hours are generated by the maintenance in Germany, the remaining part is generated in the supply chain.

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Table 30: Raw values and risk levels of RS2 for the three indicators of the subcategory Fair salary.

Life cycle stage	Production of the gearbox in Finland		Production of all other components in Spain		Maintenance in Germany	
	worker hours/USD output	USD/month	worker hours/USD output	USD/month	worker hours/USD output	USD/month
Living wage per month	0,00562	1101	0,01029	708	0,01195	1026
Minimum wage per month		1989		701		1968
Sector average wage per month		4152		2733		4590

very high risk
high risk
medium risk
low risk
very low risk

- **Subcategory Health and safety (workers)**

More information about the impact category 'Health and safety (workers)' is available in section 1.2.3.4. In the following paragraphs some raw values are provided for interpretation purposes. The values are always valid for the sector at hand and do not take into account the supply chain of the specific sector.

The production of 'All other components, metal' in Spain generates the most medium risk hours in the impact category 'Non-fatal accidents'. The raw values for the sector 'Metal products' in Spain are higher compared to for example the raw values for the sector 'Machinery and equipment' in Finland, which is used for the gearbox assembly (respectively 4 531 and 3 145 non-fatal accidents per year and per 100 thousand employees).

In the impact category 'Fatal accidents', most medium risk hours are generated in the during the production of all other components (32%) and during maintenance (28%). The raw values for the production of all other components occurring in Spain and maintenance occurring in Germany are respectively 2.633 and 1.770 fatal accidents per year and 100 thousand employees. The gearbox production takes place in Finland. The raw value for the sector 'Machinery and equipment', used as a proxy for the gearbox production in Finland is 0.300 fatal accidents per year and 100 thousand employees.

The most important life cycle stage in the impact category 'Presence of sufficient safety measures' is the production of all other components with a contribution of 51%. The raw value is 138 violations which is high compared to the violations reported for the machinery and equipment sector in Finland (used as a proxy for the gearbox production), being 37 violations per 100 thousand employees per year.

The largest contribution to the impact category 'Workers affected by natural disasters' comes from the maintenance occurring in Germany (40%). The raw value for Germany is 0.0079%. The raw value for Finland is 0% and the raw value for Spain is 0.0027%.

- **S-LCA findings related to the gearbox**

Figure 22 shows the results of the S-LCA for the gearbox production, again for a selected set of impact categories. The production of the gear materials is the hotspot in the impact categories 'Workers affected by natural disasters', 'DALYs due to indoor and outdoor air pollution', 'Safety measures' and 'Fatal accidents'. The production of the gearbox itself is the hotspot in the impact category 'Non-fatal accidents'. In the impact category 'Fair Salary' both the 'gearbox assembly' and the production of gear materials are hotspots. It is important to

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note that for the gearbox production primary data have been used for cost, while for worker hours and risk levels, generic background data have been taken from the PSILCA v2 database.

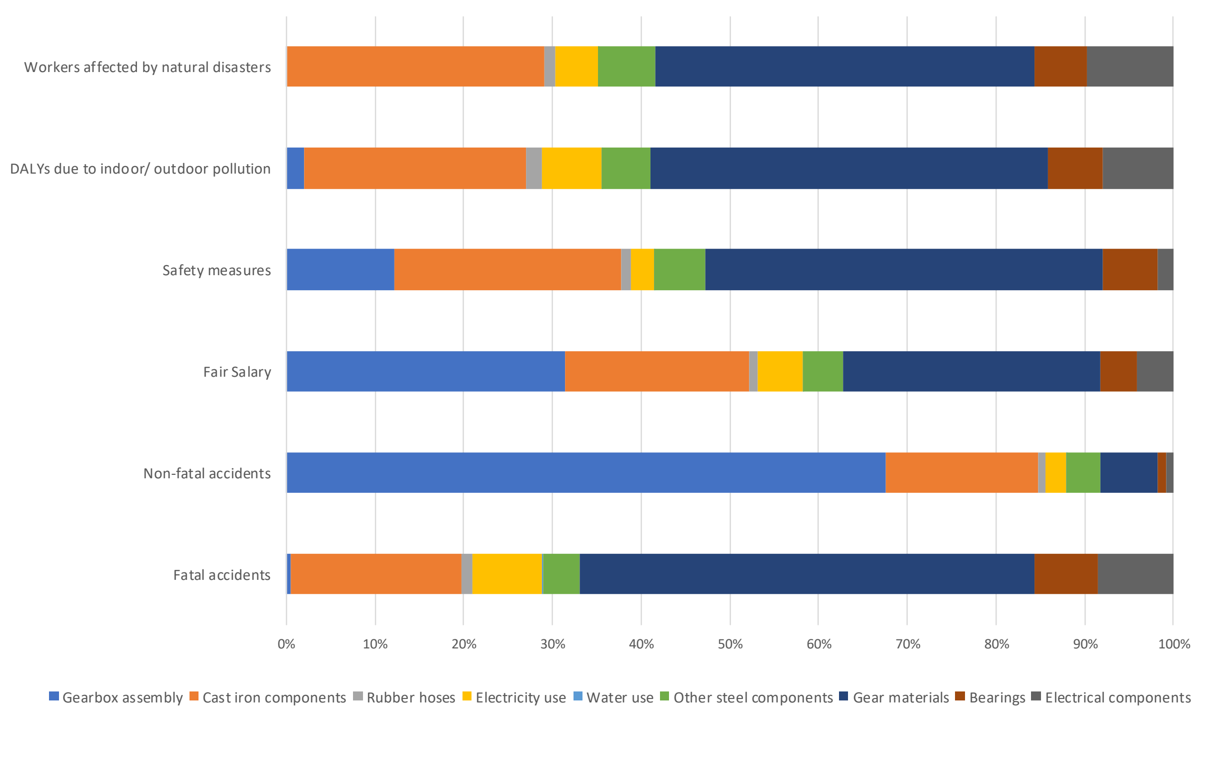

Figure 22: Results of the social hotspot analysis for RS2 gearbox production in Finland for selected impact categories

4.3. LCIA RS3

4.3.1. Findings LCA

Table 31 provides the environmental impact results in absolute values for 1 kWh generated to the grid by a 3.4 MW onshore wind turbine installed in Burgos (Spain) with a service life of 20 years. Figure is a graphical representation of the same results. The calculations are done according to the EN 15804+A2:2019 method and based on the collected LCI data for RS3 as presented in section 3.4.

The results show that the production stage (A1-A3) can be seen as the most relevant life cycle stage, as for all impact categories the production stage contributes more than 80% of the total life cycle impact[27].

[27] Please note that the life cycle stage Maintenance (B2) is excluded in the LCA of RS3 due a lack of environmental LCI data on the maintenance of the wind turbine.

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Table 31: Environmental profile of RS3 in absolute values per FU.

	Production (A1-A3)	Transport to site (A4)	Assembly (A5)	Deconstruction (C1)	EOL treatment (C2-C4)	Total life cycle
Climate change - total [kg CO2 eq]	2,27E-02	2,52E-04	6,27E-04	2,69E-04	1,75E-04	**2,40E-02**
Ozone depletion [kg CFC11 eq]	1,83E-09	6,16E-11	6,77E-11	2,90E-11	2,32E-11	**2,02E-09**
Acidification [mol H+ eq]	1,51E-04	9,93E-07	5,42E-06	2,32E-06	4,68E-07	**1,60E-04**
Eutrophication, freshwater [kg P eq]	1,58E-06	1,98E-09	2,82E-08	1,21E-08	1,10E-09	**1,62E-06**
Eutrophication, marine [kg N eq]	2,37E-05	2,23E-07	7,89E-07	3,38E-07	1,42E-07	**2,51E-05**
Eutrophication, terrestrial [mol N eq]	2,54E-04	2,49E-06	8,89E-06	3,81E-06	1,56E-06	**2,71E-04**
Photochemical ozone formation [kg NMVOC eq]	9,24E-05	9,02E-07	2,37E-06	1,02E-06	4,92E-07	**9,72E-05**
Resource use, minerals and metals [kg Sb eq]	1,24E-06	4,43E-09	1,87E-09	8,01E-10	1,83E-09	**1,25E-06**
Resource use, fossils [MJ]	2,80E-01	4,07E-03	1,45E-02	6,20E-03	1,60E-03	**3,06E-01**
Water use [m³ depriv.]	6,28E-03	1,31E-05	4,24E-04	1,82E-04	-3,54E-06	**6,90E-03**
Particulate matter [disease inc.]	1,47E-09	2,17E-11	1,17E-11	5,00E-12	1,03E-11	**1,52E-09**
Ionising radiation [kBq U-235 eq]	1,02E-03	1,78E-05	1,57E-04	6,71E-05	6,87E-06	**1,26E-03**
Ecotoxicity, freshwater [CTUe]	1,11E+00	3,23E-03	9,85E-03	4,22E-03	1,94E-03	**1,12E+00**
Human toxicity, cancer [CTUh]	1,16E-10	8,06E-14	2,09E-13	8,96E-14	6,24E-14	**1,16E-10**
Human toxicity, non-cancer [CTUh]	1,49E-09	3,52E-12	7,15E-12	3,06E-12	3,06E-12	**1,51E-09**
Land use [Pt]	1,15E-01	4,57E-03	2,77E-03	1,19E-03	1,82E-03	**1,25E-01**

Contribution to impact category X > 50% | 25% < X < 50% | 10% < X < 25% | 2,5% < X < 10% | X < 2,5%

For clarification: a negative value means a negative load, i.e. a benefit.

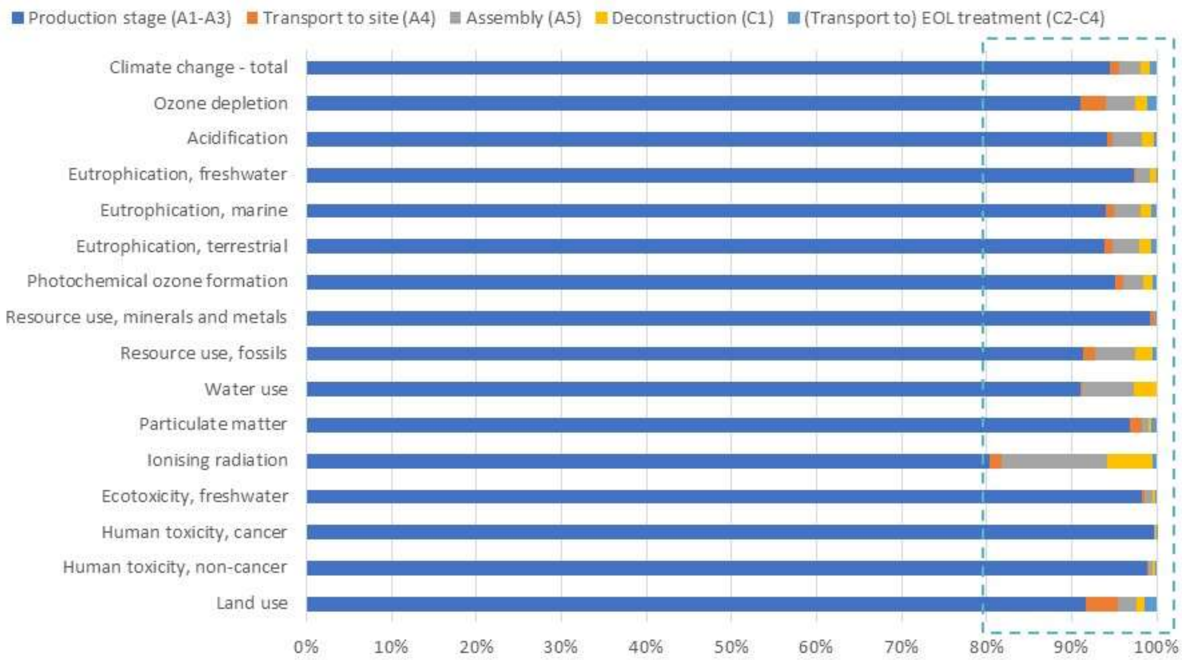

Figure 23: Relative contribution of all life cycle stages of RS3 based on the environmental profile.

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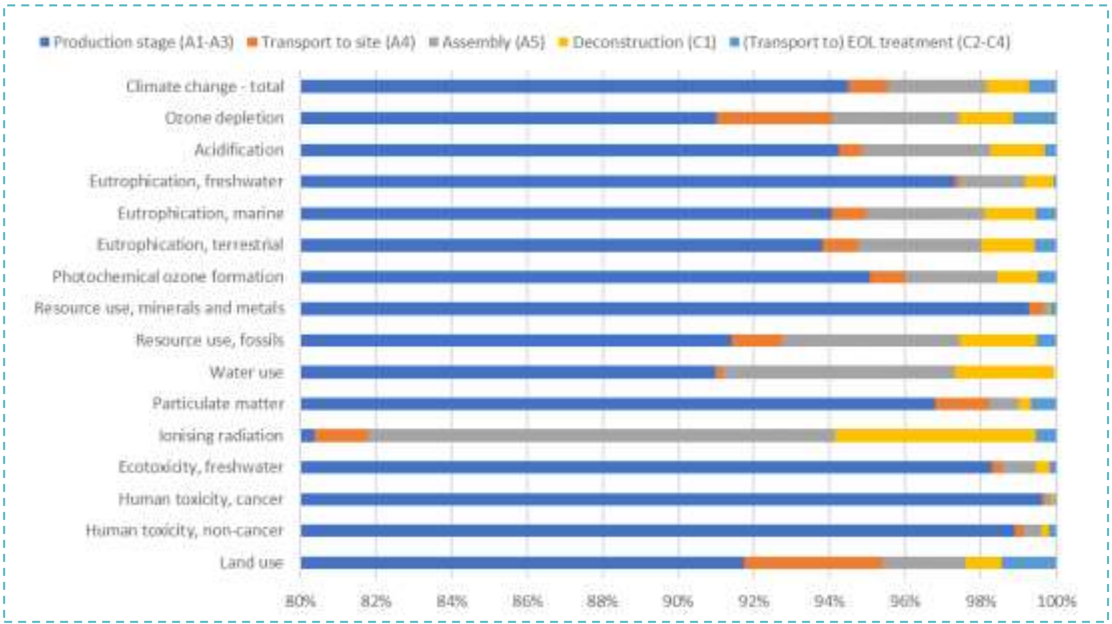

Figure 23 continue: Relative contribution of all life cycle stages of RS3 based on the environmental detailed view of the last 20%.

When analysing only the production stage of RS3 in more detail (see Figure 24), it shows that the main contributing component of the RS3 wind turbine is the tower. This can be explained by the mass of the tower (553 000 kg, which is 69.6% of the total mass of the wind turbine). Other components that have a relatively decisive contributing impact on all impact categories are: the main bearings, turbine connections and gearbox.

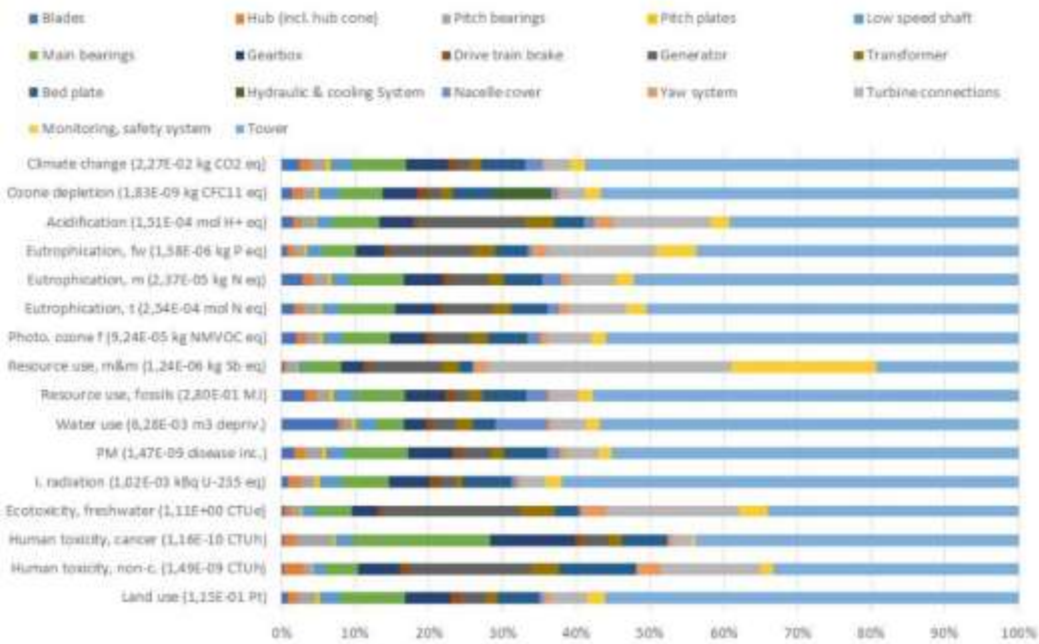

Figure 24: Relative contribution of all components of RS3 to the production stage (A1-A3). The absolute values mentioned between brackets in the vertical axis are per FU.

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- ## LCA findings related to the pitch bearing RS3

Table 32 and Figure 25 present the results of the environmental LCIA of the specific component of RS3, i.e. a pitch bearing for a 3.4 MW onshore wind turbine with a service lifetime of 20 years. Based on the results it can be concluded that the raw materials of the pitch bearings contribute the most to the environmental impact of its complete life cycle. In all impact categories, the contribution of the raw materials is more than 89%. More detailed results and findings of this LCA will be shared with Laulagun.

Table 32: Environmental profile of a pitch bearing in RS3 in absolute values per FU.

	(Transport of) raw materials (A1+A2)	Manufacturing process (A3)	Transport to site (A4)	Assembly (A5)	Deconstruction (C1)	(Transport to) EOL treatment (C2-C4)	Total life cycle
Climate change - total [kg CO2 eq]	7,28E-05	2,13E-06	4,12E-07	1,22E-06	5,23E-07	1,70E-07	**7,72E-05**
Ozone depletion [kg CFC11 eq]	4,63E-12	3,60E-13	8,71E-14	3,87E-14	1,66E-14	3,96E-14	**5,18E-12**
Acidification [mol H+ eq]	4,24E-07	1,87E-08	8,53E-09	4,32E-09	1,85E-09	7,44E-10	**4,58E-07**
Eutrophication, freshwater [kg P eq]	3,11E-09	7,67E-11	2,33E-12	9,35E-11	4,01E-11	1,50E-12	**3,32E-09**
Eutrophication, marine [kg N eq]	7,37E-08	4,15E-09	2,13E-09	7,69E-10	3,30E-10	2,25E-10	**8,13E-08**
Eutrophication, terrestrial [mol N eq]	8,15E-07	4,55E-08	2,37E-08	1,10E-08	4,72E-09	2,49E-09	**9,02E-07**
Photochemical ozone formation [kg NMVOC eq]	2,51E-07	1,26E-08	6,24E-09	2,31E-09	9,91E-10	8,01E-10	**2,74E-07**
Resource use, minerals and metals [kg Sb eq]	2,60E-09	7,86E-12	6,41E-12	4,82E-12	2,06E-12	2,94E-12	**2,62E-09**
Resource use, fossils [MJ]	8,33E-04	4,48E-05	5,65E-06	1,52E-05	6,50E-06	2,67E-06	**9,07E-04**
Water use [m³ depriv.]	1,05E-05	1,11E-06	1,17E-08	1,67E-07	7,17E-08	-1,15E-08	**1,18E-05**
Particulate matter [disease inc.]	5,30E-12	1,55E-13	1,93E-14	2,08E-14	8,90E-15	1,78E-14	**5,52E-12**
Ionising radiation [kBq U-235 eq]	2,86E-06	4,26E-07	2,45E-08	7,46E-08	3,20E-08	1,15E-08	**3,43E-06**
Ecotoxicity, freshwater [CTUe]	2,34E-03	3,13E-05	4,04E-06	2,31E-05	9,91E-06	2,68E-06	**2,41E-03**
Human toxicity, cancer [CTUh]	9,40E-13	7,55E-16	1,94E-16	3,40E-16	1,46E-16	9,55E-17	**9,42E-13**
Human toxicity, non-cancer [CTUh]	2,83E-12	2,30E-14	3,83E-15	1,16E-14	4,99E-15	2,69E-15	**2,88E-12**
Land use [Pt]	4,34E-04	8,38E-06	2,19E-06	2,52E-05	1,08E-05	3,13E-06	**4,84E-04**

Contribution to impact category	X > 50%	25% < X < 50%	10% < X < 25%	2,5% < X < 10%	X < 2,5%

For clarification: a negative value means a negative load, i.e. a benefit.

Figure 25: Relative contribution of all life cycle stages of a pitch bearing in RS3.

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4.3.2. Findings LCC

Table 33 presents the LCOE estimate (0,068 €/kWh or 68.4 €/MWh) for the complete life cycle for RS3. The results are expressed in EUR 2019 and are calculated using the LCOE method (as described in section 1.2.2) together with the economic parameters (as described in section 3.1) and the specific cost estimates and scenarios (as described in 3.4). All expenditures associated with the wind farm (DEVEX, CAPEX, OPEX and ABEX) are taken into account. In contrary to the LCA and S-LCA, costs related to the balance of plant are within the scope of the LCC assessment.

The LCOE figure is the discounted total sum of the costs in connection with the total discounted energy production, for the complete life cycle of the wind turbine. The numerator gives the discounted total sum of costs for the wind turbine. The denominator gives the total discounted energy production (which should not be confused with the total energy production of 142 963 200 kWh over the lifetime of the turbine).

Table 33: LCOE result for RS3

	LCOE [EUR/kWh]	Numerator [EUR]	Denominator [kWh]
LCOE	0,068 or 6,84 %	5 899 677	86 192 801

Table 34 presents the LCOE result for the different cost components:

- The CAPEX LCOE figure of 0,049 EUR/kWh shows the discounted total sum of capital expenditures over the annual energy production of the wind farm. This represents 71% of the LCOE for the complete life cycle for RS3 and includes costs of turbine, balance of plant, transport, assembly, installation and financial costs.
- The OPEX LCOE figure of 0,018 EUR/kWh shows the discounted total sum of operational expenditures over the annual energy production of the wind farm. This represents 26% of the LCOE for the complete life cycle for RS3.
- The sum of DEVEX and ABEX LCOE figures only represent 3% of the LCOE for the complete life cycle for RS3. DEVEX includes costs of site development, design engineering and management costs. ABEX represents the end-of-life (EOL) stage and includes costs of decommissioning, transport to EOL, waste processing and disposal on the one hand and revenues from scrap value of wind turbine components on the other hand (mostly steel, iron and copper).

Table 34: LCOE breakdown for RS3

	LCOE [EUR/kWh]	Denominator [EUR]	Numerator [kWh]	Share of total LCOE
DEVEX	0,001	103 026	86 192 801	2%
CAPEX	0,049	4 227 004	86 192 801	71%
OPEX	0,018	1 531 114	86 192 801	26%
ABEX	0,000	38 533	86 192 801	1%

Figure 26 shows a more detailed breakdown of the costs for RS3 over 20 years, discounted to the date of comparison (year 0). For the CAPEX, the biggest cost components are the costs

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of the turbine including transport (50%), followed by the BOP costs (13%) and financial costs (6%).

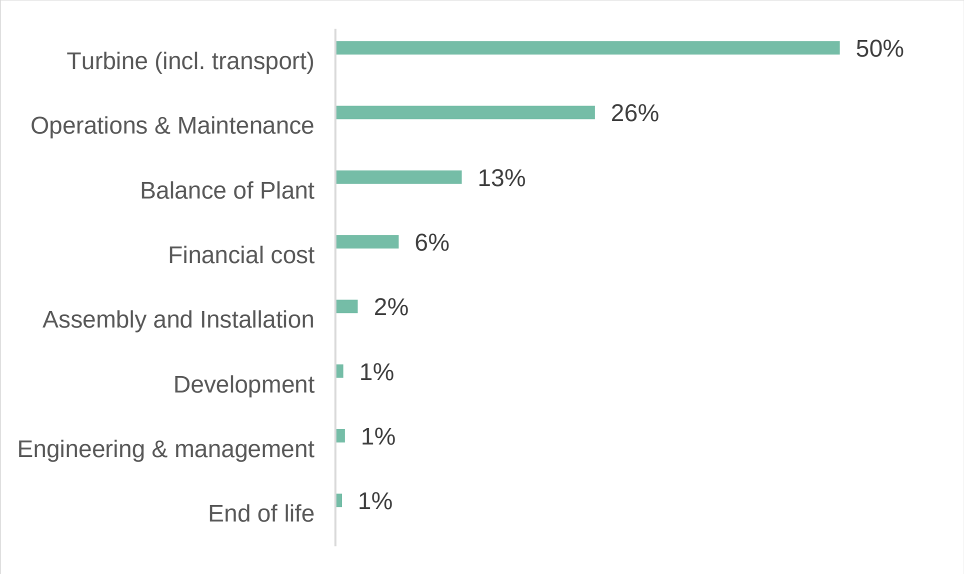

Figure 26: Detailed LCOE breakdown for RS3 - costs discounted to 2019

The goal of this LCC assessment is to assess the BAU reference scenario of which the results can be used for comparing the economic performance of the INNTERESTING solutions. Results depend on the scope, input parameters and assumptions. Therefore one-to-one comparisons to LCOE results of other projects are not possible. For a straightforward comparison of wind farms, the same boundary conditions need to be taken into account.

The RS3 results of the LCOE are high compared to average LCOE results found in literature for onshore projects (as mentioned section 3.1 on high uncertainty of data).

- **LCC findings related to the pitch bearing RS3**

For the pitch bearing of RS3, specific cost data were provided by Laulagun on the cost of raw materials and energy use in the production process. The production cost (CAPEX) of the pitch mechanism accounts for 6 % of the total production costs of the wind turbine (rotor, nacelle, tower). Specific data on the operational expenditure of pitch bearings were not available.

4.3.3. Findings S-LCA

Table 35 presents the results for the complete life cycle per indicator for RS3. The results are expressed in medium risk hours and are calculated using the PSILCA impact assessment method (see Table 4).

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Table 35: 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	1,07E-03	CONS med risk hours
Local Community		
Access to material resources		
Industrial water depletion	1,66E-02	WU med risk hours
Biomass consumption	1,08E-02	BM med risk hours
Certified envir. management systems	8,54E-02	CMS med risk hours
Minerals consumption	4,02E-03	MC med risk hours
Fossil fuel consumption	2,49E-04	FF med risk hours
Local employment		
Unemployment	1,26E-01	U med risk hours
Migration		
International migrant stock	1,47E-02	IMS med risk hours
Internat. migrant workers in the sector	1,07E-02	IMW med risk hours
Net migration	1,31E-03	NM med risk hours
Respect of indigenous rights		
Indigenous rights	3,75E-03	IR med risk hours
Safe and healthy living conditions		
Contribution to environmental load	7,11E-02	CS med risk hours
Sanitation coverage	3,51E-02	SC med risk hours
Pollution	1,06E-02	P med risk hours
Drinking water coverage	5,40E-03	DW med risk hours
Society		
Contribution to economic development		
Education	1,57E-02	E med risk hours
Illiteracy, female	8,05E-03	I med risk hours
Illiteracy, total	7,14E-03	I med risk hours
Illiteracy, male	6,42E-03	I med risk hours
Youth illiteracy, female	1,14E-03	YI med risk hours
Youth illiteracy, total	1,12E-03	YI med risk hours
Youth illiteracy, male	1,08E-03	YI med risk hours
Contribution to economic development	-3,72E-03	CE med risk hours
Health and Safety (Society)		
Health expenditure	1,20E-02	HE med risk hours
Life expectancy at birth	9,01E-04	LE med risk hours
Value Chain Actors		
Corruption		
Active involv. in corruption and bribery	3,35E-02	AI med risk hours
Public sector corruption	4,86E-02	C med risk hours
Fair competition		
Anti-competitive business pratices	1,18E-03	AC med risk hours
Promoting social responsibility		
Social responsibility along supply chain	7,30E-02	SR med risk hours

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Continuation of Table 35: S-LCA results of RS3 for the complete life cycle expressed in medium risk hours.

Stakeholder group/Subcategory/Indicator	Impact result	Unit
Workers		
Child labour		
Child Labour, male	2,08E-03	CL med risk hours
Child Labour, total	2,06E-03	CL med risk hours
Child Labour, female	1,88E-03	CL med risk hours
Discrimination		
Women in the sectoral labour force	2,70E-02	W med risk hours
Gender wage gap	2,37E-02	GW med risk hours
Men in the sectoral labour force	1,25E-04	M med risk hours
Fair Salary		
Fair Salary	4,53E-02	FS med risk hours
Forced labour		
Trafficking in persons	4,37E-03	TP med risk hours
Goods produced by forced labour	8,10E-04	GFL med risk hours
Frequency of forced labour	5,53E-04	FL med risk hours
Freedom of association and collective bargaining		
Trade unionism	1,52E-01	TU med risk hours
Association and bargaining rights	8,91E-03	ACB med risk hours
Health and Safety (Workers)		
Non-fatal accidents	1,07E-01	NFA med risk hours
Fatal accidents	1,09E-03	FA med risk hours
Safety measures	4,17E-02	SM med risk hours
DALYs due to indoor/ outdoor pollution	4,40E-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	8,56E-03	VL med risk hours
Social security expenditures	8,31E-03	SS med risk hours
Working time		
Weekly hours of work per employee	1,53E-03	WH med risk hours

The results are analysed in more detail for a selected set of impact categories (‘Fair Salary’ and ‘Health and Safety workers’). Justification for this selection is provided in section 1.2.3.2. Figure 27 shows the results of the S-LCA study for the selected impact categories. All results have been scaled to 100%. The upper bar in the graph contains the distribution of costs across the life cycle, as social risks are calculated by multiplying the risk characterisation factor with price and worker hours. The maintenance costs for 20 years and the production of all other components (except for blades, pitch mechanisms and electric installations) clearly form the biggest share in the life cycle costs. The maintenance costs are the costs for 2015 multiplied with the life span. They have not been discounted as the objective of this exercise was to calculate the social risks along the life cycle which might occur in the maintenance sector.

The 'production of all other components (which are all turbine components except for blades, pitch mechanism and electrical system) is the most important life cycle stage in all the investigated impact categories. The results are analysed in more detail in the next paragraphs.

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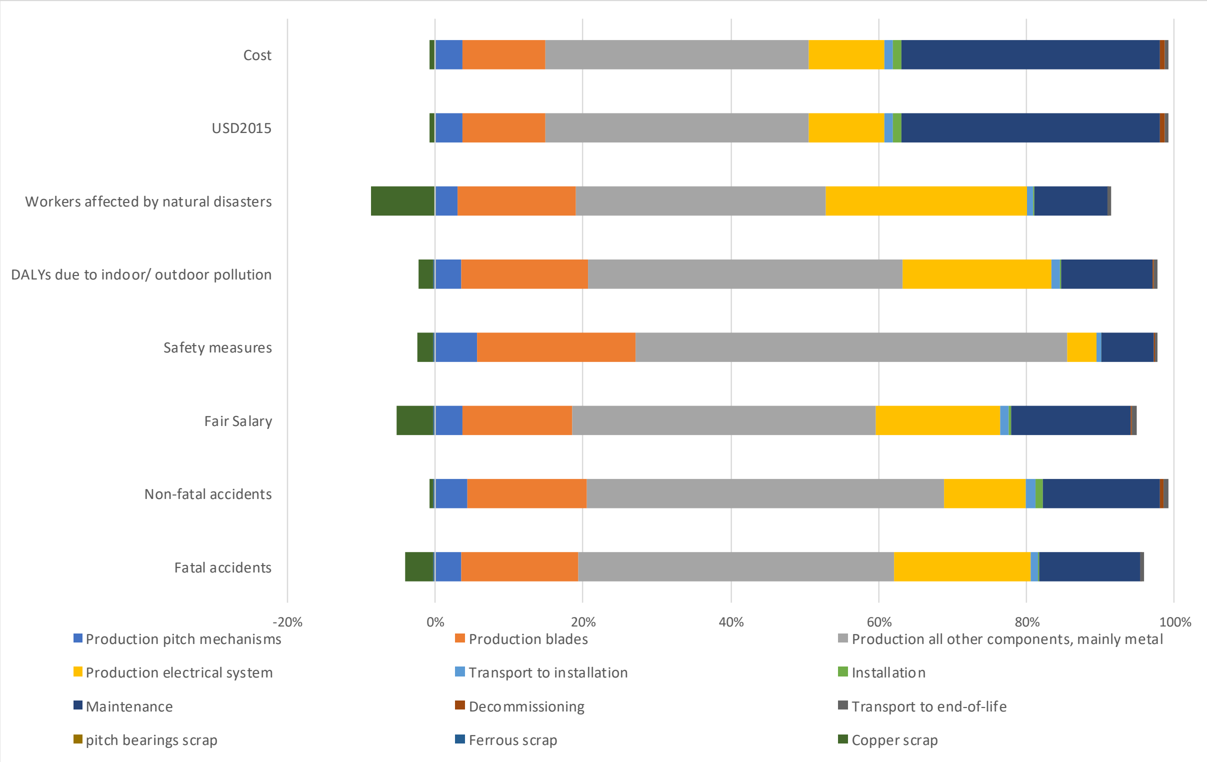

Figure 27: Life cycle results of the social hotspot analysis for RS3 for selected impact categories.

- ### Subcategory Fair salary

More information about the impact category 'Fair salary' is available in section 1.2.3.3.

The most important life cycle stage in this subcategory is 'the production of all other components' with a contribution of 43%. Table 36 summarises the raw values for the life cycle stages 'Production of pitch mechanisms in Spain', 'Production of all other components in Spain' and 'Maintenance in Spain'. As discussed in section 4.1.3 living wages are independently of limited informative value. If living wage per month would not be risk assessed (following the reasoning that it is of limited value on its own), the hotspot in the impact category fair salary would still be the 'production of all other components' with a contribution of 44%. Table 36 only shows the values for the sector at hand and not the supply chain of these specific sectors which are also taken into account in the calculations in PSILCA. The risk levels are the same for the three life cycle stages. If only the foreground system would have been taken into account, the distribution of risk over the life cycle would be equal to the distribution of the costs. Figure 27 shows that the production of all other components in the impact category Fair Salary is slightly more important than its contribution to the life cycle cost, which is opposite for maintenance. This is difference is due to differences in the background system.

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Table 36: Raw values and risk levels of RS3 for the three indicators of the subcategory Fair salary.

Life cycle stage	Production of pitch mechanisms in Spain		Production of all other components in Spain		Maintenance in Spain	
	worker hours/USD output	USD/month	worker hours/USD output	USD/month	worker hours/USD output	USD/month
Living wage per month, USD	0,01029	708	0,01029	708	0,010287279	708
Minimum wage per month, USD		701		701		701
Sector average wage per month, USD		2733		2733		2099

very high risk
high risk
medium risk
low risk
very low risk

- **Subcategory Health and safety (workers)**

More information about the impact category 'Health and safety (workers)' is available in section 1.2.3.4. In the following paragraphs some raw values are provided for interpretation purposes. The values are always valid for the sector at hand and do not take into account the supply chain of the specific sector.

The 'production of all other components, metal' in Spain generates the most medium risk hours in the impact category 'Non-fatal accidents'. There is a big cost related the production of 'All other components', which of course has its share in the high contribution. However, also the raw values for the sector 'Metal products' in Spain are higher compared to for example the raw values for the sector 'Maintenance' in Spain' (respectively 4 531 and 2 635 non-fatal accidents per year and per 100 thousand employees).

In the impact category 'Fatal accidents', again most medium risk hours are generated in the life cycle stage 'production of all other components'. The raw values for 'production of all other components' occurring in Spain and 'maintenance' occurring in Spain are respectively 2.633 and 1.212 fatal accidents per year and 100 thousand employees.

The most important life cycle stage in the impact category 'Presence of sufficient safety measures' is again the 'production of all other components'. The raw value is 138 violations which is high compared to the violations reported for the maintenance sector in Spain, being 3.55 violations per 100 thousand employees per year.

The largest contribution to the impact category 'Workers affected by natural disasters' comes from the 'production of all other components', but also the contribution of the 'production of the electrical system' is important.

- **S-LCA findings related to the pitch bearings**

Figure 28 shows the results of the S-LCA for the production of the pitch bearings, again for a selected set of impact categories.

The production of the rings is the hotspot in the impact categories 'Workers affected by natural disasters', 'DALYs due to indoor and outdoor air pollution', 'Fair salary' and 'Fatal accidents'. The production of the pitch bearings itself is the hotspot in the impact categories 'Safety measures' and 'Non-fatal accidents'. It is important to note that for the pitch bearing production primary data have been used for cost, while for worker hours and risk levels, generic background data have been taken from the PSILCA v2 database.

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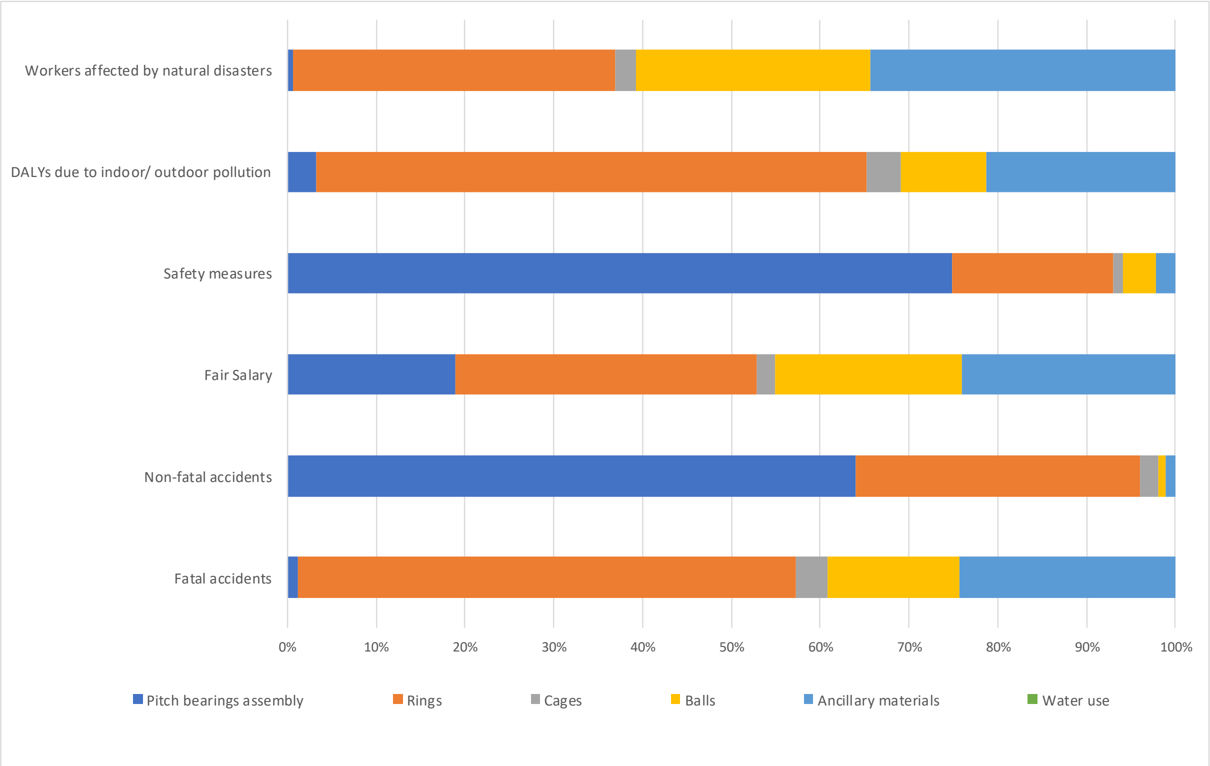

Figure 28: Results of the social hotspot analysis for RS3 pitch bearings production in Spain for selected impact categories

5. Conclusions and outputs for other work packages

5.1. General conclusions

This report described the overall approach and the different methodological frameworks applied for the three parts of the LCSA, i.e. LCA. LCC, and S-LCA. For each case study a matching BAU reference scenario has been developed and assessed. Despite the intention to have one scope for all three parts of the LCSA, during the course of the assessments the scope of the LCC had to be expanded to a full scope including the BOP and development costs due to the found data needed for the assessment, while for the LCA and S-LCA the scope stayed limited to the wind turbine. The following sections summarises, the conclusions per type of assessment.

5.1.1. Conclusions LCA

The environmental impacts of the three reference scenarios are expressed via LCAs according to the EN 15804+A2:2019 methodological framework. Although RS1, RS2 and RS3 are three different wind turbines, the LCA results show that the production stage (A1-A3) is the most relevant life cycle stage that contributes to the environmental impact of the life cycle of a wind turbine for all assessed impact categories. Which is for all three RS caused by the tower, due to its mass, which ranges between 45 and 70% of the total mass of the wind turbines. Other components that are relevant contributors to the environmental impact of the wind turbines are: the pitch mechanism (of which pitch bearings are subcomponents), the gearbox and the different electronics. Nonetheless, it should be noted that for some life cycles stages inventory data were limited or lacking.

5.1.2. Conclusions LCC

For the LCC assessment, LCOE calculations were carried out for RS1, RS2 and RS3. The Levelized Cost of Energy is the discounted total sum of the costs in connection with the total discounted energy production, for the complete life cycle of the wind turbine. In contrary to the LCA and S-LCA, costs related to the balance of plant are within the scope of the LCC assessment. All development expenditures, capital expenditures, operational expenditures and abandonment expenditures (DEVEX, CAPEX, OPEX and ABEX) associated with the wind farm are taken into account in the LCOE estimate. This also includes costs of site development, engineering, management (part of DEVEX) and financial costs, which are not taken into account in the S-LCA.

The LCOE cost breakdowns for RS1, RS2 and RS3 give similar conclusions regarding the order of magnitude of the cost components. DEVEX includes costs of site development, design engineering and management costs. For the examined cases, development expenditures do not represent a big share (1% to 3%) in the total LCOE over the lifetime. For all cases, the CAPEX has the biggest share (57% to 72%) within the total expenditures over the lifetime. Capital expenditures include costs of turbine, balance of plant, transport, assembly and installation and financial costs. For these components of CAPEX, the costs of the turbine are the biggest, followed by the BOP costs. The next biggest share of costs is represented by the OPEX (range 26% to 38%). Finally, the ABEX represents the end-of-life (EOL) stage and includes costs of decommissioning, transport to EOL, waste processing and disposal on the

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one hand and revenues from scrap value of wind turbine components on the other hand. Our findings suggest that abandonment expenditures only account for 1% to 2% of total costs.

The LCOE estimates of each case are expressed in EUR per kWh. The goal of this LCC assessment is to assess the BAU reference scenario of which the results can be used for comparing the economic performance of the INNTERESTING solutions. Results depend on the scope, input parameters and assumptions. Therefore one-to-one comparisons to LCOE results of other projects are not possible. For a straightforward comparison of wind farms, the same boundary conditions need to be taken into account.

5.1.3. Conclusions S-LCA

The S-LCA looked at the potential social impacts of the different reference systems across their life cycle. S-LCA is a relatively new technology and a standardized methodology is not yet available. Guidelines are however in place. The social impacts are assessed in connection to various stakeholder groups. In this study we have calculated results for the stakeholder groups, Workers, Local communities, Value chain actors (e.g. suppliers), Consumers. Some for the industry relevant social impact categories have been analysed in further detail. The selection of relevant social impact categories was made based on materiality assessments and sustainability reports made available by major European wind turbine manufacturers and based on the (very) high risk levels reported in the PSILCA database, a database for S-LCA. Finally the subcategories 'Health and safety (workers)' and 'Fair salary' had been selected. The subcategory 'Health and safety' in PSILCA v2 consists of the indicators 'Non-fatal accidents at workplace', 'Fatal accidents at workplace', 'DALYs (disability adjusted life years) due to indoor and outdoor air and water pollution', 'Presence of sufficient safety measures' and 'Workers affected by natural disasters'.

For the reference cases (RS1, RS2 and RS3) primary data regarding costs have been collected from literature or were provided for the gearbox in RS2 by Moventas and for the pitch bearings in RS 1 and RS 3 by Laulagun. Data on worker hours and risk levels have been taken from the PSILCA v2 database.

For the selected impact categories and RS1, the 'production of all other components' which are mainly metal parts and 'maintenance' are the most important life cycle stages. The contribution of the production of the pitch mechanisms is not important in the selected impact categories. The costs of pitch mechanisms are small compared to the total life cycle cost of the turbine. As the focus of the INNTERESTING project is on the pitch bearings (which are part of the pitch mechanism), their social impact has been investigated in more detail. The production of rings, balls and the pitch bearing assembly are the most important contributors to the investigated impact categories.

For the selected impact categories and RS2, the 'production of all other components' which are mainly metal parts and 'maintenance' are the most important life cycle stages. The contribution of the 'production of the gearbox' is not or only little important in the selected impact categories. The cost of the gearbox is small compared to the total life cycle cost of the turbine. As the focus of the Innteresting project is on the gearbox, its social impact has been investigated in more detail. The production of the gear materials is the hotspot in the impact categories 'Workers affected by natural disasters', 'DALYs due to indoor and outdoor air pollution', 'Safety measures' and 'Fatal accidents'. The production of the gearbox itself is the hotspot in the impact category 'Non-fatal accidents'. In the impact category 'Fair Salary' both the 'gearbox assembly' and the production of gear materials are hotspots.

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For the selected impact categories and RS3, the 'production of all other components' which are mainly metal parts is the most important life cycle stages. The contribution of the 'production of the pitch bearings' is not or only little important in the selected impact categories. The cost of the pitch bearings is small compared to the total life cycle cost of the turbine. As the focus of the Innteresting project is on the pitch bearings, their social impact has been investigated in more detail. The production of the rings is the hotspot in the impact categories 'Workers affected by natural disasters', 'DALYs due to indoor and outdoor air pollution', 'Fair salary' and 'Fatal accidents'. The production of the pitch bearings itself is the hotspot in the impact categories 'Safety measures' and 'Non-fatal accidents'.

5.2. Outputs for other work packages

As mentioned under the goal and scope, the LCSA of the BAU reference scenarios are intended for gaining insights in the contribution of the different components to the environmental, economic and social impact of wind turbines during their life cycle. These insights will be shared with the project partners as support for their concept development of the INNTERESTING solutions. During the development of each case study, the LCSA can be used to assess the potential effect of certain choices on the environmental, economic and social performance of the INNTERESTING solutions in comparison with the BAU references.

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Annex A

Stakeholders, subcategories and indicators with units of measurement in the PSILCA database

Stakeholder group/Subcategory/Indicator	Unit
Consumers	
Transparancy	
Precense of business practices deceptive or unfair to consumers	# per 10 000 employees
Local Community	
Access to material resources	
Industrial water depletion, related to actual renewable resources	%
Industrial water depletion, related to total withdrawal	%
Extraction of biomass, related to population	t/cap
Extraction of biomass, related to area	t/km2
Certified envir. management systems	# per 10 000 employees
Minerals consumption - extraction of industrial and construction minerals	t/cap
Minerals consumption - extraction of ores	t/cap
Fossil fuel consumption	t/cap
Local employment	
Unemployment rate in the country	%
Migration	
International migrant stock	%
Internat. migrant workers in the sector	%
Net migration	%
Respect of indigenous rights	
Presence of indigenous population	Y/N
Human rights issues faced by indigenous people	Score
Safe and healthy living conditions	
Contribution to environmental load, CO, I-AIR-CO_agg	kg emissions to air, total
Contribution to environmental load, NMVOC, I-AIR-NMVOC_agg	kg emissions to air, total
Contribution to environmental load, NOx, I-AIR-NOx_agg	kg emissions to air, total
Contribution to environmental load, PM10, I-AIR-PM10_agg	kg emissions to air, total
Contribution to environmental load, SO2, I-AIR-SO2_agg	kg emissions to air, total
Contribution to environmental load, CO2-equiv, I-GHG-CO2eTOTAL_agg	kg emissions to air, total
Sanitation coverage	% of population
Pollution level of the country	index value
Drinking water coverage	% of population
Society	
Contribution to economic development	
Education	% of GDP
Illiteracy, female	% of female population
Illiteracy, total	% of total polulation
Illiteracy, male	% of male population
Youth illiteracy, female	% of female population, 15-24
Youth illiteracy, total	% of total population, 15-24
Youth illiteracy, male	% of male population, 15-24
Contribution to economic development	% of GDP
Health and Safety (Society)	
Health expenditure, total	% of GDP
Health expenditure, public	% of total health expenditure
Health expenditure, out-of-pocket	% of total health expenditure
Health expenditure, external resources	% of total health expenditure
Life expectancy at birth	Years

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Stakeholder group/Subcategory/Indicator	Unit
Value Chain Actors	
Corruption	
Active involv. in corruption and bribery	%
Public sector corruption	index value
Fair competition	
Anti-competitive business pratices	cases per 10 000 employees
Promoting social responsibility	
Social responsibility along supply chain	# per 100 000 employees
Workers	
Child labour	
Child Labour, male	% of male children ages 7-14
Child Labour, total	% of all children ages 7-14
Child Labour, female	% of female children ages 7-14
Discrimination	
Women in the sectoral labour force	ratio
Gender wage gap	%
Men in the sectoral labour force	ratio
Fair Salary	
Living wage per month	USD
Minimum wage per month	USD
Sector average wage per month	USD
Forced labour	
Trafficking in persons	%
Goods produced by forced labour	Y/N
Frequency of forced labour	Cases per 1000 inhabitants
Freedom of association and collective bargaining	
Trade unionism	% of employees organised in trade unions
Right of association	score
Right of collective bargaining	score
Right to strike	score
Health and Safety (Workers)	
Non-fatal accidents	# per 100 000 employees
Fatal accidents	# per 100 000 employees
Safety measures	OSHA cases per 100 000 employees
DALYs due to indoor/ outdoor pollution	DALY's per 1000 inhabitants
Workers affected by natural disasters	%
Social benefits, legal issues	
Violations of empl. laws and regulations	Cases per 1000 employees
Social security expenditures	% of GDP
Working time	
Weekly hours of work per employee	h

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Annex B

As mentioned by Benoît-Norris et al. (2020), few S-LCA studies manage to cover all stakeholders and impact subcategories. Also for this screening S-LCA we will focus on some subcategories for the interpretation of the results. Inclusion and exclusion of different stakeholder groups and/or impact categories should be justified on the basis of their relevance to the goal of the study, and the choice process should be described. One way to make a selection is by means of a materiality assessment (Benoît-Norris et al., 2020, p. 42).

This annex gives the review of materiality assessments and sustainability reports of the major European wind turbine manufacturers and try as such to detect the most important stakeholder groups and sub-indicators for the sector at hand.

The table below lists the top 10 wind turbine manufacturers in the world. This analysis focuses on European suppliers and as such looks at the sustainability goals and materiality assessments made available by Vestas, Siemens Gamesa and Nordex.

Table 37: Top 10 wind turbine manufacturers in the World, 2020[28]

Rank	Company	Headquarters	Total capacity (Gigawatts)
1	Vestas	Aarhus, Denmark	9.60
2	Siemens Gamesa	Biscay, Spain	8.79
3	Goldwind	Beijing, China	8.25
4	GE	Boston, U.S.	7.37
5	Envision	Shanghai, China	5.78
6	MingYang	Zhongshan, China	4.50
7	Windey	Zhejiang, China	2.06
8	Nordex	Hamburg, Germany	1.96
9	Shanghai Electric	Shanghai, China	1.71
10	CSIC	Chongqin, China	1.46

The link between the sustainable development goals (SDGs) identified by the manufacturers as being important and the S-LCA framework is made based on figure 3 published by Benoît-Norris et al. (2020) and repeated below as Figure 29. This figure clearly shows the obvious connections of S-LCA to the seventeen SDGs that have been internationally accepted by governments, industries and organizations.

[28] https://www.bizvibe.com/blog/energy-and-fuels/top-10-wind-turbine-manufacturers-world/

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Figure 29: The S-LCA impact subcategories linked to the 17 SGDs (figure 3 as published in Benoît-Norris et al, 2020).

- **Vestas**

Vestas has published sustainability commitments on its website. In particular, Vestas has identified six SDGs which support development for Vestas, Vestas' stakeholders and the communities where Vestas plays a role. Those six SDGs are[29]: (7) Affordable and clean energy; (13) Climate action; (8) Decent work and economic growth; (4) Quality education; (12) Responsible consumption & production; and (17) Partnerships for the goals.

In 2016, the Vestas materiality analysis has identified a range of sustainability issues[30]. Amongst these, Business performance, Innovation, Health & safety, Product environmental performance and Local community development are understood to be some of the most important sustainability issues.

[29] https://www.vestas.com/en/about/sustainability#!commitments
[30] https://www.vestas.com/en/about/sustainability#!material-issues

- **Siemens Gamesa**

Siemens Gamesa identified high as well as medium and low impact SDGs in its Consolidated non-financial statement[31]. The SDGs having a high impact are strongly correlated to Siemens Gamesa's products and services (for the most part). Medium and low impact SDGs are mainly enablers that relate to responsible business practices. The SDGs identified by Siemens Gamesa with high impact are: (7) Affordable and clean energy; (5) Gender equality; (8) Decent work and economic growth; and (16) Peace, justice and strong institutions. In order to be able to prioritize on impact categories, we will look at the SDGs defined as being of high impact by Siemens Gamesa and exclude the ones of medium and low impact.

Siemens Gamesa also reports the results of their materiality assessment in its Consolidated non-financial statement[31]. This is the top 5 of the material aspects: Health and safety; Ethics, integrity and anti-corruption; Regulatory compliance; Equal opportunity, diversity and non-discrimination; and Human rights.

- **NORDEX**

Also the Nordex Group has integrated the SDGs into its sustainability approach[32]. Nordex sees their potential for influence particularly in three SDGs: (7) Affordable and clean energy; (8) Decent work and economic growth'; and (13) Climate action.

The material aspects of high importance reported by Nordex Group in its sustainability report[32] are: Environmental behaviour of the Group; Environmental footprint of wind power systems; Health and safety; Corporate culture; and Values and standards in the supply chain.

- **Summary table**

The table below summarizes the results of the SDGs and material issues identified by Vestas, Siemens Gamesa and Nordex as described above. The topics mentioned by **all** three companies are in **bold**.

[31] https://www.siemensgamesa.com/en-int/-/media/siemensgamesa/downloads/en/sustainability/siemens-gamesa-consolidated-non-financial-statement-2019-en.pdf
[32] https://www.nordex-online.com/wp-content/uploads/sites/2/2020/03/200323_Nordex_NHB_2019_eng_web.pdf

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	Topic	Company	Linked subcategories[33]
SDG	**7 – Affordable and clean energy**	Vestas, Siemens Gamesa, Nordex	Access to material resources
	13 – Climate action	Vestas, Siemens Gamesa, Nordex	Covered by LCA
	8 – Decent work and economic growth Promote sustained, inclusive and sustainable economic growth	Vestas, Siemens Gamesa, Nordex	Freedom of association, Child labor, Forced labor, Working hours, Social benefits/security, Local employment, Contributions to economic development, Fair salary, Employment relationship
	4 – Quality education	Vestas	
	12 – Responsible consumption & production	Vestas	
	17 – Partnerships for the goals	Vestas	
	5 – Achieve gender equality and empower all women and girls	Siemens Gamesa	
	16 – Promote peaceful and inclusive societies for sustainable development	Siemens Gamesa	
Materiality	Business performance	Vestas	
	Innovation	Vestas	
	Health & safety	Vestas, Siemens Gamesa, Nordex	Health and safety (Workers)
	Product environmental performance[34], Environmental behaviour	Vestas, Nordex	
	Local community development	Vestas	
	Ethics, integrity and anti-corruption	Siemens Gamesa	
	Regulatory compliance	Siemens Gamesa	
	Equal opportunity, diversity and non-discrimination	Siemens Gamesa	
	Human rights	Siemens Gamesa	
	Product responsibility (cost of energy, customer satisfaction)	Nordex	
	Corporate culture	Nordex	
	Values and standards in the supply chain	Nordex	

[33] The link with the SDGs is made based on figure 3 of the draft guidelines for social life cycle assessment (Benoît-Norris et al., 2020), copied as Figure 29 of this deliverable.
[34] By Nordex called ‘Environmental Footprint of wind power systems.

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Annex C

Impact categories with high and very high risk in four important life cycle stages in the life cycle of the wind turbine.

Impact category	Stakeholder group/Subcategory	Machinery and equipment in Finland	Metal products in Spain	Maintenance in Germany	Maintenance in Spain
Gender wage gap	Workers/ Discrimination		High risk	High risk	High risk
Evidence of violations of laws and employment regulations	Workers/ Social benefits, legal issues				High risk
Living wage per month	Workers/ Fair salary	Very high risk	High risk	Very high risk	High risk
Presence of sufficient safety measures	Workers/ Health and safety	High risk	Very high risk		
Rate of non-fatal accidents at workplace	Workers/ Health and Safety	Very high risk	Very high risk	High risk	High risk
Trade union density	Workers/ Workers' rights		Very high risk	Very high risk	Very high risk
Women in the sectoral labour force	Workers/ Discrimination				
Active involvement of enterprises in corruption and bribery	Value Chain actors/ Corruption				
Public sector corruption	Value chain actors/ Corruption		High risk		High risk
Social responsibility along the supply chain	Value chain actors/ Promoting social responsibility	High risk		Very high risk	Very high risk
Certified environmental management systems	Local community/ Access to material resources			High risk	
Extraction of biomass (related to population)	Local community/ Access to material resources	High risk			
Extraction of biomass (related to area)				Very high risk	

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Extraction of industrial construction minerals	Local community/ Access to material resources	Very high risk			
International migrant stock	Local community/ Migration		High risk	High risk	High riks
International migrant workers in the sector	Local community/ Migration		High risk		
Level of industrial water use (related to renewable water resources)	Local community/ Access to material resources			Very high risk	
Level of industrial water use (related to total withdrawal)	Local community/ Access to material resources	High risk		Very high risk	
Unemployment rate in the country	Local Community/ Local employment		Very high risk		Very high risk
Public expenditure on education	Society/ Contribution to economic development		High risk		High risk
Contribution to sector environmental load				Very high risk	
Public expenditure on education				High risk	

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