Applying Life Cycle Sustainability Assessment to maximise the innovation potential of new technologies for critical components in wind turbines

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Abstract. Future wind turbines require flexible and economically affordable product development processes to obtain reliable and validated new concepts for larger wind turbines. Pitch bearings and gearboxes are considered critical components, due to their high contribution to the operational costs of wind farms and their high failure rates. Within the Horizon 2020 project INNTERESTING (Innovative Future-Proof Testing Methods for Reliable Critical Components in Wind Turbines) new concepts and technologies concerning two critical components are being developed for future wind turbines. Life Cycle Sustainability Assessment (LCSA) is applied iteratively to gain insights in the more demanding requirements for future wind turbines, specifically on the reduction of capital and operational expenditures and improvement of the environmental and socio-economic performance aspects of wind turbines in order to reduce the economic, environmental and social impact of the newly developed technologies. This paper focusses on the results of the first LCSA iteration for the business-as-usual reference scenarios which will serve as a benchmark and reference for the newly to be developed solutions in the project.

1. Introduction

Wind power has become an essential part of the world's energy mix. Since the early 1990s, wind turbines have been erected in increasing numbers [1]. Wind turbine manufacturers are competing in the race to design and manufacture more powerful turbines with increasing size and efficiency. Guiding principles to achieve sustainable production while stimulating innovation, are advisable. The application of life cycle thinking (LCT) is a way to incorporate sustainable development in decision-making processes [2], which means going beyond the narrow manufacturer’s scope of turbine composition and processing stage and taking into account the whole life cycle of the turbine, from cradle to grave [3].

Life Cycle Sustainability Assessment (LCSA) can play a crucial role in this, combining three LCT techniques: 1) environmental life cycle assessment (LCA); 2) life cycle costing (LCC); and 3) social life cycle assessment (S-LCA) [2, 4]. In the H2020 project INNTERESTING (Innovative Future-Proof Testing Methods for Reliable Critical Components in Wind Turbines) LCSA is applied to disruptive technologies for critical components in wind turbines in order to maximise the innovation potential of
the technological developments of the project without losing their potential of lowering environmental, social and economic impacts.

This paper presents some of the results of the first LCSA iteration for one of the business-as-usual (BAU) reference scenarios that will serve as a benchmark for one of the newly to be developed disruptive solutions.

2. Case study
The three-year H2020 project started in January 2020. The project aims to develop a novel hybrid methodology and breakthrough design tools to assess the reliability of larger critical wind turbine components without the need of building expensive larger test benches in the future. Figure 1 shows the three case studies in which disruptive technologies are being developed for new pitch bearings and gearboxes, and a novel lifetime extension concept for existing pitch bearings.

![Figure 1. Three different case studies of the project.](image)

The LCSA presented in this paper focuses only on the second case study, more specifically on the BAU reference scenario. Case Study 2 (CS2) consists of the development of a next generation gearbox concept, including novel gearing and bearing systems to increase torque density and reliability, to be installed in a 10 MW onshore wind turbine from the year 2030 onwards. The specific life cycle inventory data of the gearbox was provided by Moventas Gears Oy (Finland). The other wind turbine components are based on a 10 MW reference wind turbine [5, 6] with a hub height of 119 m, a rotor diameter of 202 m and a torque density up to a level of 200 Nm/kg.

3. Overall approach

3.1. LCSA Iterations
Three LCSA iterations will be executed within the project. In the first iteration, performed in 2020, BAU reference scenarios (one per case study) were defined and assessed. The aim of these assessments is to set a benchmark and to gain insights in the environmental, economic and socio-economic performance of the different components during the entire life cycle of a wind turbine. The results will serve as a reference in the next LCSA iterations against which the solutions that are still under development will be assessed and compared to. By doing so the LCSA can support the further technological developments by identifying options for improvement with respect to financial costs and impacts to the society and environment.

3.2. LCSA Methodology
The LCSA consists of an environmental life cycle assessment (LCA), a life cycle costing (LCC) and a social life cycle assessment (S-LCA). The LCA, LCC and S-LCA assess the impact on the environmental, economic and social/socio-economic aspects of the wind turbine components, respectively. The ISO standards 14040:2006 [7] and 14044:2006 [8] are applied as the main
methodological framework for the LCSA. In addition to the general ISO 14040/14044 methodology, specific methodologies are applied per sub-assessment of the LCSA which are described in the following subsubsections.

3.2.1. Applied Life Cycle Assessment methodology. For the LCA part of the LCSA, the EN 15804:2012+A2:2019 standard [9] was selected as the additional methodological framework to the ISO 14040/14044 framework. 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, services and processes are derived, verified and presented in a harmonised way.

For this study, the in the EN 15804 so-called information modules A-C are assessed, also known as a cradle-to-grave LCA. The recycled content approach is used with regard to the recycling of waste, which is in line with the EN 15804, meaning that secondary (recycled) materials are burden-free and bear only the impacts of the recycling process. To model and calculate the environmental impacts, the LCA software SimaPro (version 9.1.0.7) [10] and generic life cycle inventory database ecoinvent 3.6 [11] are used. For the selection of environmental impact indicators the EN 15804 is used.

3.2.2. Applied Life Cycle Costing methodology. LCC methodological rules are based on the ISO 15686-5:2008 standard [12] and SETAC “Environmental Life Cycle Costing: a code of practice” [13]. According to Myhr et al. [14], it is advisable to utilize a levelized cost, which is 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, and is often referred to as a Levelized Cost of Energy (LCOE) Analysis [14], a measure for estimating the cost of the electricity that is produced over the life of a generating plant.

For this study, life cycle costs are calculated by using the LCOE approach. 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. This approach is derived from the commonly accepted LCOE model developed by Megavind [15]. The discounted lifetime costs (the numerator) are equal to the present value of all expenditures associated with the wind farm. 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. The cost perspective is the developer’s perspective before tax. The pre-tax developer costs are the sum of the discounted investment expenditures (in the form of development and capital expenditures), operational expenditures and abandonment expenditures.

3.2.3. 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 [16]. It is a relatively new research field and uniform guidelines are still missing. For this study the S-LCA guidelines developed by UNEP/SETAC Life Cycle Initiative in 2009 [17] and their draft update [16] have been followed. 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 [18]. The S-LCA guidelines [17] consider five stakeholder categories: 1) workers; 2) local communities; 3) value chain actors, e.g. suppliers; 4)consumers; and 5) 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. Due to the large number of possible sub-categories and indicators it is common practice in S-LCA to identify and focus on the most important stakeholder groups and sub-categories for the product group.

In this study, the selection of relevant stakeholder categories and sub-categories has been done based on materiality assessments and sustainability reports made available by major European wind turbine
manufacturers. To ensure that no major risks for the sector in question were overlooked, a check was performed on the PSILCA (Product Social Inventory Life Cycle Assessment) database. For the most important sectors in the life cycle of the wind turbine, it was examined which indicators had been assigned a high or very high risk. This exercise has led to a focus on the stakeholder category ‘workers’ and the subcategories ‘fair salary’ and ‘health and safety’.

The calculations were done using the S-LCA database PSILCA v2 developed by Greendelta [19].

3.3. Scope of the LCSA.

The assessed product system is a wind turbine developed, produced, installed, used and decommissioned on the European market. For the LCA and S-LCA the product system boundaries include the tower, nacelle and rotor, but exclude the balance of plant (BOP) (i.e. the foundation, transformer, substation, and new roads to/on the windfarm) due to lack of data. For the LCC the BOP is included.

The functional unit (FU) for the BAU reference scenario of CS2 is defined as “1 kWh of the total electricity output delivered to the grid over the service life of 20 years by a 10 MW onshore wind turbine with a so-called classical Danish design”. The location of CS2 is assumed to be in north Germany with an average wind speed of 9 m/s. Based on the INNWIND EU Costs Model [6] and the assumed wind turbine specifications for CS2, an annual energy production of 46 211 MWh/y is considered for calculating the LCA, LCC and S-LCA results per FU.

4. Results BAU Case Study 2

4.1. LCA results

The results of the LCA of the BAU scenario for CS2 show that, from an environmental point of view, the production stage is the biggest contributing life cycle stage (> 88% of the total life cycle impact) for all impact categories, due to the large amount of materials used in a wind turbine. When analysing the production stage in more detail (see Figure 2), it shows that the main contributing component of the BAU CS2 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.

Regarding the environmental impacts of the BAU CS2 gearbox, the raw materials are also the biggest contributor in the total life cycle impact. This is also true for all impact categories with the exception of the impact category ionising radiation due to the part nuclear energy of the Finish electricity mix.

Figure 2. Relative contribution to the environmental impact of all BAU CS2 components of to the production stage (information module A1-A3) for a selection of the assessed environmental indicators. The absolute values per FU are given between brackets behind each indicator in the vertical axis.
4.2. LCC 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 [13]. The LCOE is estimated at 0.030 €/kWh for the complete life cycle of the wind turbine. The results are expressed in EUR 2019. The LCOE calculation shows that the capital expenditures have the biggest share in the total life cycle costs, of which 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 costs account for 5%.

For the gearbox, 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 (capital expenditure) of the rotor, nacelle and tower. The gearbox operational costs account for 6% of the total maintenance costs of the wind turbine.

4.3. S-LCA results
The S-LCA methodology has been used to identify the potential social impacts of the BAU CS2 wind turbine across its life cycle in the subcategories identified as being important for the product group. The life cycle phases considered in the S-LCA are: production gearbox, production pitch mechanisms, production blades, production electrical system, production of all other wind turbine components, transport to installation, installation, maintenance, decommissioning, transport to end of life, and end of life. Figure 3 shows 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 ‘non-fatal accidents’, ‘fatal accidents’, ‘Presence of sufficient safety measures’, and ‘DALYs (disability-adjusted life years) due to indoor and outdoor pollution’. Maintenance is the most important life cycle stage in the impact categories ‘fair salary’ and ‘workers affected by natural disasters’.

![Figure 3. Relative contribution to the social impact of the different life cycle stages of BAU CS2 for selected impact categories.](image)

For the gearbox production, a more in depth analysis has been made as this is one of the focus areas of the project. The gearbox assembly has the highest contribution in the impact categories ‘non-fatal accidents’ and ‘fair salary’. In the latter category, also the production of the gear materials is important. The production of the gear materials is also important in the impact categories ‘workers affected by natural disasters’, ‘DALYs due to indoor and outdoor air pollution’, ‘safety measures’ and ‘fatal accidents’.

5. Discussion
Overall, an LCSA approach can support decision makers to prioritise resources and investments and to choose sustainable concepts and technologies for future wind turbines. The goal of this LCSA is to assess the BAU reference scenario of which the results can be used for comparing the performance of the solutions that are still under development within the project. Results depend on the scope, input
parameters and assumptions. Therefore one-to-one comparisons to LCSA results of other projects are not possible. For a straightforward comparison of wind farms, the same boundary conditions need to be taken into account.

At the moment of writing, a revision of the BAU scenarios is ongoing, as (generic) data on current testing methods for gearboxes could not be collected yet. Without that data a fair comparison would not be possible between the BAU reference scenarios and the INNTERESTING case studies, in which the impacts due to the hybrid testing methods will be included.

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