Fraunhofer Institute for Wind Energy Systems IWES

Hochschule für Angewandte Wissenschaften Hamburg (HAW – Hamburg)

Faculty Life Sciences, Department of Environmental Engineering

Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.

Fraunhofer Institute for Wind Energy Systems (IWES)

Large Bearing Laboratory

Life Cycle Assessment of Large Structure Mechanical Endurance Tests - Identifying Hotspots and Reduction Potentials

Presented by

Moises Guzman

1st examiner: Prof. Dr.-Ing. Sebastian Timmerberg

2nd examiner: Dr.-Ing. Matthias Stammler

Hamburg, February 2024

Declaration

I hereby confirm that this thesis was written independently by myself without the use of any sources beyond those cited, and all passages and ideas taken from other sources are cited accordingly.

[redacted]

Hamburg, 13.02.2024

Acknowledgements

First and foremost, I express my deepest gratitude to my wife, Nancy. Thank you for taking a leap of faith with me, for supporting me unconditionally and especially for being my perfect match.

My deepest gratitude extends to my family, especially my mother who has been an absolute believer and held my head up in times of doubt. At this point I can only tell you *gracias mamá, lo logramos!* (Thank you, Mom, we made it!).

I would also like to thank the outstanding professors of the Faculty of Life Sciences at the Hamburg University of Applied Sciences, your dedication to sharing your knowledge shall never go unnoticed from my side. Thank you for helping me to continue developing my analytical thinking and problem solving abilities. I am particularly grateful to Prof. Dr. Ing. Sebastian Timmerberg for the time and effort you have invested in ensuring the quality of my work.

I am extremely grateful to Fraunhofer IWES for allowing me the opportunity to work with such an exceptional research team. My gratitude extends to each of my colleagues at the Large Bearing Laboratory, I can guarantee you have set a really high standard for team excellence. I will carry with me the invaluable experiences gained during my time in the team. Matthias, thank you for your belief in me since day one. Working alongside you has been an honor and I am genuinely grateful for the support and guidance you provided. You are a role model of an excellent professional with a golden heart. I would also like to thank Claudia Rudolph and Hendric Schäfer for believing in the potential impact of my research and for providing vital information for it.

I am also grateful to Adil Aslam, Ramses Bermudez and Iria Alvarez; I can never be thankful enough with life for crossing our paths. I am also grateful to Jahanzeb Tariq, thank you for your kindness, selfless support and for sharing your life cycle assessment knowledge with me.

I would not be able to close my acknowledgments without thanking all the friends and colleagues who have come across my path in the last couple of years. You have definitely made the journey lighter and more enjoyable.

Table of contents

List of abbreviations

aLCA	Attributional life cycle assessment
BEAT	Bearing Endurance and Acceptance Test rig
CFP	Carbon footprint
cLCA	Consequential life cycle assessment
CMFD	Condition monitoring and fault diagnosis
$CO_{2\text{-eq}}$	Carbon dioxide equivalent
DRI	direct reduced iron
EL1	Europe location 1
EL2	Europe location 2
EOFP	Photochemical oxidant formation potential: ecosystems
EoL	End of life
FEP	Freshwater eutrophication potential
FETP	Freshwater ecotoxicity potential
FFP	Fossil fuel potential
GHG	Greenhouse gases
GWP	Global warming potential
HOFP	Photochemical oxidant formation potential: humans
HTPc	Human toxicity potential: carcinogenic
HTPnc	Human toxicity potential: non-carcinogenic
IPCC	Intergovernmental Panel on Climate Change
IRP	Ionising radiation potential
ISO	International Standard Organization
JRC	Joint Research Center
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LOP	Agricultural land occupation
MEP	Marine eutrophication potential
METP	Marine ecotoxicity potential
NMVOCs	non-methane volatile organic compounds
NREL	National Renewable Energy Laboratory

NZE	Net zero emissions
ODP	Ozone depletion potential
OEF	Organizational environmental footprint
O-LCA	Organizational life cycle assessment
PLCA	Product life cycle assessment
PMFP	Particulate matter formation potential
SALCOS	Salzgitter Low CO_2 Steelmaking
SETAC	Society of environmental toxicology and chemistry
SGRE	Siemens Gamesa Renewable Energy
SOP	Surplus ore potential
TAP	Terrestrial acidification potential
TETP	Terrestrial ecotoxicity potential
TS	Technical specifications
UNEP	United Nations Environment Programme
WCP	Water consumption potential
WES	Wind energy systems

List of figures

List of tables

1. Introduction

The pitch system, a critical component in wind turbines, adjusts the angle of the blades to control the power output and protects the turbine during high wind speeds. Bearings play a vital role in the pitch system, ensuring smooth operation and longevity of the wind turbine. It is also important to mention that the replacement of a pitch bearing of a large offshore wind turbine comes at costs far above one million euro. Therefore, conducting endurance tests on pitch system bearings is essential for guaranteeing the reliability and efficiency of wind turbines. The Large Bearing Laboratory (LBL) at Fraunhofer IWES specializes in testing bearings for pitch systems in state-of-the-art wind turbines. Real-sized machine elements are manufactured, and their endurance is tested under special conditions over a prolonged period of time in the BEAT 6.1 (Bearing Endurance and Acceptance Test rig).

Fraunhofer Society is working towards becoming climate-neutral by 2030. The present study is the first effort from the LBL, one of the test labs of the Fraunhofer Institute for Wind Energy Systems, to quantify its current environmental impact footprint, and more importantly, to be able to identify and understand the hotspots, which are the stages or processes that contribute most significantly to the environmental burdens of the organization and its product. This study explores initial actions that could lead to a better performance on the environmental footprint, enabling the management to make well informed decisions regarding the allocation of resources and implementation of strategies for reducing its environmental impacts.

The present thesis opens with a literature review that provides a theoretical basis for this study, followed by the methodology used in it. In the next two chapters, two case studies are developed; a product life cycle assessment (PLCA) and an organizational life cycle assessment (O-LCA).

Interesting for the LBL is to understand how the environmental footprint of its activities is composed, and the share arising from the large structure testing activities and from the operation of its office, and also to identify preliminary actions that could lead to a reduction in them. This is particularly important because multiple research facilities of the Fraunhofer Society share similarities, meaning that the results found in the analysis of the LBL could also apply to other locations that conduct long term testing activities of large structures.

After 2020, new test rigs have been built in the LBL, they are of smaller size but follow the same principles as the BEAT 6.1. This study aims to be the cornerstone on which the LBL will continue to build on its environmental impact studies, on both organizational and on the product level through the implementation of performance tracking. To the knowledge of the author, there are no studies that either focus on identifying the environmental hotspots of large structure testing or propose measures that could lead to a reduction in environmental emissions. Therefore, this study aims to address this knowledge gap. To conclude this thesis, a thorough analysis of both case studies is developed, and finally, the conclusions are presented.

2. Literature Review

2.1. Life Cycle Assessment (LCA)

2.1.1 Overview of LCA

Even though the number of countries pledging to reach Net-Zero Emissions (NZE) by 2050 has risen, the total greenhouse gases (GHG) emissions have also grown. Closing the gap between rhetoric and real actions is imperative to still have a chance of reaching NZE and to limit global warming to 1.5°C (IEA, 2021a).

Life cycle assessment (LCA) is a tool used to assess the environmental impacts of a product, process, or activity during its entire life cycle. It considers the life cycle from the extraction of the raw materials to the End-of-Life management (EoL). LCA methodologies propose a systematic approach to identify and quantify the different environmental burdens associated with each life stage of the complete life cycle of the analyzed product or process.

Life cycle assessment finds its modest origins in the 70s and 80s. A decisive and progressive phase came in 90s when the Society of Environmental Toxicology and Chemistry (SETAC) managed to harmonize different methods and published the guidelines for life cycle assessment: A code of practice. Further standardization came with the International Standard Organization (ISO) with the ISO 14040 and its accompanying norms and technical specifications (TS) (Klöpffer & Grahl, 2014, pag. 11).

2.1.2 LCA Framework. ISO 14040 and ISO 14044

According to ISO in the norm ISO 14040 (2006a), life cycle assessment (LCA) is a technique which can help in better understanding the environmental impacts associated with products across all life stages by:

- Identifying opportunities to improve the environmental performance of products at various points in their life cycle.
- Informing decision makers in industry, government, and non-government organizations.
- Selecting relevant indicators of environmental performance, including the measurement techniques.
- Marketing (ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).

ISO 14040 is not a methodology as such, instead it details the principles and framework for conducting an LCA (ISO, 2006a), it provides the LCA practitioner a guideline of what needs to be done and what should not be done. ISO 14044 is a more detailed norm that focuses on the requirements and operational guidelines for performing an LCA study in each of its phases (ISO, 2006b).

There are four phases in an LCA study as shown on Figure 1 (ISO, 2006a), where it can be appreciated that each stage has arrows going in and out, this is due to the iterative nature of LCA. A brief description of each phase is provided below.

1. Goal and scope definition: firstly, the objectives need to be defined; what is the purpose of performing the LCA and how are the results intended to be used and with whom they are to be shared. Second, the function of the systems needs to be analyzed and a unit that represents this function needs to be defined; this is known as functional unit. Finally, the system boundaries need to be described (Jolliet et al., 2015, pag. 7 and 23).
2. Inventory analysis phase: here, the polluting emissions to the environment are quantified. The usage of renewable and non-renewable raw materials is also analyzed. The various flows of material extractions and substance emissions crossing the system boundary need to be quantified (Jolliet et al., 2015, pag. 7 and 47).
3. Impact assessment phase: Also known as life cycle impact assessment (LCIA). During the LCIA, the results obtained in the inventory phase are used to evaluate the environmental impacts. This is done by classifying the emissions into different impact categories, which are then characterized into midpoint impacts and finally to damage categories (end point). There are multiple methods to conduct an LCIA and none is standard. Some LCIA methods are the IMPACT 2002+, ReCiPe 2016 (Jolliet et al., 2015, pag. 7 and 105) (Jolliet et al., 2003) (M.A.J. Huijbregts et al., 2016).
4. Interpretation phase: LCA is an iterative process, it should be applied throughout each phase, nevertheless, the last phase of the LCA is the exhaustive analysis and interpretation to identify the stages and processes at which intervention can substantially reduce the environmental impacts of the systems or product. This phase should provide clear and usable information for decision-making (Jolliet et al., 2015, pag 8 and 149).

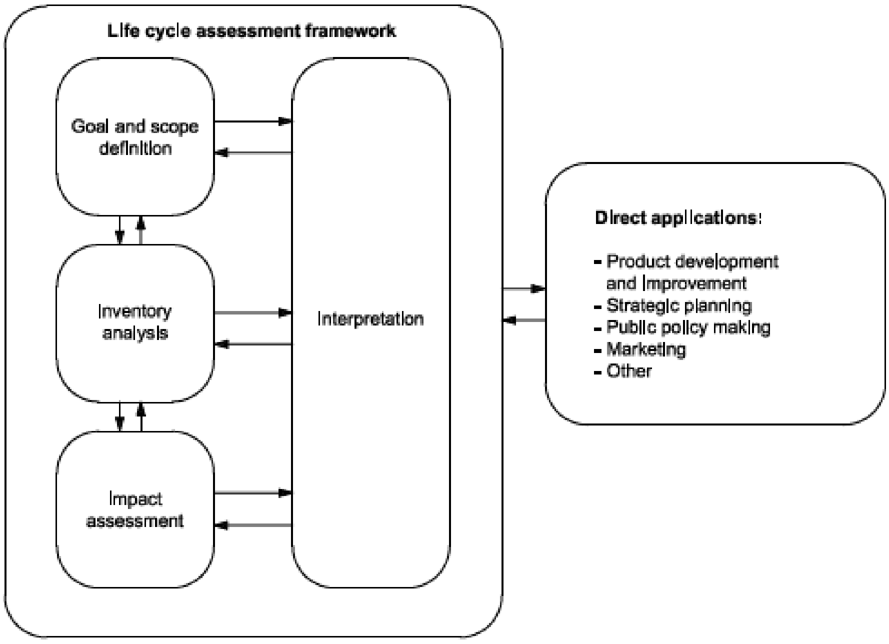

Figure 1. Stages of an LCA (ISO, 2006a).

2.1.3 Functional Unit

Once the goal of the study has been set, the function of the service or product needs to be defined. This is complicated since one product can have multiple functions (in that case, the most important function and the secondary ones should be identified) and one same function can be achieved by more than one system (Jolliet et al., 2015). It is important to define the system function as clearly as possible because it is the basis for determining the functional unit and the system boundaries.

The functional unit is a quantified description of the function of a product that serves as the reference basis for all calculations regarding impact assessment, or in other words, is the reference unit to analyze the system. Arzoumanidis et al., 2020 found that mass, energy, and volume are among the most used functional unit among LCA practitioners. In this study, it is also discussed that the required attention is not always given to the definition of the functional unit, not even in peer reviewed publications.

The functional unit is also important in terms of comparison and communication since it provides a common basis for comparison of different products or for doing performance tracking of one product over time. It also enables easy and clear communication of the LCA results to the stakeholders of the organization.

2.1.4 System Boundaries

After defining the functional unit, the LCA practitioner needs to define the system boundaries. This process implies limiting which unit processes, activities are to be analyzed in the LCA and which fall outside of the scope of it. The product system needs to be defined as models that describe the key elements of the physical system (ISO, 2006b). According to the Greenhouse Gas Protocol, when setting the boundaries, companies should follow the 4 steps (2011):

- Identify the attributable processes along the life cycle that are directly related to the analyzed product.
- Group these processes into life cycle stages (material acquisition and pre-processing, production, distribution, use, and EoL).
- Identify all material and energy flows for each process.
- Illustrate the product life cycle processes through a process map.

Companies have the flexibility to choose between cradle-to-gate and cradle-to-grave approach for establishing the boundaries of the LCA study, however, it is important that the decision of which approach to follow is properly detailed and justified (Greenhouse Gas Protocol, 2011). The difference in the scope of each option is that cradle-to-grave considers the scope three downstream environmental impacts, that means the impacts occurring during the use and EoL phases, as shown in Figure 2 (see Section 2.1.5).

As a general guideline, final products shall include the complete life cycle (cradle-to-grave) (Greenhouse Gas Protocol, 2011), providing a more comprehensive understanding of the product's environmental performance across its complete life cycle . On the other hand, cradle-to-gate is more appropriate when the main goal is evaluating the production of manufacturing phase of a product, that is why more recent guidelines, which are focused on product LCA or product carbon footprint, recommend using the cradle-to-gate approach (Together for Sustainability, 2022) (BASF SE, 2021).

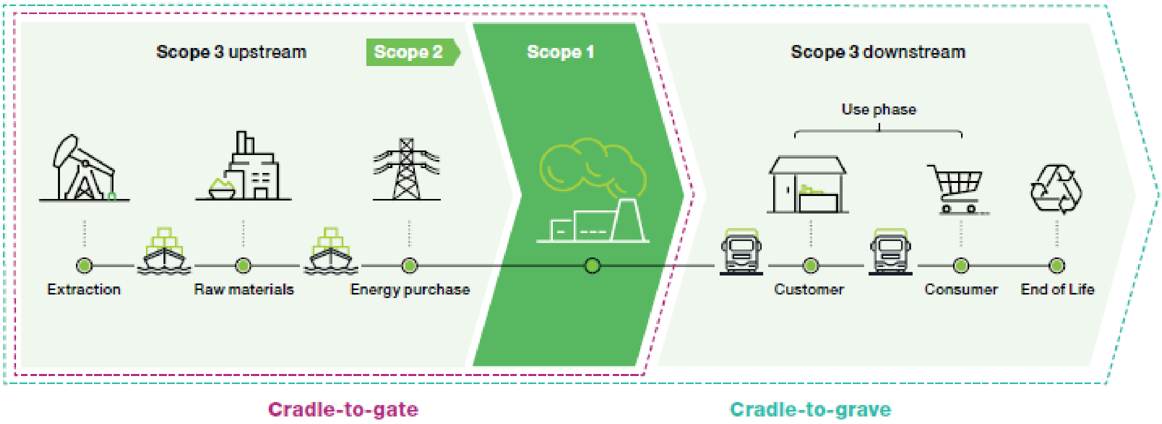

Figure 2. System boundary definition (Together for Sustainability, 2022).

ISO 14044 presents three cut-off criteria that can be followed (mass, energy and environmental significance) (ISO, 2006b), nevertheless concrete values are not provided. Guidelines as the ones from Together for Sustainability (2022) and BASF SE (2021) provide values that LCA practitioners can follow:

- Mass: all material inputs that make up at least 95% of the total mass inputs to the unit process shall be included. Although 98% is recommended to avoid uncertainties.
- Energy: similarly, to mass, at least 95% of the total energy input to the unit process shall be included, nevertheless 98% is recommended to improve the completeness of the calculation.
- Environmental significance: input materials that have a considerable upstream environmental footprint should be considered for the calculation, regardless of the total percentage of the total mass.

2.1.5 Definition of Environmental Impacts Scopes in LCA

Even though these definitions are not present in the ISO norms, the definitions of scope 1, scope 2, scope 3 upstream and scope 3 downstream are very broadly used among LCA practitioner, they can be appreciated in Figure 2. A brief explanation of each of them is provided below (Greenhouse Gas Protocol, 2004).

- Scope 1: refer to the environmental impacts deriving from activities owned or controlled by the assessed organization, in other words, these are the impacts produced from activities within the organization’s boundaries.
- Scope 2: are the environmental impacts associated with the generation of purchased or produced electricity, heat and/or steam consumed by the organization.
- Scope 3 upstream: are the indirect environmental impacts occurring in the supply chain before the products or raw materials reach the organization’s boundaries.
- Scope 3 downstream: refer to the indirect environmental impacts occurring in the value chain after the product leaves the organization boundaries. These are associated with the use phase, distribution and EoL management.

2.1.6 Attributional Life Cycle Assessment (aLCA)

When defining the scope of the LCA, two different approaches can be followed: attributional and consequential assessment. The distinction is important in terms of system boundaries, data collection, and allocation.

As defined by Finnveden et al., 2009 , attributional LCA focuses on describing the environmentally relevant physical flows from and to a life cycle and its environments. In other words, an aLCA focusses primarily on assessing the current or existing environmental performance of a production system. It aims to quantify the inputs and outputs associated with each life cycle stage with the objective of providing a detailed inventory of the environmental burdens associated with the production, use, and disposal associated with the reference flow under the existing conditions. Typically, upstream supply is assumed to be fully elastic. The induced demand for one unit of product leads to the production and supply of one unit of product (Rebitzer et al., 2004).

One of the main characteristics of attributional LCA is the use of average data in the modelling of subsystems of the life cycle, which is the data representing the average environmental burdens for producing a unit of the product in the system.

2.1.7 Consequential Life Cycle Assessment (cLCA)

Consequential life cycle assessment is defined by its aim to describe how environmentally relevant flows will change in response to possible decisions, unlike aLCA, which tries to assess the system or product as it currently is. The cLCA focusses on analyzing the potential environmental impacts of different scenarios, choices, or policy changes. In contrast to aLCA, cLCA uses marginal data, which represents the effects of a small change in the outputs of products from a system on the environmental burdens of the system (Ekvall & Weidema, 2004).

Another contrast to aLCA comes from the system boundary definition. In a cLCA the main goal is to assess the changes in the environmental burdens coming from a change, so the system boundaries include those processes that are deemed to contribute significantly to the studied product or function. Processes and activities that stay the same and don’t represent a change in the burdens may be left out of the scope (Rebitzer et al., 2004).

2.1.8 Limitations and Challenges in LCA Studies

2.1.8.1 Data Acquisition and Quality

According to Rebitzer et al. (2004) compilation of required data is one of the main difficulties an LCA practitioner may encounter. Companies do not always compile environmental data, and if they do, they tend to do it on an organizational level rather than a functional level. Another difficulty comes from the lack of measurements of relevant points of information, for example, the electricity consumption of a single process.

New guidelines and methodologies for LCA or carbon footprint (CFP) strongly recommend pursuing the highest level of data quality so the assessment can be applicable and meaningful. If available, primary data should be used, this refers to data from specific processes in the studied product’s life cycle that are under control of the organization (Together for Sustainability, 2022).

Secondary data, which is defined as data that are not directly collected, measured, or calculated based on specific production data available for the organization, shall be used only where the collection of primary data is not practicable or for processes with minor importance or for processes where for some reason, secondary data provides higher quality than primary data. Secondary data includes industry averages, estimates based on literature, associations, published production data, government statistics, patents or any other generic data (Together for Sustainability, 2022).

It is possible that the LCA practitioner encounters data gaps, where no primary or secondary data that is sufficiently representative of the a given process is available, nevertheless it should be possible to obtain enough information to provide a reasonable estimate.

2.1.8.2 Involvement and Collaboration of Multiple Actors

The system boundary usually consists of a large number of unit processes, thus, the involvement and collaboration of many processes responsible, from inside and outside the organization, is necessary (Rebitzer et al., 2004). This type of communication most likely falls outside the regular business information flow of many actors, so requests might be overlooked or take a longer time to process.

2.1.8.3 System Boundaries and Scope Definition

Defining the system boundaries and scope of the LCA study can be challenging. Decisions regarding what to include and what to exclude from the analysis can have a significant impact on the results. Setting the boundaries too narrow might lead to an incomplete analysis, while overextending the boundaries might introduce too much uncertainty and complexity to the assessment. It is also important to take the available resources into account.

Baumann and Tillman discussed about how ideally, all inputs and outputs of a system should be traced upstream and downstream until all elemental flows of materials and energy have been considered, nevertheless, the decision of considering or not certain processes (cut-off criteria) are usually done in practical, rather than scientifical, considerations (Baumann & Tillman, 2004).

2.1.8.4 Simplifications and Assumptions

Simplifications and assumptions are often made to handle complex systems and uncertainties, nevertheless they can introduce limitations, potential biases and can also influence the results, therefore it is necessary to carefully check the assumptions and their consequences on the results of the study. Special care is necessary during the interpretation phase and with the communication of the results (Jolliet et al., 2015).

2.1.8.5 Static or “Snapshot” Assessment

According to Hammond et al. (2015) LCA methodologies rely on data and assumptions based on the technology that prevails at that time, this complicates the assessment for forecasting.

2.1.8.6 Spatiotemporal Analysis

Current LCA methodologies are still very limited in considering the variability of environmental impacts across different regions and in examining how these impacts change over time.

According to Jordaan et al. an approach that consider these factors would provide more relevant and robust results (2021)

2.1.9 Software and Databases

Preliminary calculations, for example energy consumption and CO_2 emissions, can be done by hand, but the complete life cycle assessment studies involve the use of large amounts of data which usually translate into tedious hand calculations (Jolliet et al., 2015). Over the last years, many different software to simplify this task have been developed.

Some of the most commercially used software are:

- OpenLCA: open source and free software for sustainability and LCA, it offers a well detailed insight into calculations and the analysis of the results. It offers the possibility of using free and licensed databases and multiple impact assessment methods (OpenLCA, 2022).
- SimaPro: commercial software developed specifically for LCA studies with over 30 years in the market. SimaPro also offers the possibility of using a wide range of databases and impact assessment methods. SimaPro is known for its advanced modelling features and ability to handle complex LCA projects (SimaPro, 2023).
- GaBi: commercial software developed by Sphera Solutions; it is also specially designed to conduct LCA studies. It provides a comprehensive set of tools for modelling, analyzing, and optimizing product life cycles. It also offers a wide selection of databases, from which their sector specific databases have become very attractive for LCA practitioners (Sphera Solutions, 2023).
- Umberto: commercial LCA software, it has integrated the ecoinvent and Carbon Minds databases. Umberto states to be a high performance and easy to use software. The LCA practitioner might choose between the most common LCA methods (iPoint, 2023).

As mentioned in section 2.1.8, obtaining high quality data is of high importance and obtaining primary data is not always possible, therefore databases play a crucial role in LCA studies. These databases offer multiple benefits including reliable and periodically updated information. On 2011, the life cycle initiative of the United Nations Environment Programme (UNEP) published a document which provides guidance principles for LCA databases, including how to collect raw data, how to develop databases, and how to manage them (UNEP, 2011).

Among the LCA databases, ecoinvent is widely accepted as the most popular and widely used database. At its beginnings, the project aimed to combine and enhance different existing databases to obtain unified and high quality data sets (Jolliet et al., 2015). In 2016, Wernet et al. praised how ecoinvent had managed to reach its goals of stablishing a robust, flexible data system for the management of an inventory database, the support for regionalized LCI data and LCIA, complex supply chain and increased transparency.

ecoinvent offers a comprehensive, constantly updated and expanding database. It currently contains more than 18,000 activities (also known as datasets) covering a wide range of sectors. One advantage of the ecoinvent database is that it attributes a geographic location to each of its activities and aims to cover activities in the most relevant geographies for the selected product or service. This database also provides the life cycle impact assessment (LCIA) scores for different impact assessment methods (ReCiPe 2016+, IMPACT 2002+, IPCC 2021, etc.) and corresponding impact categories (ecoinvent).

2.1.10 LCA of Energy Systems

It is important to maintain consistency across system boundaries if different energy systems are to be compared. It is common but not standard that energy sector LCA follow a cradle-to-gate system boundary (Jordaan et al., 2021); this enables the LCA practitioner to compare the scope 3 upstream environmental burdens associated with the analyzed energy systems (Hammond et al., 2015). It is worth noting that cradle-to-gate refers to the product electricity being delivered to the client and leaving out of the scope of the analysis the impacts associated with the use by the client; aspects such as end of life management and recycling of components are taken into account in this system boundaries definition. In Figure 3, a diagram that illustrates the system boundaries for energy systems is shown (Jordaan et al., 2021).

Hammond et al. also note the well-defined and understood state of the initial stages of LCA studies for energy systems (goal and scope definition and inventory analysis), but also mentions the subjective state of the later stages such as normalization and weighing, which usually leads problems when the results of the impact assessment are interpreted.

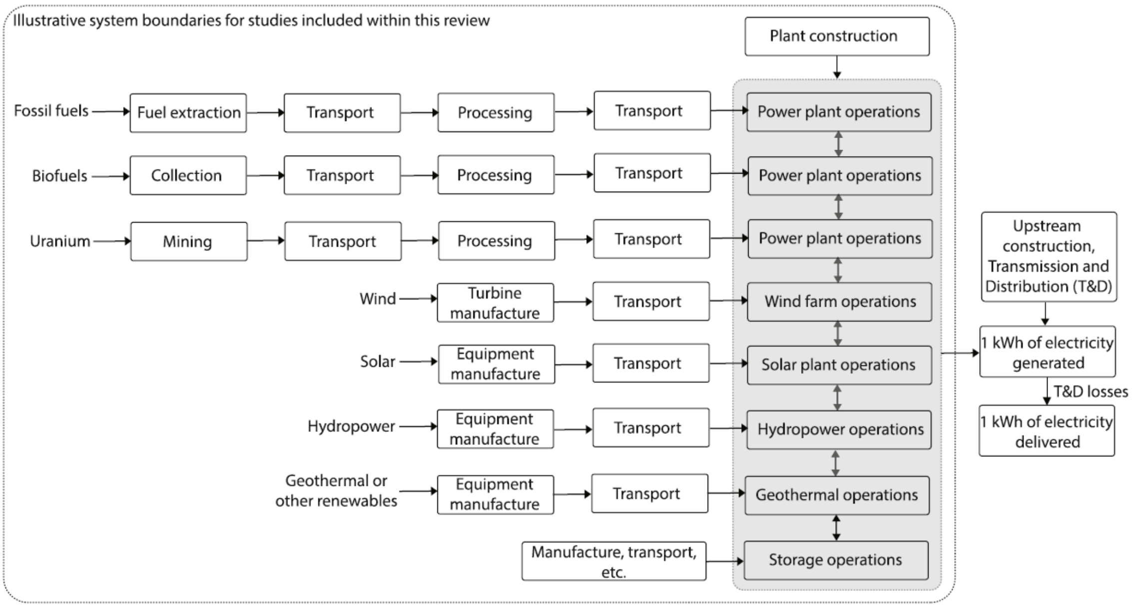

Figure 3. Common system boundaries for different electricity generation systems (Jordaan et al., 2021).

Jordaan et al. noted the current limitation that LCA studies of energy systems tend to heavily weigh the impact categories towards the greenhouse gas emissions and focus less on impacts such as eutrophication and land use (2021), although they noted that the trend seems to be slowly changing over time. In their study, they also addressed the pressing spatiotemporal limitations that many LCA practitioners have previously discussed; even though they noted that between 2009 to 2018 the employed methodologies have evolved to start considering these factors in the fields, there is no apparent event triggering patterns of evolution in the field, other than the growing number of studies on climate change.

In a more recent publication, M. A. Parvez Mahmud et al. (2023), conducted a thoroughly review of LCA studies for renewable energy projects, they concluded that replacement of fossil fuel by renewables is of paramount importance and the selection of the technologies needs to align with the renewable resources but also on the LCA studies for each technology in each geographical location. They also note on the knowledge gap of life cycle inventory databases still not focusing on renewable energy technologies all over the world.

2.1.11 Carbon Footprint (CFP)

Carbon footprint is defined in ISO 14067 (2018) the sum of GHG emissions and GHG removals in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using the single impact category of climate change. And the mentioned norm specifies principles, requirements, and guidelines for the quantification and reporting of CFP in a consistent manner with ISO 14040 and ISO 14044.

Since CFP is a ramification of LCA, it shall include the same four phases of LCA. The same process to describe a goal and scope definition must be followed (ISO, 2018). A functional unit must be clearly defined as so the system boundaries. CFP methodologies suggest paying special attention to the scope 3 upstream emissions (Greenhouse Gas Protocol, 2011).

2.2. Organizational Life Cycle Assessment (O-LCA)

2.2.1 Overview of O-LCA

Until the early 2010s, there were no methodologies that integrated the organizational, life cycle, and multi-criteria approach. The two main methodologies with broader acceptance among LCA practitioners are the organizational environmental footprint (OEF) and the organizational life cycle assessment (O-LCA) (Rimano et al., 2019). The first one was developed by the Joint Research Center (JRC) and other bodies of the European Commission and aimed to develop a technical guide for calculating the environmental footprint of organizations while increasing the reproducibility and comparability of the studies, emphasizing the principle "comparability over flexibility" (European Commission, 2013). The second, the O-LCA, is the methodology regulated by the ISO/TS 14072. It is described more comprehensively in the publication *Guidance on Organizational Life Cycle Assessment* developed by the United Nations Environment Programme (UNEP), which provides requirements and additional guidelines to make the implementation easier and more effective (Martinez-Blanco et al., 2016).

According to ISO/TS 14072, the benefits and potentials of the life cycle assessment approach are not limited to an application in products (2014). O-LCA uses an LCA perspective to evaluate the inputs, outputs, and environmental impacts associated with the overall operation of an organization. O-LCA is designed to be applicable by organizations of various sizes, different geographical locations and is able to be used by public and private sectors across different industries (UNEP, 2015). The ultimate aim of O-LCA is to reduce the impacts of the organization activities on all aspects of the environment or to find an appropriate balance between those aspects while preventing trade off or shifting of burdens (UNEP, 2015).

2.2.2 O-LCA Framework: ISO/TS 14072 and UNEP Guidance on O-LCA

O-LCA is a methodology that allows the compilation of the inputs, outputs, and environmental impacts of the activities associated with an organization according to a life cycle approach (Martínez-Blanco et al., 2019). According to Finkbeiner and König (2013) the vast majority of the requirements (“shalls”) in the ISO 14044 are applicable in both product and organizational level. The ISO technical specification 14072 provides additional requirements and guidelines to effectively apply the ISO 14044 and 14044 norms to organizations (ISO, 2014). The guidance on O-LCA published by UNEP (2015) is intended to be a detailed accompanying document to ISO/TS 14072 and strives in aligning to it.

One of the main differences between O-LCA and product LCA is the goal and scope definition. While on the product LCA the clear definition of a functional unit was necessary, O-LCA requires the definition of its counterpart, the reporting unit. There is also a difference in the system boundary definition, since organizations are ultimately embedded in networks of social, financial and physical relationships, it is necessary to define a boundary that formally defines which of these relationships are to be considered (UNEP, 2015).

It is important to mention that ISO/TS 14072 explicitly states that organizational LCA results shall not be used for comparative assertions between different organizations intended to be disclosed to the public, for example, to create a ranking system to compare the organizations that perform better in comparison to others.

2.2.3 Reporting Unit

The reporting unit is defined as the quantified performance expression of the organization under study to be used as a reference (ISO, 2014). In contrast to product life cycle assessment, measurements like mass, volume, or units are not suitable reporting unit to take as a reference, since a suitable reporting unit should allow to track and consistently compare the organization’s environmental performance over time (based on the same time period, system boundary and reporting unit) (Marx et al., 2020). The Guidance on O-LCA (UNEP, 2015) provides further information on how the reporting unit should be stated. UNEP proposes that the reporting unit is broken down into two elements:

- Reporting organization: this is comparable with the functional unit and the main purpose is to define the unit of analysis. In this section, it is necessary to define the name and description of the organization (or subject of study) and the consolidation method; these factors answer the question “who is the organization under study?”. To complete this section, a reference period must be stated.
- Reporting flow: is the measure of the outputs of the reporting organization. It is the quantitative amount and constitutes the basis of completion of the inventory of O-LCA. The main purpose of it is to link the different units in the value chain with the portfolio of the reporting organization and should answer the questions “what?”, “how much?”, “how well?”, “how long?”.

The consolidation method refers to the process of aggregating the environmental impacts across its various activities, processes, and products. This is especially important for bigger and complex organizations, where the subject responsible for environmental impacts is ambiguous. UNEP (2015) proposes to use one of the three following consolidation approaches:

- Financial control
- Operational control
- Equity share

If the organization wholly owns and controls all its units, the reporting organization will be the same, regardless of the approach used.

2.2.4 System Boundaries

The main requirements to define the O-LCA system boundaries can be applied similarly to the product LCA, nevertheless the approach is slightly different. For the O-LCA the value chain considers the upstream and downstream organizations' operations/processes/activities involved in the production of the product portfolio of the reporting organization, while also considering the raw materials and energy consumption (UNEP, 2015). This is very significant, because the indirect impacts can be as, or more significant than the impacts occurring within the organization physical boundaries.

A distinction needs to be made when the reporting organization is the entire organization, a brand of the organization, or just one facility of the organization.

Similar to product LCA, cradle-to-gate and cradle-to-grave approaches might be used. In accordance with ISO/TS 14072 (ISO, 2014), a cradle-to-grave approach should be used if products directly consume energy or generate emissions during the use phase, for example, automobiles, aircrafts, power plants, or indirectly consume energy or cause emissions during the use phase, for example washing and drying, food that requires cooking or refrigeration. Challenges arise when the modeling of downstream emissions is not feasible and the final fate of the products at the end of life needs to be assumed.

If the organization has no influence on the use and end of life stage of its products, it may select the cradle-to-gate perspective.

2.2.5 State of the Art in O-LCA

Rimano et al. (2019) conducted a research to define the state of the art in life cycle approaches for the environmental impact assessment of organizations, here, they stated the main weaknesses and strengths that have emerged in O-LCA, as presented in Table 1. main weaknesses and strengths identified by .

Even though Rimano et al. study was published in 2019, they publication does not consider the results of the road testing on O-LCA which were presented by Martínez-Blanco et al. in the same year.

The project R*oad Testing Organizational Life Cycle Assessment Around the World* was a flagship project which followed the publication of the *Guidance on Organizational Life Cycle Assessment* from the UNEP (2015). During the following two years, the road testing project accompanied 12 organizations in the conduction of O-LCAs. Companies from four regions of the world, different sizes and industries took place. The main objective of the road testing project was to complement the O-LCA guidance through the road testers experience and to deliver advice to future practitioners and inspiration to future method developers (Martínez-Blanco et al., 2018).

Table 1. main weaknesses and strengths identified by Rimano et al., 2019

Weaknesses	**Strengths**
Difficulty to categorize the organizational activities and to gather all the data necessary to conduct the assessment, especially because some indirect activities were not previously considered in the system boundaries in product LCA.	The methodology allows to gain a complete view of the analyzed system, and to identify the hotspots while avoiding burden shifting.
The lack of necessary data on the LCA databases, both for the inventory phase and for the impact assessment phase. This is also due to the omission of some activities and processes until the organizational approach emerged.	A higher level of collaboration with the supply chain actors is achieved, potentiating the relationships, the quantity and quality of data collected.
For industry that have a very broad catalog of products, the selection of a representative product might not really be representative in the event that product variations are significant even in the same product family.	Previous experience with other environmental assessment tools is beneficial when applying the organizational approach.

On 2019, Martínez-Blanco et al. published the paper *Challenges of Organizational LCA: Lessons Learned from Road Testing the Guidance on Organizational Life Cycle Assessment* in which the key challenges that arose on the road testers' study cases are discussed. Table 2 presents a small description of these challenges. A clarification is done by the authors that each study case proved to be different, thus they are not to be assumed as a complete overview of all possible challenges.

Table 2. Main challenges identified during the O-LCA road testing. Adapted from Martínez-Blanco et al., 2019.

Category	**Identified challenge**	**Description**
Challenges in the goal and scope definition	Delineating the reporting organization	Definition of the unit of analysis and subject of study that is consistently delimited is challenging. The consolidation method was not always straightforward.
	Selecting the reporting flow	The reporting flow is an independent part of the scoping phase along with the reporting organization, which is the subject of study to be used as a unit of analysis. The main difficulty arises when an organization has several

	Setting system boundary	products or family products and needs to choose a representative product or family of products to proceed with the assessment. O-LCA offers flexibility in the system boundary so it aligns better with the goal and scope of the study, and it states that the “system boundary shall be defined to include direct as well indirect resource use and emissions”. Challenge arises when deciding which processes should be included and which should be omitted from the analysis.
Challenges in the inventory phase	Categorization and grouping of activities	Practitioners deal with large amounts of inventory data. For data collection, calculation, and interpretation, it is useful to categorize inventory data and to group or aggregate those categories. Difficulties arise especially for higher organizations in the categorization of indirect, EoL and particular activities.
	Inventory modelling and data collection	Mapping the data needed and effective data collection also proved challenging. LCI databases, for example ecoinvent, still do not include datasets regarding supporting activities.
Challenges in the impact assessment and interpretation phase	Local impact assessment	One difference to product LCA, is the fact that direct impacts occur at known locations. There might be the case that these impacts might seem irrelevant if the upstream impacts are much higher, nevertheless they could still be hotspots and a key area of concern for local stakeholders.
	Scoping performance tracking	Performance tracking is defined as a comparison of the performance of the same organization’s products and operations over time, based on a consistent reference period, system boundary and reporting organization. This means that comparability needs to be assured over years.
	From results to action	Interpretation of the results of an O-LCA is a key step. Due to that, enough time should be allocated to it, nevertheless, since it is usually addressed at the end of the process, it is often performed with haste.

Even though Martínez-Blanco et al. explicitly state that each O-LCA study will face its own challenges, it can be seem that these challenges tend to align with the main weaknesses that were simultaneously identified by (Rimano et al., 2019) in their own research. These challenges and weaknesses might define the main knowledge gaps present in O-LCA to this date.

2.3. Wind Energy Systems (WES)

Wind energy has become a prominent and vital renewable energy source. According to the IEA, in 2021, wind electricity generation totaled 1870 TWh, increasing by a record 273 TWh in one year (17% increase) (IEA, 2022). However, greater efforts are needed if the NZE by 2050 plan is to be reached. According to it, approximately 8000 TWh of wind electricity generation should be reached by 2030 (IEA, 2021b). WES are becoming more competitive each year. By 2022, costs had declined by 18% for onshore and 40% for offshore since 2015 and further reductions are expected by 2030 (IPCC, 2022).

According to the last IPCC Assessment Report (AR6) (2022), offshore wind has a higher potential than onshore because wind is stronger and less variable in open sea. Nevertheless, offshore is more expensive because of higher cost for construction, maintenance, and transmission (Bosch et al., 2018).

2.3.1 Environmental Impact of WES

According to the last IPCC Assessment Report (AR6) (2022), wind power plants pose a relatively low environmental impact, but sometimes locally significant ecological effects. The main impacts, including CO_2 emissions, are concentrated during the manufacturing, transport and building phases, and in disposal as EoL is reached. The operation per se does not produce significant waste or pollutants. Other local environmental impacts that might be affected are animal habitat and movements, biological concerns, health concerns, and bird and bat fatalities from collisions with rotating blades, nevertheless solutions to these have been studied in the last years (Michael L. Morrison & Karin Sinclair, 2004).

As previously mentioned in Section 2.1.10, energy systems are commonly analyzed following a cradle-to-gate approach; wind energy systems are not the exception, and they usually consider the following life stages (Yang & Chen, 2015):

- Transportation
- Construction
- Operation
- Dismantling of the system

On (2013) Oebels and Pacca studied the emissions of a 141.5 MW wind farm in Brazil, their study showed that more than 50% of the emissions come from the manufacturing of the tower, and the whole production phase accounted for over 90% of them. On the other hand, only around 6% came from the component's transportation.

Since most of the environmental impacts come from the production phase, efforts on reduction of environmental impacts through recycling have also been made. In 2012, Ghenai stated that a net reduction of 55.4% CO_2 emissions was possible through recycling of the wind turbine materials at the end of the wind turbine's life cycle. This was confirmed in 2014 when Uddin and Kumar analyzed the effect of the reuse of material strategy, and found that a reduction of nearly 50% of the environmental impacts was possible.

On 2012, Davidsson et al. found great variation between the environmental impacts results of different studies. Therefore, they addressed the need to discuss how the assessment process for renewable energy resources should be done, more specifically, the assessment for environmental impacts, energy performance and natural resources use. His critique was not towards the ISO methodology or to any LCA practitioner but to the lack of transparency regarding fundamentals and underlying assumptions, and calculations done in LCA. The author of the present work identified some of the assumptions that more recent LCA on WES are the following (Yang & Chen, 2015) (Vestas, 2017):

- Geographical location of the wind farm
- Total installed capacity of the wind farm
- Annual optimal gross electricity production and capacity factor
- Number of turbines in the wind farm
- Construction time of the wind farm
- Years of operation
- Impacts of material production and recycling

The results presented by Oebels and Paca are in line with those reported by Martínez et al. (2009), who stated that most of the environmental impacts of a wind turbine come from the production and installation phase. Nevertheless, the model presented by Martínez et al. (2009) followed different assumptions including almost complete recyclability of the tower and nacelle. His study showed that the foundation was the main contributor to the environmental impacts from a wind turbine due to the high environmental impacts from cement (2009). On 2012, Dolan and Heath performed a systematic review and harmonization of LCA literature for utility scale wind power system, their findings showed a median of 11 g $CO_{2\text{-eq}}$/kWh.

In Oebels and Pacca's (2013) LCA of a Brazilian wind farm, their results showed a total $CO_{2\text{-eq}}$ output of 7.1 g $CO_{2\text{-eq}}$ per kWh of produced electricity, this value was much smaller than the 64 g $CO_{2\text{-eq}}$ /kWh for the average Brazilian electricity grid, which was already almost 8 times smaller than the world average at that time. The lower carbon footprint in this study is explained by the composition of the electricity mix in Brazil, which includes a significant share of hydropower. A more recent study proposed a harmonized global warming potential (GWP) for wind energy systems of 9.4 g $CO_{2\text{-eq}}$ per kWh (Asdrubali et al., 2015).

Higher values as high as 28.6 g $CO_{2\text{-eq}}$ per kWh have been reported more recently in China (Wang et al., 2019), but this might be explained by the higher carbon emissions during the manufacturing phase.

C. Thomson and Harrison (2015) stated that credible estimations for offshore carbon emissions are in the range from 7 to 23 g $CO_{2\text{-eq}}$ per kWh. They also stated the importance of not only evaluating the total carbon emissions from the life cycle of wind energy, but also, to analyze the carbon emissions displacement values, which are composed by the total carbon emissions and the reduction of greenhouse gas emissions that are prevented from being released by using this technology. As an example, the most reliable estimation for the emissions displacement of wind power in Great Britain was 550 g $CO_{2\text{-eq}}$ per kWh for 2020 (R. C. Thomson, 2014).

In the year 2017, Vestas published an LCA for electricity production from an onshore wind farm featuring 3.45 MW wind turbines and reported a GWP of 4.8 g $CO_{2\text{-eq}}$ per kWh.

Regarding end of life management, Yang and Chen (2015) stated that for WES, end of life is not merely the dismantling of the wind turbines, instead, disposal and recycling should also be considered. They found that despite higher energy input, the substitution of raw materials through recycling can help reduce the overall GHG emissions and total energy consumption.

2.3.2 Environmental Impacts of Machine Elements Manufacturing

Manufacturing traditionally is done by one of two family of methods: formative or subtractive methods. In the first one, the machine element's final geometry is achieved by pouring the molten metal into the mold or by plastically deforming the bulk of material in solid state; on the other hand, subtractive methods are performed through the gradual removal of material from the bulk of raw material until the desired shape is achieved (DeBoer et al., 2021).

A new family of machine elements manufacturing technologies is rapidly growing. Additive manufacturing methods produce parts by adding layer-by-layer until the desired shape is obtained. Additive manufacturing has many advantages, for example, it eliminates the need for complex molds and tools to access internal cavities. Due to this reason, additive manufacturing has found great acceptance within high-tech industries, where highly customized parts are needed (DeBoer et al., 2021).

Recent studies concluded that additive manufacturing shows a modest reduction in environmental impacts when compared to traditional manufacturing processes. The modest reduction in impacts for additive manufacturing can be explained on one hand by the high savings in raw materials to produce one machine element and by the higher energy demand needed to melt the raw materials on the other. One very important take on these studies, is that additive manufacturing can show greater improvement in environmental impacts in those cases where the electricity mix is greener, since it involves the use of highly energy demanding processes (Shah et al., 2023) (DeBoer et al., 2021).

2.3.3 Environmental Impacts of Iron and Steel Industry

The iron and steel industry are highly energy intensive and associated with significant GHG emissions and other environmental impacts, which are part of the scope 3 upstream emissions in machine element manufacturing. According to the IEA, each ton of crude steel results in approximately 1.5 tons of total CO_2 emissions (IEA, 2023). One of the main reasons for the high emissions levels in the sector is that around 75% of the energy and feedstock of the sector is met with coal. According to the NZE scenario, by 2030 the share of emissions-intensive blast furnaces in the production of iron should decline by around 10% through the phase-out of existing plants, while the production share of scrap-based should increase by at least 5%. Scrap-based production is significantly less energy-intensive than blast furnaces (IEA, 2023).

Even though this industry is hard to decarbonize due to its high energy demand and chemical reactions involved, there are already numerous technologies that can support these efforts in an integrated manner. These developments are especially driven by the urgency of addressing the climate change and meeting the Paris Agreement goals (Guevara Opinska et al., 2021).

Examples of these efforts are the projects *H_2 green steel* and *SALCOS*. The first one is a project that has developed a renewable hydrogen based integrated steel mill in northern Sweden, operations are expected to start on 2025 and a reduction in CO_2 emissions of 95% in comparison to traditional steel production processes is expected. An initial production of 2.5 tons per year are planned, with potential to increase up to 5 million ton per year (Bararzadeh Ledari et al., 2023) (H2 green steel, 2022) (SMS group). SALCOS (Salzgitter Low CO_2 Steelmaking) is a project in Germany which aims to gradually phase Salzgitter's production from blast furnace technology to direct reduced iron (DRI) technology, which uses hydrogen produced from renewable sources to produce steel with a lower carbon footprint than the traditional methods. Currently the project is in the pilot plant phase and the first expansion stage, which will reduce CO_2 emissions by 30%, is expected by 2025 (Bararzadeh Ledari et al., 2023) (Salzgitter AG, 2023).

2.4. Pitch Bearings

2.4.1 Pitch Systems. Description and importance

Bearings are machine elements that connect two parts of larger machines and allow movements in certain degrees of freedom while locking all others (Stammler, 2020). Wind turbine pitch bearings, also known as blade bearings, are large slewing bearings installed between the blade and the hub of wind turbines to make oscillation of the blade against the hub, the purpose of this oscillation (pitch control) is to control the power generation of wind turbines and to reduce the aerodynamic loads by adjusting the blade angle (Burton, 2011). To fulfill this task, a pitching range between 20 to 25 degrees is enough, nevertheless the pitch system is also used as an aerodynamical braking mechanism, for the rotor to come to a stop, the blades need to be pitched to the feathered position, which is close to 90° (Hau, 2013).

Pitch bearings are grease lubricated rolling bearings, as shown on Figure 4. Rolling elements (in this case, balls), roll on the faces of the rings, which are called raceways. Commercially available types are four-point contact bearings, with one or two rows, three-row roller bearings, and mixed types (also known as "T-Solid") (Stammler, 2020).

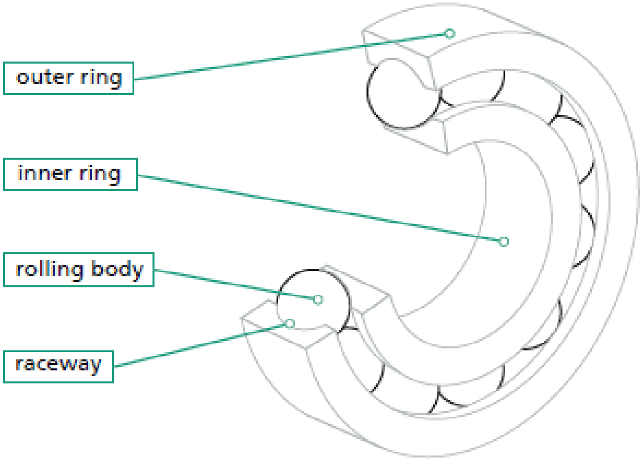

Figure 4. Rolling bearing (Stammler, 2020).

Pitch bearings are essential for the successful operation of wind turbines. They oscillate at low speed, nevertheless the supporting load is large, which can be tilting moments as well as radial and axial forces. They are connected with the hub and blades through fastening bolts (Han et al., 2015).

2.4.2 Materials and Selection Criteria

Bearing rings of pitch bearings are usually made of 42CrMo4-type steel, while the rolling bodies are from 100Cr6. 42CrMo4 is a high strength low-alloy steel, nevertheless, to be able withstand the contact pressures, additional hardening is needed. The raceway, which is responsible for carrying the high dynamic loads, is hardened by induction. The section that is not hardened is called core and maintains good ductility (Stammler, 2020) (Hidalgo et al., 2023).

Induction hardening is a surface heating treating method in which a metal part is heated by induction and then cooled in a quenchant, such as water, polymer, oil, or high-pressure gas. During the quenching process, the metal undergoes a phase transformation and the hardness of the quenched parts increases (Hidalgo et al., 2023). It should be noted that other kinds of materials such as structural steel S355J2+N and steel S690Q are also used in bearings testing activities, more specifically for interface pieces; although, no explicit reference to this was found in the literature.

Structural steel S355J2+N belongs to the non-alloy and normalized structural steels. It is suitable for all common welding methods. It is commonly used in steel construction, pressure vessel and boiler construction, mechanical engineering, mould making, mining and construction machinery sector (UnionStahl).

S690Q is a hot-rolled hardened structural steel that has undergone subsequent quenching and tempering treatment. It is usually used in structures subject to extreme loads, for example mining and heavy-construction equipment, crane equipment, offshore drilling platform, bridges, and supporting structure for wind turbines (METINVEST).

2.4.3 Pitch Bearing Failure Modes

Some of the components of pitch bearings are shown on Figure 4 (raceway, outer ring, inner ring and rolling body), on top of those, there are other elements worth mentioning as the bolts, cage seals, gears, and grease. As a result of their complex interphases and extreme operating conditions, they have abundant possibilities of failure. Depending on the location, different failures can happen, among those fatigue, wear, static overload, corrosion and lubricant degradation; If certain failures occur, they can trigger other failures (Stammler, 2020).

Blade bearing failure leads to poor pitching and aerodynamic imbalance of blades. In serious scenarios, blades might lose control and crack which cause curtailment in energy productivity. The assemble and repair cost of blade bearings are very high, therefore condition monitoring and fault diagnosis (CMFD) of pitch bearing is a field to which significant resources are expected to be allocated in the coming years (Liu et al., 2020).

Wear is a type of material failure, which happens when the base body and counterbody come into contact with poor lubricant. Wear is defined as a continual loss of material of one body by the mechanical action of a solid, fluid, or gaseous counterbody. The removed materials are wear particles and debris which can change the bearings frictional characteristics. (Liu & Zhang, 2019).

With raceway fatigue, micro-cracks form below the surface of the raceway, where the highest material stress occurs. When the rolling elements continue to roll across these cracks, they can migrate to the surface and cause the surface of the raceway to flake. In an ideal case, load and speed are constant and below limit for immediate failure and lubrication is optimal. In that scenario, the service life of the bearing will be determined by the raceway fatigue (Stammler et al., 2019).

Lubricant's purpose is to protect the rolling contact surface with a piece of thin oil film, avoiding the balls contacting the raceway directly. Proper lubrication can protect the bearing from wear, remove frictions heat from the bearing and extend the bearing's service life. Lubricant failure is possible due to insufficient lubricant, over-lubricant, lubricant contamination, and using the incorrect lubricant (Liu & Zhang, 2019).

2.4.4 Pitch Bearings Endurance Testing

Testing wind turbines pitch bearings on full size test rigs is very time consuming and costly, however, there are multiple precedents about large scale slewing bearings testing as described by Schwack et al. (2022). Due to the limitations mentioned above, most of the conclusions on wind turbine pitch bearings' operational behavior have been drawn based on testing conducted on small diameter bearings (100 mm and smaller) (Schwack et al., 2022). Although, as some damage modes are not completely understood, it is necessary to conduct full acceptance runs with realistic interface conditions and loads in order to minimize failures prior to the installation in wind turbines. The Bearing Endurance and Acceptance Test (BEAT) 6.1 Rig is the result of Fraunhofer IWES to assess these damage modes; the 6.1 in the name makes reference to the pitch bearing diameter of about 6 m and the .1 indicates that this is the first test rig of this size at Fraunhofer IWES. For this test rig, wear profile and rolling contact fatigue are the main conducted acceptance tests. The duration of a full wear run described in the publication of Stammler was 117 days (Stammler, 2020).

As it is mentioned by Stammler et al. (2023), the knowledge about oscillating bearings, slewing bearings and wind turbines has grown significantly since 2009, the year in which the Design Guideline 03 was published by the NREL. Said guideline is widely used in the wind industry to get acquainted with design aspects and methodologies to determine pitch and yaw bearing static capacity and fatigue life. Due to this, NREL and IWES are to update the mentioned methodology in 2023 (Stammler et al., 2023).

To the knowledge of the author, there are no studies that address the environmental impacts of mechanical endurance of pitch bearing, or any other large structure.

2.5. End-of-Life (EoL) Management Strategies

2.5.1 EoL Overview

When a complete LCA is conducted (cradle-to-grave), the last life phase is the EoL phase. Usually, this phase is implemented by recycling or by conventional waste disposal procedures, mostly by waste incineration and disposal sites (Klöpffer & Grahl, 2014).

The EoL stage begins when the used product is discarded by the consumer and ends when the product is returned to nature. Because the main attributable process in the EoL stage is the method used to treat the product (land filling, incineration, etc.), companies need to know or assume the fate of the product to map this stage. In this stage, it is common to consider the following processes: Collection and transport, waste management, dismantling of components, shredding and sorting, incineration and sorting of ashes, land filling and land filling maintenance (Greenhouse Gas Protocol, 2011).

For a service, the production and use stage may be combined into the service delivery phase. This includes all the operations required to complete a service. All material flows, energy flows, and EoL considerations of materials and wastes make up the attributable processes along the service life cycle (Greenhouse Gas Protocol, 2011).

EoL management is very significant in the overall environmental impacts of a product or service, and the concept is tightly related to the concept of circular economy. In 2017, Kirchherr et al. defined circular economy as an economic system that replaces the “end-of-life” concept with reducing, alternatively reusing, recycling and recovering materials on production/distribution and consumption processes.

2.5.2 Circular Economy Overview

Circular Economy is defined by the ISO norm 50904 as “an economy system that uses a systemic approach to maintain a circular flow of resources by recovering, retaining or adding to their value while contributing to a sustainable development” (ISO). circular economy is most frequently depicted as a combination of reduction/reuse/recycling activities, potentially linked to the sustainable development concepts (Talens Peiró et al., 2020). The importance of circular economy can be appreciated in its slowly but increasing presence in policies, guidelines, and legislations (Niero & Rivera, 2018).

Circular economy is a concept that has been widely accepted by the government and industries. In Europe, in 2015 the European Commission adopted the circular economy package. Up to 2020, the Ecodesign Directive was identified as one of the most suitable legislative tools (Talens Peiró et al., 2020), even when the standing Ecodesign regulations only covered energy-related products. On March 2022, the European Commission published the new Ecodesign for Sustainable Products Regulation (ESPR), which is the cornerstone of the commission’s approach to more environmental sustainable and circular products (European Commission, 2023).

Current views on circular economy are shaped by the butterfly diagram presented by the Ellen Macarthur Foundation, as shown on Figure 5. Butterfly diagram . Biological cycles are designed to recycle natural materials through composting and biodegradation, nevertheless the focus of Figure 5. Butterfly diagram is to show the technical cycles, where finite materials are considered and kept inside the cycles shown (maintenance, reuse, rehabilitation and finally recycling). From an environmental point of view, the “tighter” cycles are more valuable than the “wider” cycles, because in them, a greater product value, integrity and complexity are retained and the energy and material input of the cycle is lower (Ellen Macarthur Foundation, 2015).

It is important to note that circular economy does not only imply environmental performance improvements, but also economic opportunities, which have already been identified by businesses and policymakers. The Ellen Macarthur Foundation stated that by adopting circular economy principles, Europe could create a net benefit of 1.8 trillion Euros by 2030, which represented 0.9 trillion more Euros than the linear development plan at that time (2015). The economic opportunities are in the following areas: economic growth, substantial net material cost savings, job creation potential and innovation.

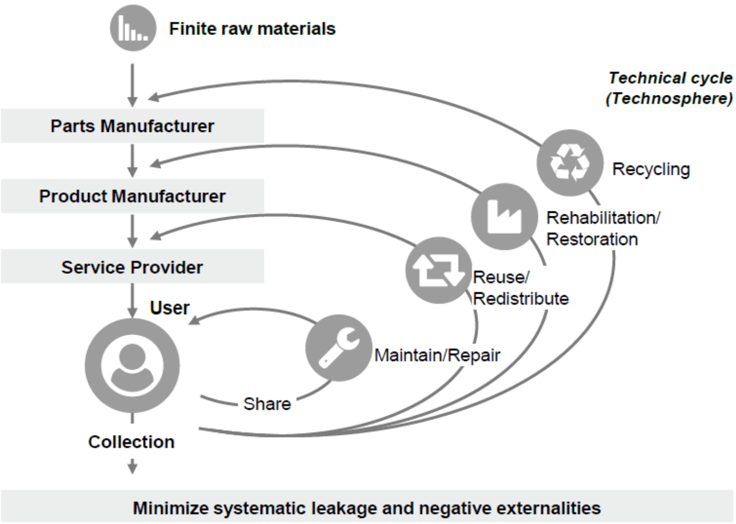

Figure 5. Butterfly diagram (Ellen Macarthur Foundation, 2015)

2.5.3 End-of-life Principles Applied to WES

One of the main arguments against wind energy had been until very recently the lack of recyclability for the composite wind blades, which, in order to withstand complex fatigue and environmental loads for decades, are designed of various materials such as thermoplastic coatings, thermoset/glass fiber composites, often also carbon fibers, balsa wood and adhesives (Jensen et al., 2020) (Stella, 2019). Nevertheless, both Vestas and Siemens Gamesa Renewable Energy (SGRE) already presented their own circularity solution to prevent wind blades from ending up in landfills. It is estimated that each installed MW generated between 9.5 tons (Arias, 2016) to 15 ton of composite waste (Lerides & Reiland, 2019).

SGRE solution implies a change in the composition of the wind turbine resin. SGRE claims the technology is ready for commercial use. Upon decommissioning, wind blades will be immersed in a warm, mildly acidic solution to dissolve the resin which can be recovered afterwards (SGRE, 2023). On the other hand, Vestas' solution does not require a change in design or composition of wind blades and can be applied to all epoxy based wind blades in operation. Vestas claims the epoxy resin can be separated and recovered through a chemical process, after which the resins can be used once again (Vestas, 2023).

In November 2023, ACCIONA Energía and RenerCycle announced the construction of a wind blade recycling plant in Navarra, Spain with a capacity of 6,000 tons of material per year. The project’s name is Waste2Fiber and is expected to be operational in 2025. The facility will use a thermal treatment technology for recycling the composite materials present in wind turbine blades while preserving the properties of the reinforcement fibers allowing them to be used as secondary raw materials in new production processes (ACCIONA, 2023).

2.5.4 Ecodesign Normative

Ecodesign is a normative that enables circular economy, it was born as a framework to address the minimization of environmental impacts in the early stages of product development without compromising the quality, performance, and functionality of a product (European Commission, 2022). The early development stages make reference to the selection and conceptualization of materials, waste treatment, energy consumption, significant emissions, among others that determine the environmental performance of a product during its lifetime (Kamp Albæk et al., 2020) (Riesener et al., 2023). Nevertheless, Ecodesign takes into account all the environmental effects of a product during its lifetime, without explicitly aiming towards circular economy.

Ecodesign pays great attention to the product LCA. Fabrication is the beginning of a product’s life cycle, from which the primary raw materials show one of the most significant contributions on the environmental impacts of products. The next great emphasis is done in “slowing the loop” or “closing the loop”; the first one, is achieved by following the inner cycles in the butterfly diagram, while the second is achieved by following the recycling cycle, because it closes the loop between the end of product use and production (Babbitt et al., 2021).

It is worth noting that the newest ESPR, that is expected to come into effect from 2024 expands the previously considered energy-related industries to new, high environmental impacts sectors such as textiles, and construction products, this means, the industry sectors with the most significant environmental impacts on the environment and climate (European Commission, 2022). The approval of the new ESPR was a long process, and the inclusion of new industry sectors is expected to take place at a lower but constant phase. Some industries, like the chemical industries are already preparing themselves for the ESPR, for example, Together for Sustainability’s Carbon Footprint Guideline for the Chemical Industry (2022) is expected to be a cornerstone for said industry to align with newest regulations.

One of the key takeaways of the ESPR is the so called digital product’s passport, which is an instrument that will improve the traceability along the supply chain for the materials and the components used in the manufacturing processes of products and facilitate the verification of product compliance by competent national authorities (European Commission, 2022).

To the author’s knowledge, to this date there is no timeline for the inclusion of Research and Development (R&D) in the ESPR.

3. Methodology

This Master Thesis aims to address knowledge gaps identified in the literature review. To the author's knowledge, there are no life cycle assessment studies that address the mechanical endurance testing of large structures, neither on product nor organizational level. Consequently, there are also no studies that evaluate measures that could be applied to reduce environmental impacts in large structures endurance testing activities and in the organizations conducting them.

Given the mentioned gaps in the existing literature, this Master Thesis seeks to answer the research question: How can potential measures be identified and explored to reduce environmental impacts associated with mechanical endurance testing of large structures?

To address the research question, a structured approach involving key tasks is needed. First, an attributional product life cycle assessment (PLCA) case study is conducted for a representative project which has been executed in the BEAT 6.1 (Bearing Endurance and Acceptance Test rig). This assessment is conducted according to the norms ISO 14040:2006 and ISO 14044:2006. The primary objective of this product LCA is to identify and understand the environmental hotspots of mechanical endurance testing activities executed in the mentioned test rig.

Subsequently, a second case study in which the scope of the analysis is expanded to contemplate the large bearing laboratory (LBL) of Fraunhofer's Institute for Wind Energy Systems (IWES) as an organization is conducted. The attributional organizational life cycle assessment (O-LCA) expands the system boundaries of the product LCA by including processes that are needed for the operation of the institute and are not directly allocated to the mechanical endurance testing projects execution. The case study complies with the norms followed by the product LCA and the TS/ISO 14072 as well. The goal of this case study is to identify and understand the environmental hotspots of an organization conducting mechanical endurance testing activities.

After the hotspots have been considered from both product and organizational level, sensitivity analyses are performed in the processes that significantly contribute on the environmental impacts footprint and where feasible modifications from the business as usual (BAU) scenario are possible. The scenarios in which the performance of the midpoint impact categories is significantly better than the BAU scenario are identified as potential measures that can lead to a reduction in environmental impacts associated with mechanical endurance testing activities of large structures.

The methodology used in each case study is explained in further detail in their respective case study chapter. Nevertheless, an initial overview of the scope and system boundaries is presented in this chapter. Each case study follows the four stages proposed by the norm ISO 14040 (2006a):

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

Both product LCA and organizational LCA follow an attributional approach. Cradle-to-grave has been chosen for the system boundaries, as depicted in Figure 6. Firstly, the figure shows the system boundaries for the product LCA in blue, and then expands them to include the group of processes that correspond to the offices operation. The expanded system boundaries correspond to the organizational LCA and are presented in green. For both case studies, the processes have been classified as upstream, direct, and downstream activities. Finally, the processes that have been excluded from the system boundaries are presented in the red block at the bottom of the figure.

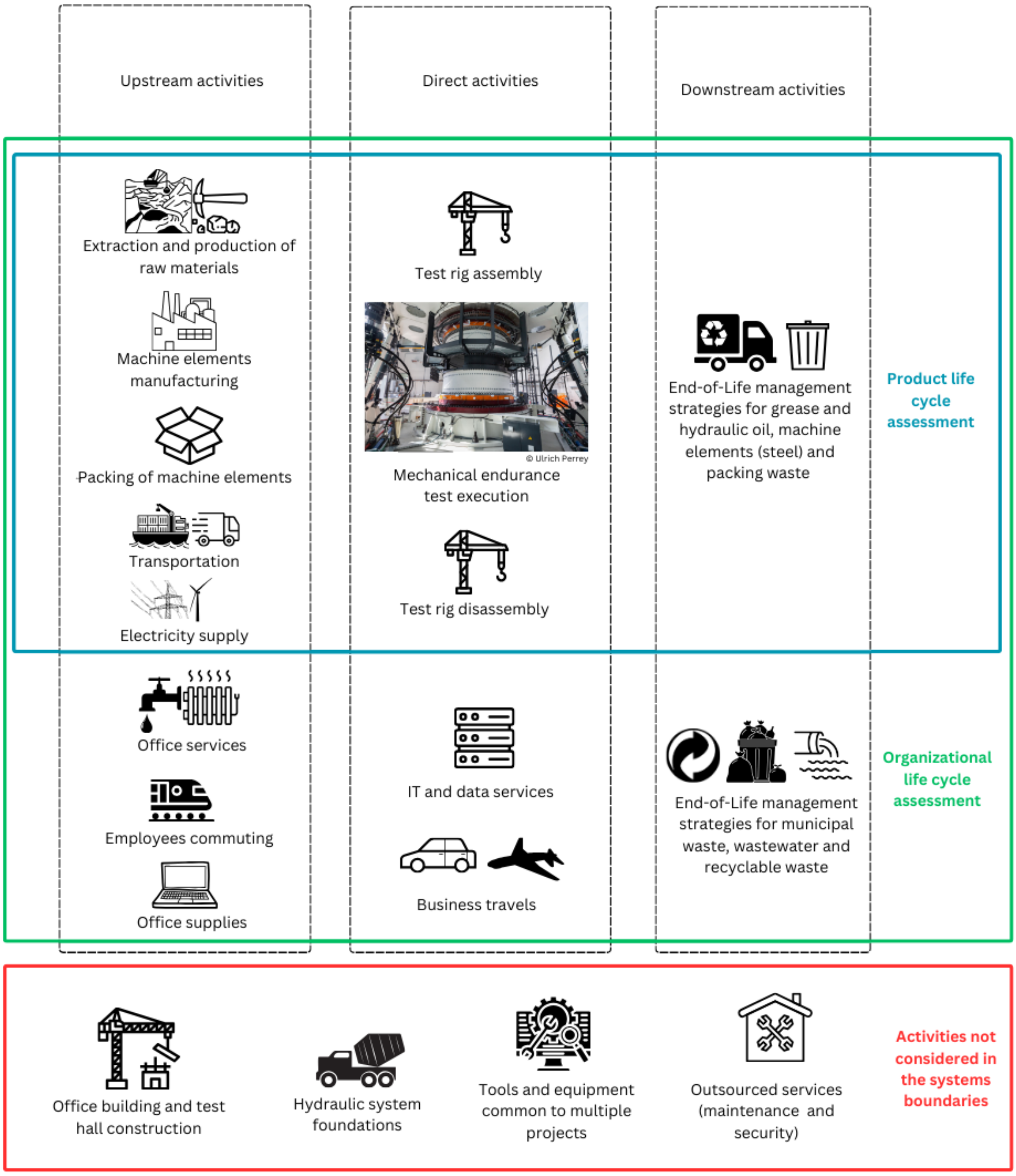

Figure 6. System boundaries for both case studies.

The product LCA has been developed based on a reference project which is representative of mechanical endurance testing projects conducted at the LBL. The functional unit of the first case study is defined as "an endurance test project carried out at the BEAT 6.1 test rig for 120 days at an average power consumption of 120 KW”. Even though each project developed at the LBL is unique, this project has been chosen as reference since there are many characteristics that are common to other projects, for example:

- Testing conditions (time, hydraulic power profile and energy supply).
- Machine elements that are commissioned as interface for the devices under testing are used in multiple projects.
- Machine elements suppliers.
- Logistics.
- End-of-life management strategies.

The reporting unit chosen for the organizational LCA is the year 2020, which has been chosen to allow a good integration with the product LCA. In this year, only minor testing activities were conducted at the LBL besides the reference project.

Table 3. Analyzed impact categories.

Impact category	**Impact category abbreviation**	**Reference unit**
Acidification: terrestrial acidification potential	TAP	kg SO_2-Eq
Climate change - global warming potential	GWP100	kg CO_2-Eq
Ecotoxicity: freshwater ecotoxicity potential	FETP	kg 1.4-DCB-Eq
Ecotoxicity: marine ecotoxicity potential	METP	kg 1.4-DCB-Eq
Ecotoxicity: terrestrial ecotoxicity potential	TETP	kg 1.4-DCB-Eq
Energy resources: non-renewable, fossil fuel potential	FFP	kg oil-Eq
Eutrophication: freshwater eutrophication potential	FEP	kg P-Eq
Eutrophication: marine eutrophication potential	MEP	kg N-Eq
Human toxicity: carcinogenic - human toxicity potential	HTPc	kg 1.4-DCB-Eq
Human toxicity: non-carcinogenic - human toxicity potential	HTPnc	kg 1.4-DCB-Eq
Ionizing radiation - ionizing radiation potential	IRP	kBq Co-60-Eq
Land use - agricultural land occupation	LOP	m^2*a crop-Eq
Material resources: metals/minerals - surplus ore potential	SOP	kg Cu-Eq
Ozone depletion - ozone depletion potential	ODPinfinite	kg CFC-11-Eq
Particulate matter formation potential	PMFP	kg PM2.5-Eq
Photochemical oxidant formation potential: humans	HOFP	kg NOx-Eq
Photochemical oxidant formation potential: ecosystems	EOFP	kg NOx-Eq
Water use - water consumption potential	WCP	m3

For the modelling of the systems, the software Open-LCA in combination with the ecoinvent 3.9.1 database has been selected. These models are then used to generate the life cycle inventories and impact assessments, which are the base for the proposed sensitivity analyses, the discussion, and conclusions presented in this thesis. ReCiPe 2016 v.1.03, midpoint (H) has been chosen as life cycle impact assessment (LCIA). The impact categories analyzed in this study are presented in Table 3. It is also important to note that this thesis does not consider the damage pathways and endpoint categories which can be assessed from the midpoint impact categories.

4. Case study: Product Life Cycle Assessment (PLCA)

4.1. Goal and Scope Definition for the Product Life Cycle Assessment (PLCA): Endurance Test for Pitch Bearing Systems

The present master thesis has been carried out by the LCA practitioner Moises Guzman, an internal employee of Fraunhofer IWES, deployed at the Large Bearing Laboratory (LBL) in Hamburg. This study is to comply with the norms ISO 14040:2006 and ISO 14044:2006.

4.1.1 Goal

The present LCA is intended to be a guideline for the LBL personnel to identify and understand the environmental hotspots in the endurance testing process, and to propose initial measures that could lead to an improvement in the environmental performance of the endurance tests carried out at the facility making use of the BEAT 6.1 (Bearing Endurance and Acceptance Test rig, the six refers to the pitch bearing diameter of about 6 m and the .1 designates that this is the first test rig of this size at Fraunhofer IWES) (Stammler, 2020). Wear and raceway fatigue are the two endurance tests that are generally conducted with this test equipment.

The Fraunhofer Gesellschaft has pledged for climate neutrality by 2030 (Fraunhofer-Gesellschaft e.V., 2021), therefore this study will significantly contribute to this goal by understanding the current environmental impacts associated with the testing conducted at the LBL and thus, by identifying opportunities to reduce them.

4.1.2 Scope

Each endurance test done at the LBL is different and therefore establishing one unique functional unit that enables the comparison between different systems is not possible. Factors such as the variation in the weight of the machine elements manufactured for each project and the materials used in the interface elements contribute to the uniqueness of each project. On the other hand, there are aspects, like the logistics, that remain common from project to project. For this reason, in this LCA, a reference project will be used. For this study, a fatigue test was carried out for a state-of-the-art wind turbine pitch bearing.

The Functional Unit in this LCA is defined as an endurance test project carried out at the BEAT 6.1 test rig for 120 days at an average power consumption of 120 KW.

The present study is an attributional LCA (aLCA) in which the product as previously mentioned is the knowledge transfer of the fatigue test for a large-diameter offshore pitch bearing. This study will include the following stages:

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

4.1.2.1 System Boundary

The system boundary considers the machine elements that were allocated to the reference project, including their manufacturing, the packing and the electricity consumption needed for the test rig assembly, the test execution and test rig disassembly. The execution of the endurance test also requires supplies of grease and hydraulic oil, these are also considered within the system boundaries. Finally, the system contemplates the EoL management for the system outputs as presented in Figure 6.

This study does not consider within its system boundaries the construction of the facilities where the testing activities are executed, the test rig foundations, and hydraulic system. Common machinery is also left out of the system boundaries. This decision has been influenced by time constraints and the reasoning that their inclusion does not contribute to the main goal of this assessment. On top of that, these elements are not expected to be modified for future tests.

The system boundaries are presented in Figure 6 in the Methodology Chapter.

4.1.2.2 Cut-off Criteria

A proportion of 1% (mass, energy, and environmental relevance) has been chosen as the cut-off criterion at system (product) level. In addition, the portion to be cut off shall not exceed 5% per unit process.

4.1.2.3 Allocation Procedures

When a new pitch bearing is to be tested, a complete new set of machine elements needs to be commissioned. Some elements might be used more than one time, in the scenario where multiple tests are done to the same wind turbine pitch bearing type, in that case, machine elements are allocated throughout the total testing projects in which they are used. For the reference project assessed in this report, a complete list of all the machine elements that were acquired is available, so no allocation complexities are expected.

Hub adapters and force transmitting element (FTE) are allocated to 3 different projects. In this project, only 1/3 of their total mass is considered. On the other hand, bolts, bearings, stiffeners, and extender are used in only one project each.

The hydraulic system, which has a peak power of 800 kW, represents the biggest energy consumer in the testing process. Electricity consumption data has been measured with a power logger during the testing phase and can be double checked with electricity bills; therefore, no allocation complexities are expected either.

4.1.2.4 Modelling the Life Cycle Phases

The software OpenLCA and the database ecoinvent 3.9.1 are used to model the processes and the overall system; they have also been used to generate the life cycle inventories and impact assessment which are the base for the conclusions of this case study. OpenLCA follows the approach of first modelling flows, which are followed by a process capable of generating said flow. Processes are gathered and used to simulate systems. When multiple systems are to be compared, they can be grouped in a project.

During the modelling of the processes, all the material and energy flows going in and out of the system are considered, including material losses from the production processes. OpenLCA allows the modelling of processes by using products and secondary processes which can be taken from the chosen databases, in this case ecoinvent. This database also allows the user to assign a geographic location to these processes, nevertheless there are several processes which have not yet been modelled for multiple locations.

4.1.2.5 Impact Categories Selected and Methodology of Impact Assessment, and Subsequent Interpretation to be Used

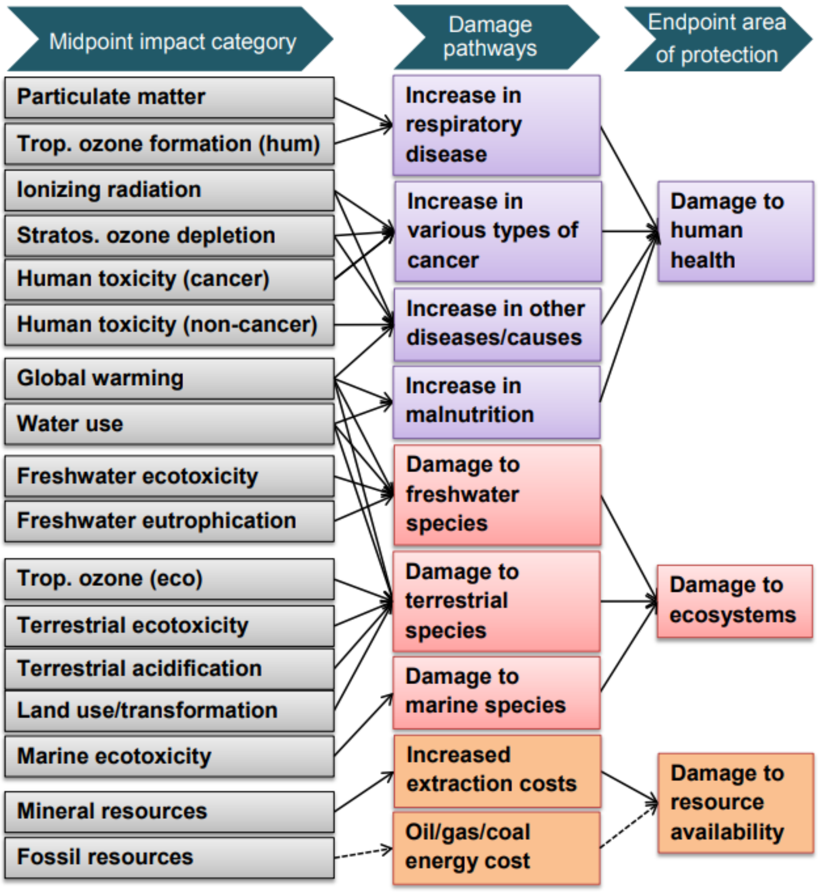

Figure 7. Midpoint categories, damage pathways and endpoint area of protection from the ReCiPe 2016+ methodology (M.A.J. Huijbregts et al., 2016).

This study follows an attributional, process based approach, which aims to quantify the relevant environmental flows related to the endurance testing carried out at the LBL based on physical and energy flows. In this case study, an initial model is created and called baseline, which serves as the business as usual (BAU) scenario. Sensitivity analyses are to be performed to evaluate the effect in environmental impacts that the modification of certain parameters could have.

The results of the inventories will be assigned to the impact categories which are shown on Figure 7, following the ReCiPe 2016 v.1.03, midpoint (H) life cycle impact assessment (LCIA) method, which allows a harmonic way to characterize the impacts at midpoint level (M.A.J. Huijbregts et al., 2016). A more detailed definition of the midpoint level impact categories is presented in Annex 0. ReCiPe 2016 has gained a high degree of acceptance among LCA practitioners, and it also benefits from recent data. The assessment on this report limits itself to the midpoint categories shown on Figure 7. endpoint categories or damage pathways are not analyzed.

4.1.2.6 Data Requirements

This study follows the five accounting principles proposed by the Greenhouse Gas protocol (Greenhouse Gas Protocol, 2011) which are relevance, completeness, consistency, transparency and accuracy to ensure that the product inventory constitutes a true and fair representation of its environmental impacts.

To do so, high quality data is necessary, primary data is used for all processes under the ownership or control of the LBL. If primary data is not available or measurable, secondary data is used.

Among the data requirements that fall under the ownership or control of the LBL are:

- Specific testing period
- Electricity consumption during the testing period
- End of Life (EoL) management strategy for the outputs
- Electricity supply contract
- Complete list of commissioned machine elements (including weight and material)

Machine elements that were commissioned for the testing will also require high data quality, nevertheless, this is complicated since it depends highly on the suppliers and their confidentiality policies. Using the complete list of commissioned machine elements, the supplier is requested information such as:

- Composition of electricity supply
- Steel suppliers (location, production technologies)
- Ratios of final product to raw materials
- Manufacturing technology

4.1.2.7 Assumptions

The most significant assumptions made for this assessment are outlined below:

- For modelling purposes, it is assumed that the testing time is limited to 120 days at a constant electric load. In reality, the assessed project was executed between March 2020 and September 2020, nevertheless the test execution was interrupted for some time in between. Also, during testing the hydraulic load is slowly but steadily increasing over time. This assumption is verified by the total electricity consumption from the electricity bills and also with the information available from the power logger in the test rig.
- Electricity bills are available, but they reflect the total consumption of the building including the offices and a server room. Constant monthly consumptions of 1280 KWh and 4000 KWh are allocated to the offices and server room respectively.
- The contract with the electricity supplier states that the LBL receives electricity that has been generated by renewable sources, on top of that, Fraunhofer IWES acquires renewable energy certificates, to be able to guarantee that their emissions from electricity supply are offset. Therefore, the baseline scenario will be modelled with the renewable matrix available in Germany in the year 2020. A sensitivity analysis is to be conducted using the German energy market dataset available in ecoinvent to dimension the avoided environmental impacts of this measure.

- At the time the study was carried out, it was not possible to obtain reliable data to trace back the location of manufacture and amount of recycled content in the steel used for the machine elements, due to this reason, it has been decided to use the global markets datasets from ecoinvent for these materials. The mentioned datasets consider average amounts in the global market taking into account the different technologies used for production and also the geographical locations, therefore, they also consider the transportation impacts. The selection of these datasets also allows a fair and representative approach to assess the impacts of using recycled steel scrap and electric arc furnace for steel production in the sensitivity analysis.
- It is assumed that the machine elements manufacturing consists of three operations: steel milling, steel drilling and welding. For the FTE manufacturing, hot rolling has also been included. Estimations from the manufacturers for steel removed through milling and drilling are used.
- The transportation of the machine elements manufactured in Europe is modelled using 16-32 ton lorry transport. Machine elements whose origin is Europe are assumed to be transported 2000 km.
- Machine elements manufactured in China are modeled using both sea and road transport. First it is assumed they travel a total of 15500 km by water to Europe, where they are received and inspected by IWES's counterpart that provides the bearings to be tested. Then, they travel 2000 km by 16-32 ton lorry to Hamburg.
- Manpower has not been considered in this model.

4.1.2.8 Limitations

- Tracing machine elements supply chain specifications.

4.1.2.9 Type and Format of the Report Required for the Study

The reporting format follows the regulations stated in Sections 5.1 and 5.2. from the ISO 14044: 2006b norm.

4.2. Inventory Analysis

4.2.1 Endurance Testing Process Description.

The flow diagram for the analyzed system is shown on Figure 8. The system needs to be divided into smaller processes which are then modelled on OpenLCA. The descriptions of these processes are shown below. The data presented in this section has been obtained through reports, inquiries to suppliers and some assumptions. A validation process using mass and energy balances has been conducted to assess the data quality gathered by the LCA practitioner.

4.2.1.1. Machine Element Manufacturing

This process uses low alloyed steel as raw material, in Figure 8, the word "market" can be appreciated accompanying this input. This means that the selected dataset provides an average of the different technologies and geographical locations for low alloyed steel manufacturing. By selecting this dataset, the upstream processes (mining, steel making and steel post-processing) and the needed raw materials (minerals, ores, steel scrap, coal, energy, etc.) are implicitly accounted for.

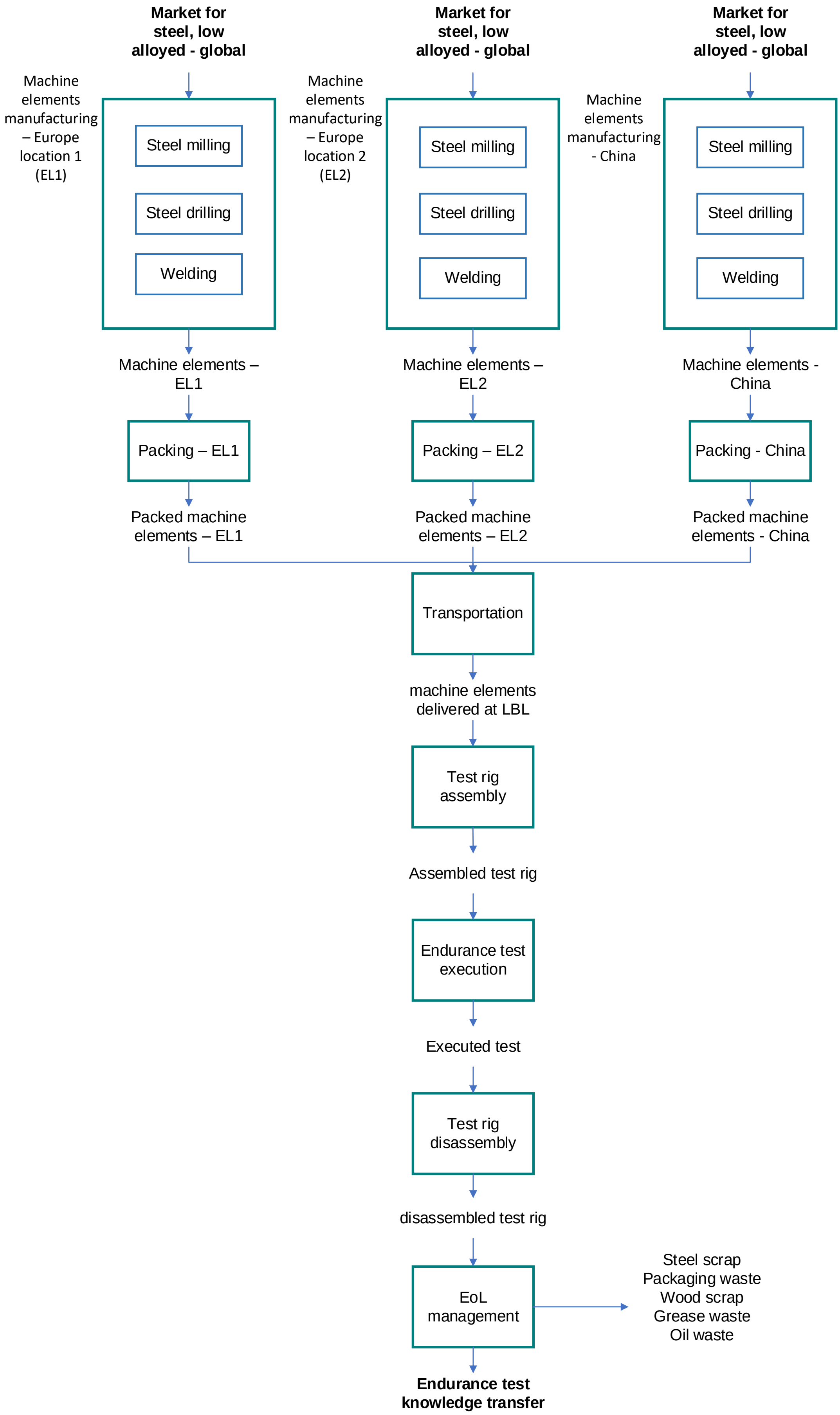

Figure 8. Flow diagram for the baseline analyzed system.

Table 4 summarizes the machine elements necessary for the analyzed project and indicates the location where they are manufactured. As seen in Table 4, the supplier corresponding to Europe location 1, is in charge of the manufacturing of the machine elements that are directly commissioned by IWES, while the supplier corresponding to Europe location 2, is in fact the counterpart whose bearings are to be tested at IWES; the stiffeners and extenders are also provided by them, but these machine elements are usually manufactured in China.

The modelling of machine elements manufacturing consists of three different processes: steel milling, steel drilling and welding. For the manufacturing of the FTE, an additional process for steel rolling is added. The datasets for these processes are available in the ecoinvent 3.9.1 database.

Table 4. Description of machine elements manufactured.

Machine element	Unit	Total mass	Project count	Allocated mass	Production location
Hub adapters	kg	53012	3	17671	Europe location 1
Bolts	kg	2160	1	2160	Europe location 1
Force transmitting element (FTE)	kg	27042	3	9014	Europe location 1
Bearings	kg	27008	1	27008	Europe location 2
Stiffeners	kg	18134	1	18134	China
Extenders	kg	15754	1	15754	China

4.2.1.2. Packing of machine elements

These processes take place in the production location of each machine element and represent the preparation of the manufactured machine elements for delivery. The packaging of big steel machine elements consists mainly of wood crates, pallets, and wood parts to fix the elements to the crates. Some machine elements like the FTE and bearings are wrapped with a plastic coating to prevent contact with dirt and other external elements.

Table 5. Packaging amount located to the different manufacturing locations.

Packaging	Unit	Total amount	Amount allocated to China	Amount allocated to Europe location 1	Amount allocated to Europe location 2
EUR flat pallets	kg	1140	570	570	0
Wood crates	kg	1000	500	500	0
Supporting wood	kg	2000	1000	1000	0
Plastic packaging	kg	400	0	200	200

The total amount of packaging has been estimated using waste disposal reports of the LBL for the year 2020. The allocation has been done through the analysis of pictures taken at the time of delivery of the different machine elements and by making some assumptions. The summary of the packaging is shown on Table 5.

4.2.1.3. Transportation

As previously mentioned in the assumptions, transportation is modelled from the manufacturing location to the LBL in Hamburg. The machine elements manufactured in Europe are transported only by ground, which is modelled with a 16-32 ton lorry. On the other hand, it is assumed that machine elements manufactured in China are transported by water to Europe, and then by ground to Hamburg. The weight of the packaging needs to be added to the machine elements before transportation. Table 6 details the total weights and travel distances for the transportations.

Table 6. Transportation summary

Machine elements	Route	Type of transport	Mass (kg)	Distance (km)
Hub adapters, FTE, bolts	EL1 - Hamburg	Road	31115	2000
Bearings	EL2 - Hamburg	Road	27208	2000
Stiffeners, extenders	China – EL2	Water	35958	15500
Stiffeners, extenders	EL2 - Hamburg	Road	35958	2000

4.2.1.4. Test Rig Assembly

Once the machine elements have been delivered to the LBL, it is necessary to assemble the test rig. This process is done through a crane system present at the LBL and manpower, nevertheless the latter is not considered in this report. Making use of the electricity bills and the power logger reports 15,000 KWh are allocated to this process.

4.2.1.5. Endurance Test Execution

This is the longest and most energy intensive process analyzed in this report. At the LBL, both wear and raceway fatigue can be tested for wind turbine pitch bearings. To simulate operating conditions, a hydraulic system applies different loads over multiple weeks or months. For modelling purposes, it is assumed that the hydraulic system exerts a constant load over a determined period of time.

As defined by the functional unit, the system is analyzed for a testing time of 120 days at a constant electric load of 120 KW. It is important to note that electric energy used at the LBL comes from renewable sources, as it is stated in the contract with the service provider.

Other inputs required for the testing phase are hydraulic oil and grease. The hydraulic system has 6 m^3 of hydraulic oil, it is expected that 5 testing projects take place before renewing it, thus 1.2 m^3 of hydraulic oil are allocated to this project. Regarding the grease, an approximate 250 kg are acquired for each project.

4.2.1.6. Test Rig Disassembly

After the execution of the endurance test has been concluded, the test rig is disassembled. Making use of the electricity bills and the power logger reports 15,000 KWh are allocated to this process.

4.2.1.7. End-of-Life (EoL) Management

This process models the EoL management of the different material outputs (Table 7) of the endurance testing. The main output is the machine elements that have been used for the testing. They are gathered in a container and when full, it is sold as steel scrap. In this model, the complete weight of steel machine elements allocated to this project are considered to be treated in this stage.

Other flows that are treated in this phase include the packing waste, degraded hydraulic and lubricating oil, waste lubricating grease and wood scrap. Most packaging waste is collected by a company part of the *Grüner Punkt* scheme for recycling. The amounts presented in Table 7 have been obtained from internal reports of the LBL.

Table 7. Summary of material output flows

Material flow	unit	amount	EoL management
Steel scrap	kg	89741	Sold as steel scrap
Wood scrap	kg	2140	Incinerated
Wood	kg	2000	Sold for recycling
Degraded oil	m3	1.2	Incinerated
Grease rags	kg	980	Incinerated

4.3. Impact Assessment

4.3.1 Summary of Results

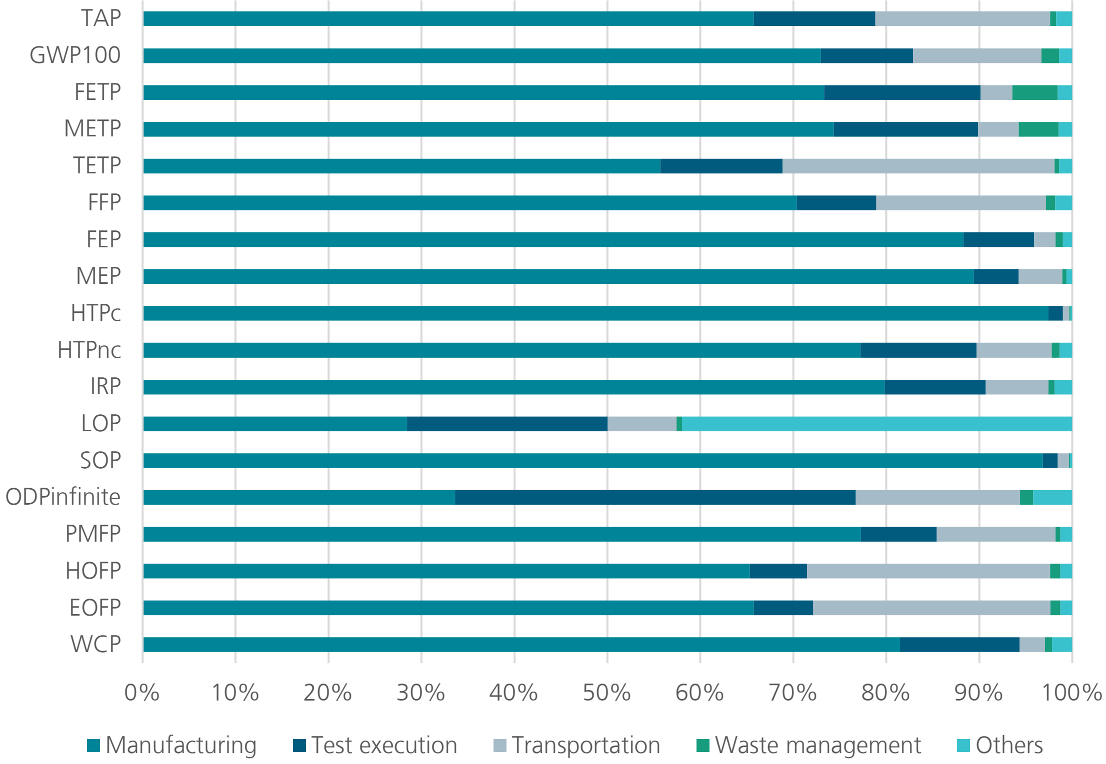

Figure 9. Overview of the contribution of each process for every analyzed impact category – product life cycle assessment.

On Table 8 is presented an overview of the environmental impacts of the endurance testing of pitch bearings, carried out by Fraunhofer IWES at the large bearing laboratory. Results have been obtained using the software OpenLCA and the system has been modelled making use of the ecoinvent 3.9.1 cut-off database. The impact categories presented correspond to the LCIA method ReCiPe 2016, midpoint (H). The (H) makes reference to a hierarchist time horizon, which considers the environmental impacts for 100 years. As previously stated, the definition of the midpoint level impact categories is available in Annex A. A more detailed breakdown of the results obtained is presented in the following section.

Table 8. Environmental impacts associated with endurance testing of pitch bearings at the large bearing laboratory.

Impact category	Reference unit	Result
TAP	kg SO_2-Eq	909.6
GWP100	kg CO_2-Eq	304,910.2
FETP	kg 1.4-DCB-Eq	27,882.9
METP	kg 1.4-DCB-Eq	38,177.9
TETP	kg 1.4-DCB-Eq	2,412,322.8
FFP	kg oil-Eq	71,489.1
FEP	kg P-Eq	116.6
MEP	kg N-Eq	24.2
HTPc	kg 1.4-DCB-Eq	292,800.5
HTPnc	kg 1.4-DCB-Eq	360,522.8
IRP	kBq Co-60-Eq	9,011.4
LOP	m^2*a crop-Eq	18,523.8
SOP	kg Cu-Eq	61,992.6
ODPinfinite	kg CFC-11-Eq	0.12
PMFP	kg PM2.5-Eq	510.0
HOFP	kg NOx-Eq	831.3
EOFP	kg NOx-Eq	886.8
WCP	m^3	2,291.1

Figure 9 shows the percentage that each process described in Section 4.2 contributes to the total of each environmental impact category. It can be easily appreciated that for all categories, with the exception of land use – agricultural land occupation, the processes of manufacturing of the machine elements, the test execution, and the transportation to the testing site account for well over 90% of the total contributions. From the three processes mentioned, the manufacturing of the machine elements is clearly the one with the highest contributions in almost all the analyzed impact categories, accounting for over 50% of the total contributions in 16 of the 18 categories.

4.3.2 Impact Categories Results Description

4.3.2.1 Acidification: Terrestrial - Terrestrial Acidification Potential (TAP)

Figure 10 shows the contributions of each process per functional unit to this impact category. It can be clearly appreciated that the processes that have the highest contribution to this impact category are the machine elements manufacturing (accounting for almost 66% when added), followed by lower contributions from the transportation and test execution, with approx. 19% and 13% respectively. The high impact from the manufacturing processes can be explained due to the mining and ore processing activities needed for obtaining the raw materials.

As shown in Figure 10, the contributions to this impact category coming from waste management, test rig assembly and disassembly, and packing are very small.

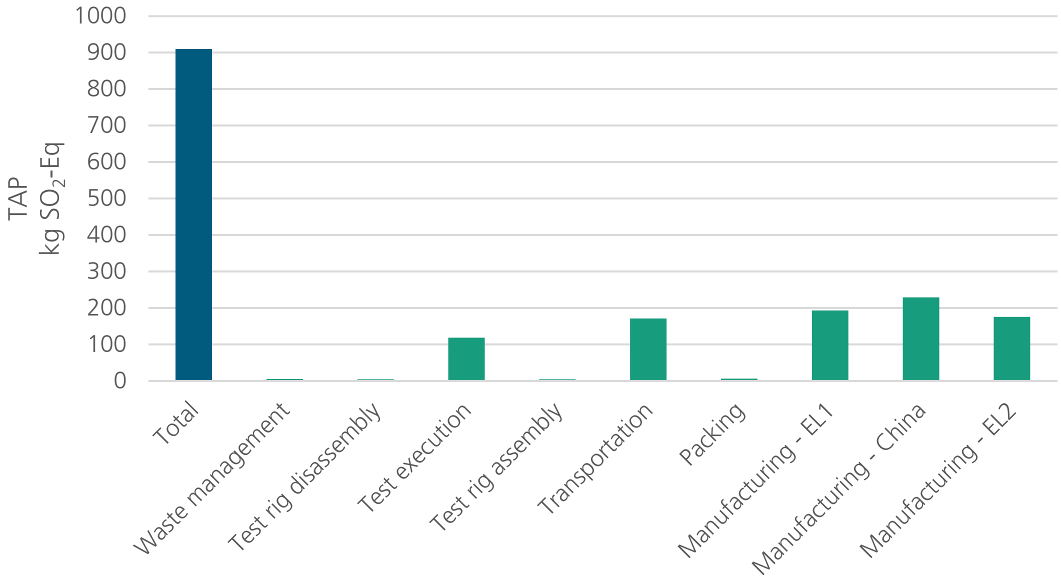

Figure 10. Contributions to terrestrial acidification potential by process.

4.3.2.2 Climate Change - Global Warming Potential (GWP100)

Figure 11 presents the contributions of each process to the total GWP100 for one endurance testing project. It can be appreciated that the manufacturing process dominates the contributions to this category with approx. 73%. This can be explained due to the high amounts of energy that are required for the steelmaking process and the high degree of fossil fuels usage during its production. Close to 59.5% of the total GHG emissions derive from the steelmaking process. On the other hand, the contributions from the machining processes are indeed smaller, but not negligible, with GHG emissions accounting for nearly 13.5% of the total.

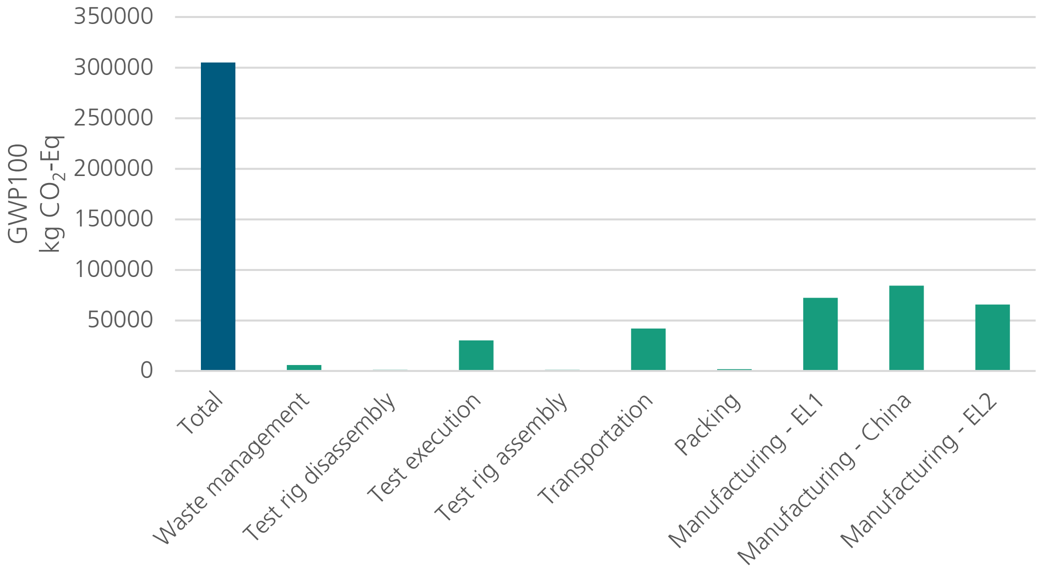

Figure 11. Contributions to climate change- global warming potential by process.

The test execution is also very energy intensive but the low contribution of only 10% of the total GHG emissions is explained due to the renewable energy supply that has been modelled for this scenario. The contribution for transportation is a little under 14%, from which most come from the road transportation (11.9%) and only a smaller share from the sea transportation for the machine elements coming from China (1.9%).

4.3.2.3 Ecotoxicity: Freshwater Ecotoxicity Potential (FETP)

Figure 12 shows that the main contributions to this impact category come again from the manufacturing of the machine elements and from the test execution itself (approx. 73 and 17% respectively).

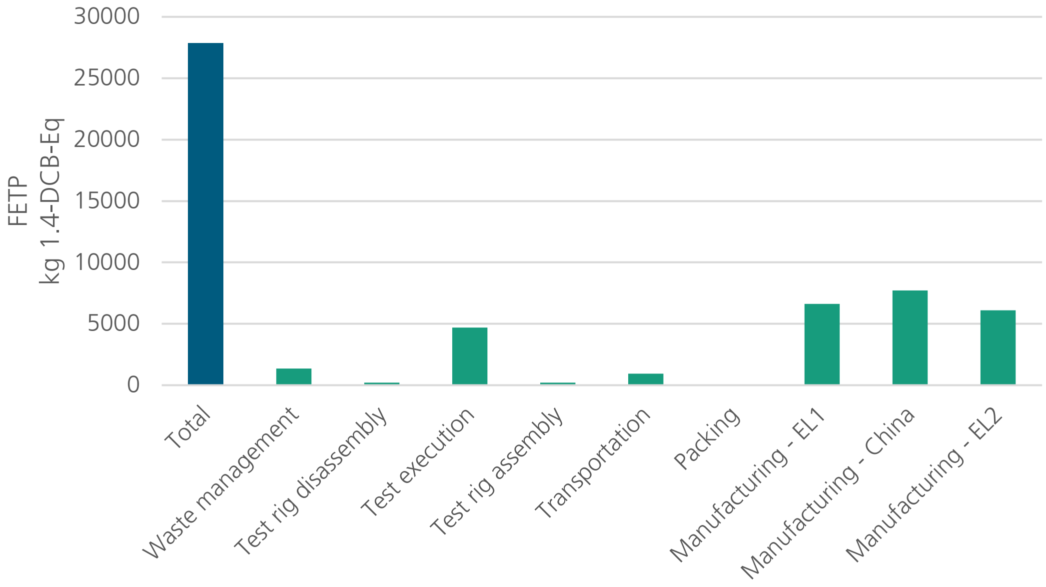

Figure 12. Contributions to freshwater ecotoxicity potential by process.

In the case of the manufacturing processes, most of the contributions come from the steelmaking and a smaller proportion from the machining operations (steel milling, drilling, and welding), while for the test execution the contributions can be traced back to the manufacturing of the renewable energy sources components (wind turbines and photovoltaic modules).

4.3.2.4 Ecotoxicity: Marine Ecotoxicity Potential (METP)

Figure 13 shows the individual contributions of each process to this impact category. It can be seen that the distribution is almost identical to the previous impact category (freshwater ecotoxicity potential). The manufacturing of the machine elements represents around 74% of the total emissions while the test execution is close to 16%.

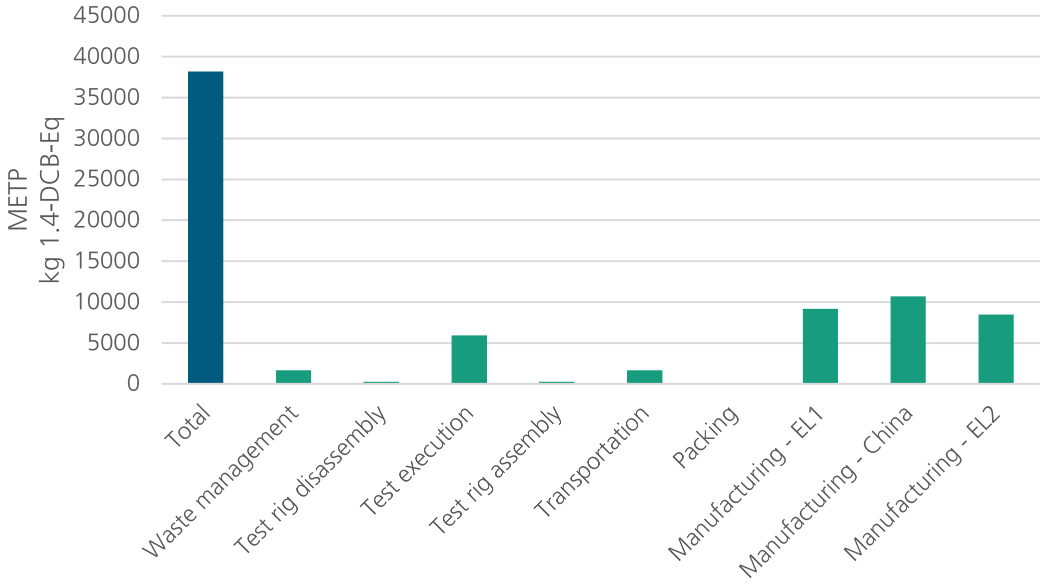

Figure 13. Contributions to marine ecotoxicity potential by process.

4.3.2.5 Ecotoxicity: Terrestrial Ecotoxicity Potential (TETP)

Figure 14 presents the contributions of each process into the total TETP. In contrast to freshwater and marine ecotoxicity, transportation plays a bigger role in TETP. This can be explained due to the treatment of brake wear emissions, which represent around 26% of the total contributions to terrestrial ecotoxicity potential. The manufacturing of the machine elements always represents the major contributor to this impact category, with approx. 55.7% of the total, contributions which come mainly from the steel making process and its respective supply chain emissions.

4.3.2.6 Energy Resources: Non-Renewable, Fossil Fuel Potential (FFP)

As seen in Figure 15, the manufacturing processes are also the main contributor to this category (70.4%). This is explained due to the high energy amounts needed for the steelmaking process. Other categories as transportation (18.3%) and test execution (8.5%) represent a smaller contribution. Test execution's contribution is very small because the electricity supply is from renewable sources instead of Germany's electricity grid.

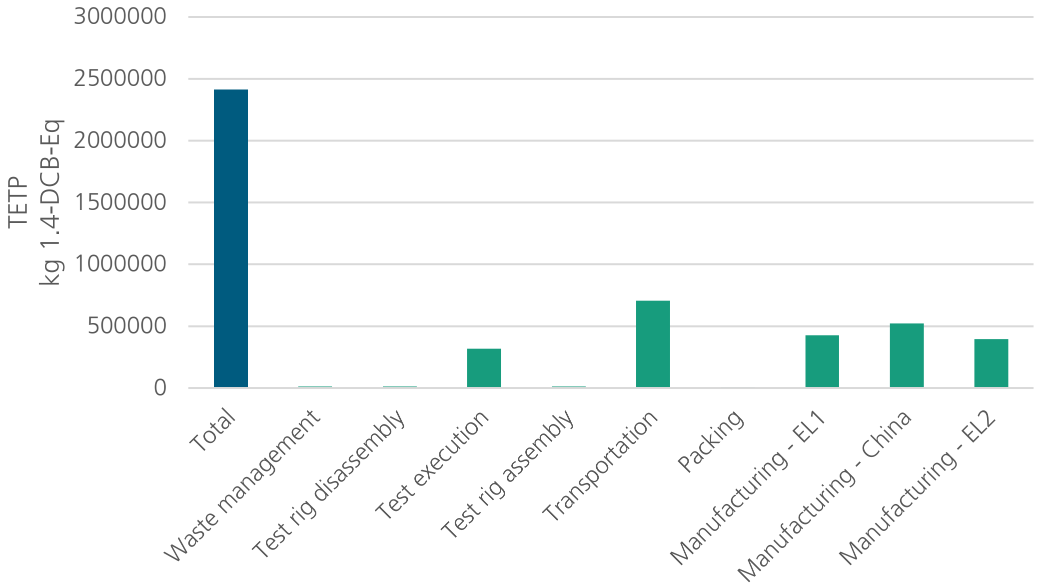

Figure 14. Contributions to terrestrial ecotoxicity potential by process.

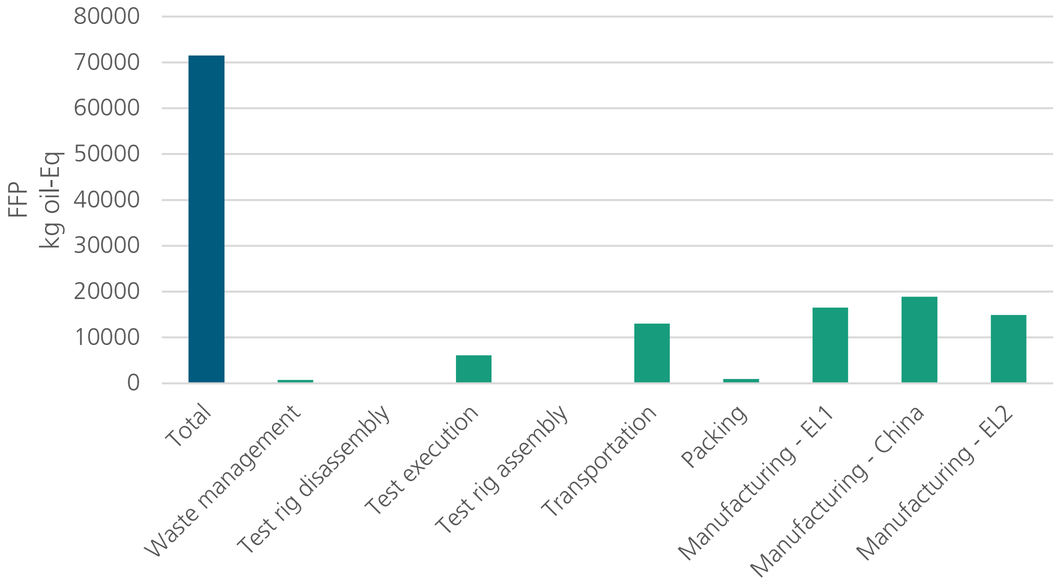

Figure 15. Contributions to non-renewable, fossil fuel potential by process.

4.3.2.7 Eutrophication: Freshwater Eutrophication Potential (FEP)

Figure 16 presents the contribution of each process into this impact category. It is easy to notice that manufacturing is the process with the highest contribution to this environmental impact with almost 90%. Digging a little deeper into this process, it is found that most of the contributions come from the pig iron production for steelmaking.

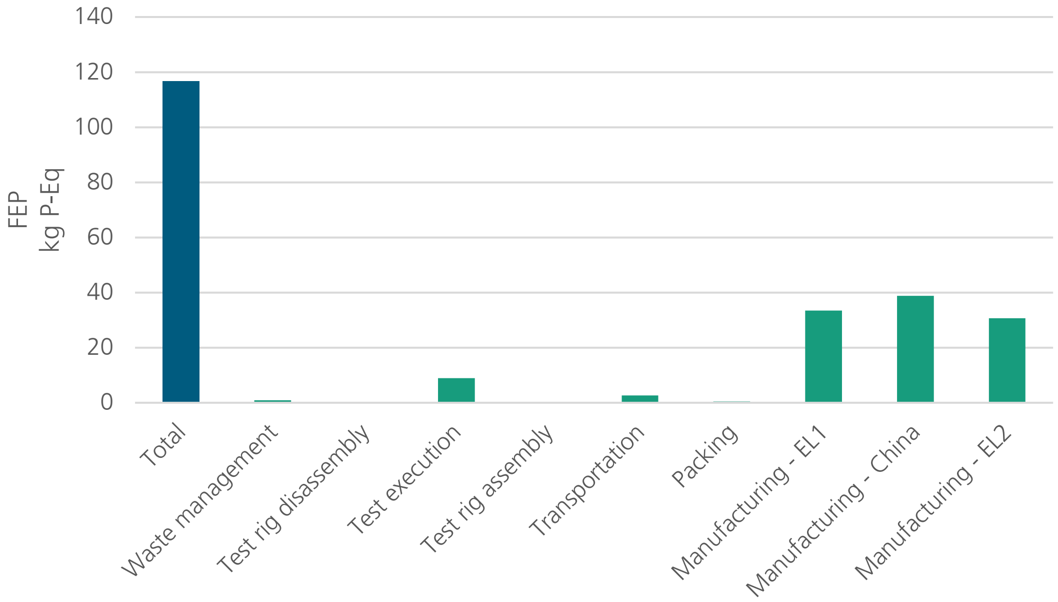

Figure 16. Contributions to freshwater eutrophication potential by process.

4.3.2.8 Eutrophication: Marine Eutrophication Potential (MEP)

Figure 17 presents the contribution of each process into this impact category. The results show that around 90% of the contributions come from the machine elements manufacturing process. From this process most of the emissions come from steel making. The contribution of test execution and transportation is a little under 5% each.

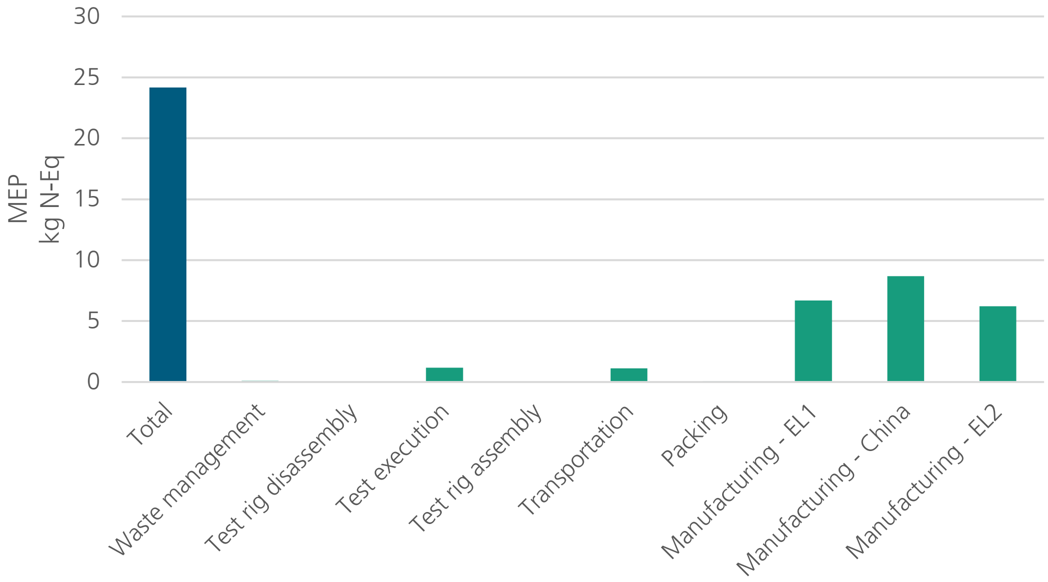

Figure 17. Contributions to marine eutrophication potential by process.

4.3.2.9 Human Toxicity: Carcinogenic - Human Toxicity Potential (HTPc)

As presented in Figure 18, almost all emissions (97.5%) for this impact category are produced during the manufacturing processes. Looking a little bit deeper, around 87% of the emissions come from the steel making process.

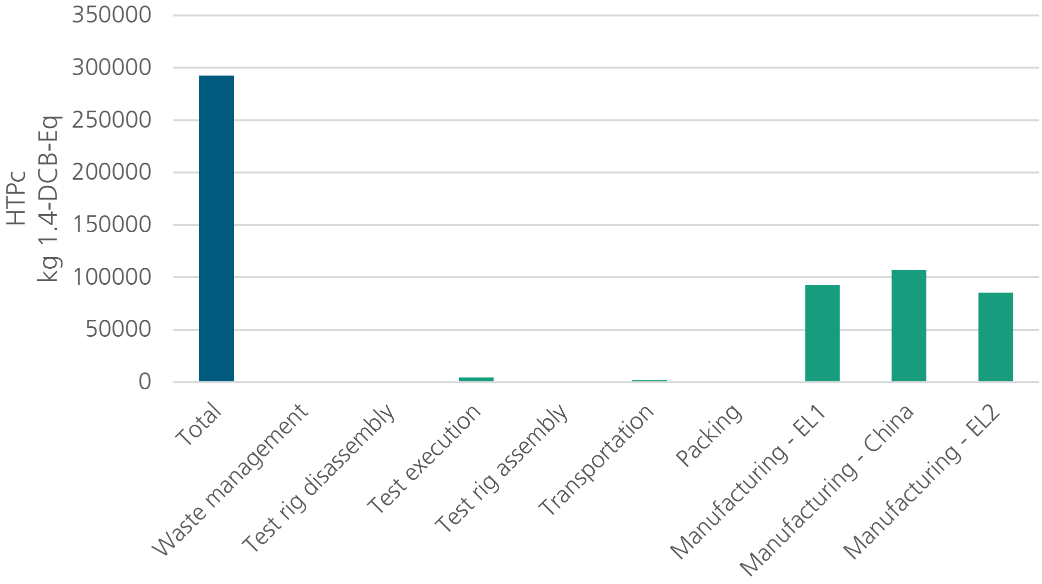

Figure 18. Contributions to carcinogenic - human toxicity potential (HTPc) by process.

4.3.2.10 Human Toxicity: Non-Carcinogenic - Human Toxicity Potential (HTPnc)

As appreciated in Figure 19, most of the contributions come from the manufacturing process, where most of the emissions come from the steelmaking process. A share of 12.5% of the total emissions of this category come from the test execution, emissions which come from the different renewable energy sources used to model the electricity supply.

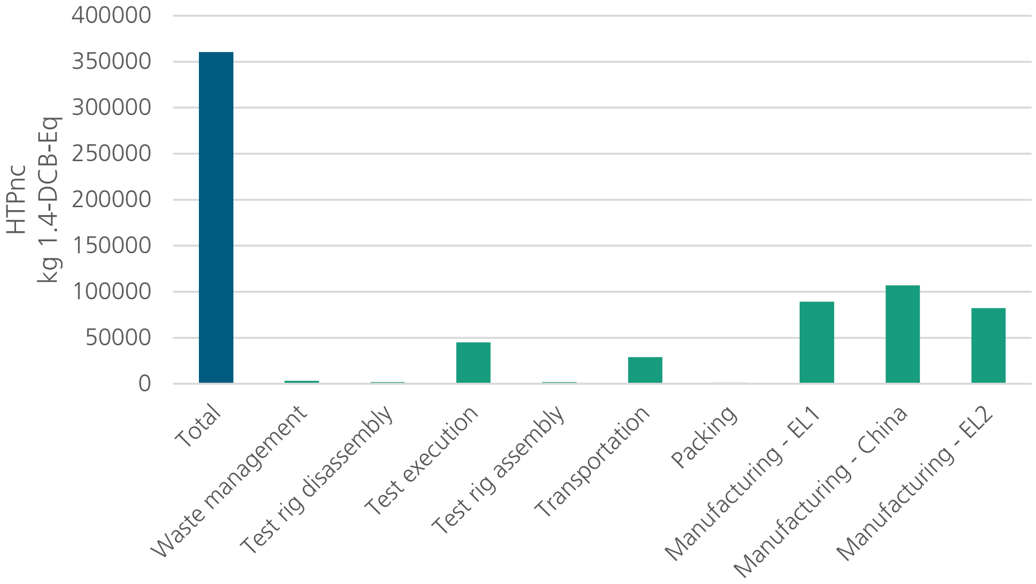

Figure 19. Contributions to non-carcinogenic - human toxicity potential (HTPnc) by process.

4.3.2.11 Ionising Radiation - Ionising Radiation Potential (IRP)

As it can be appreciated in Figure 20 almost all the emissions of this impact category come from the manufacturing phase (80%). When looking more closely, from this 80%, around 24% come from the machining operations (milling, drilling, and welding), while the resting 56% come from the steelmaking processes.

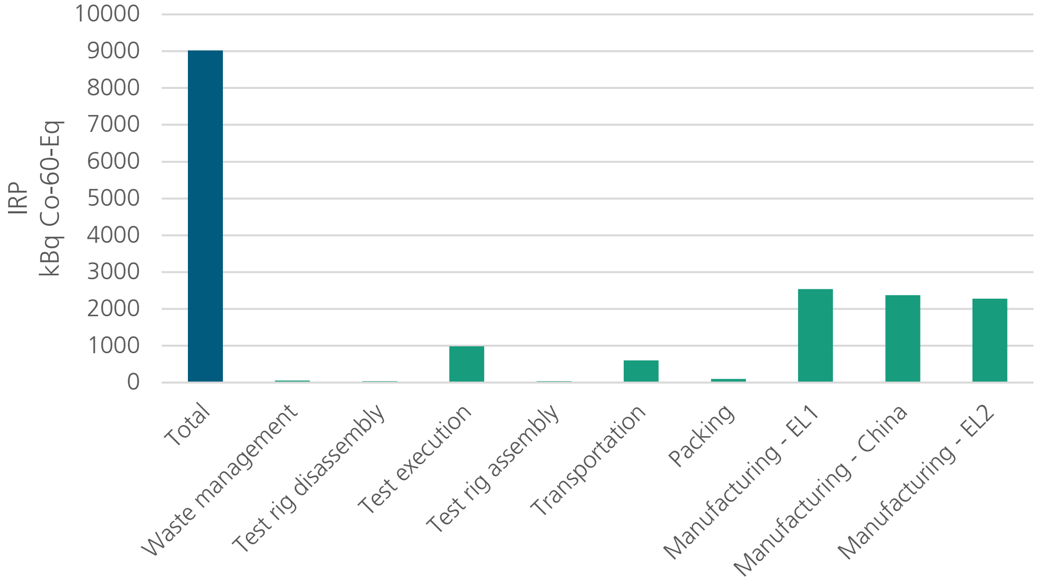

Figure 20. Contributions to ionizing radiation potential (HTPnc) by process.

4.3.2.12 Land Use - Agricultural Land Occupation (LOP)

Figure 21 shows the contributions from each process to the impact category. This is the first impact category where either the test execution or the manufacturing don't represent the main contribution.

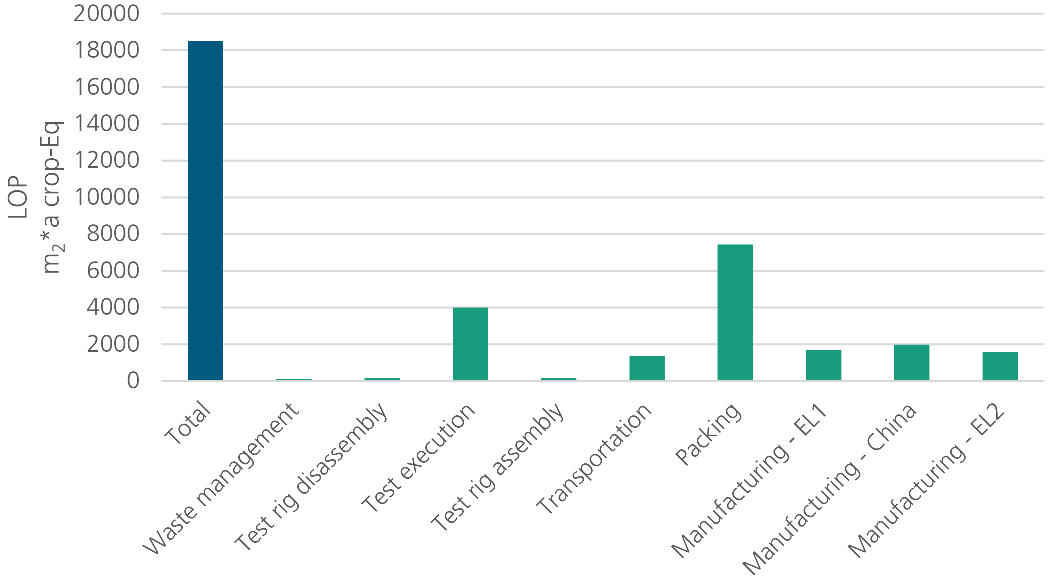

Figure 21. Contributions land use – agricultural land occupation (LOP) by process.

In this case, the packing of the machine elements for transportation represents around 40% of the total impacts, which can be explained by the wood that is used during this operation.

Manufacturing of the machine elements is the next in line with 28.5% of the contributions, in this case, most of them come from the mining of metals required for the steelmaking process.

4.3.2.13 Material Resources: Metals/Minerals - Surplus Ore Potential (SOP)

As shown in Figure 22, the manufacturing of the machine elements is the process which has the highest influence in this impact category with 96.8% of the total contributions. This is explained by the high amounts of steel that are required in this process and by the assumption that steel comes from the world market.

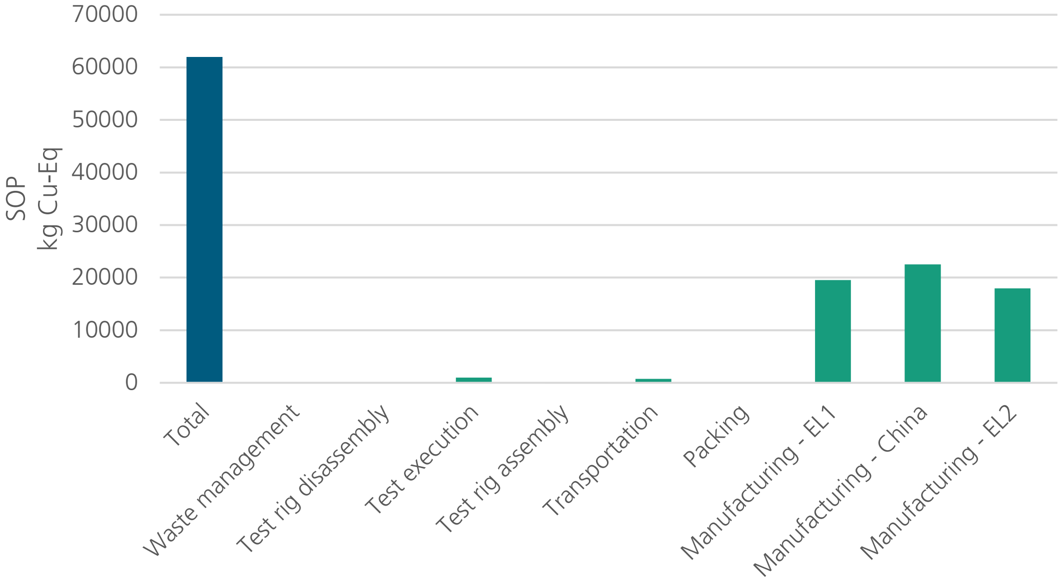

Figure 22. Contributions to metals/ minerals – surplus ore potential by process.

4.3.2.14 Ozone Depletion - Ozone Depletion Potential (ODPinfinite)

Figure 23 shows the contributions to this impact category by process. It can be appreciated that around 43% of the total emissions in this category come from the test execution. When digging a little deeper, almost all the emissions are generated due to the electricity share generated through biogas. Ozone depleting emissions are released during the anaerobic digestion of manure.

Manufacturing processes follow behind with approx. 33.6% of the total emissions of this category, of which most are released during the steelmaking process.

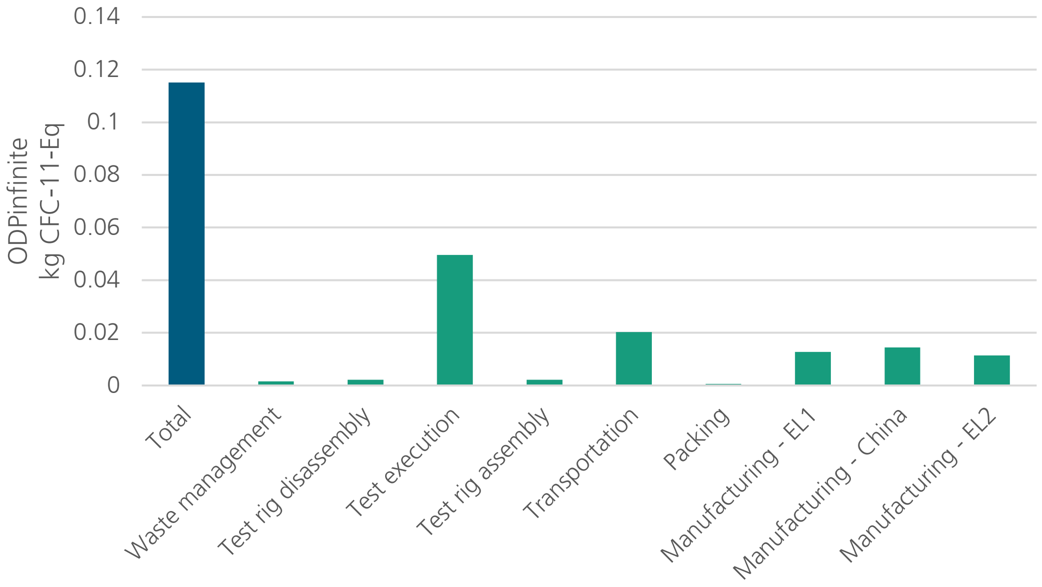

Figure 23. Contributions to ozone depletion potential by process.

4.3.2.15 Particulate Matter Formation Potential (PMFP)

The manufacturing process leads the total emissions in this category with nearly 77%, as shown on Figure 24, from which almost all are linked to the steelmaking process. Transportation is the process with the second highest contributions, with around 12.8% of the total emissions in this category.

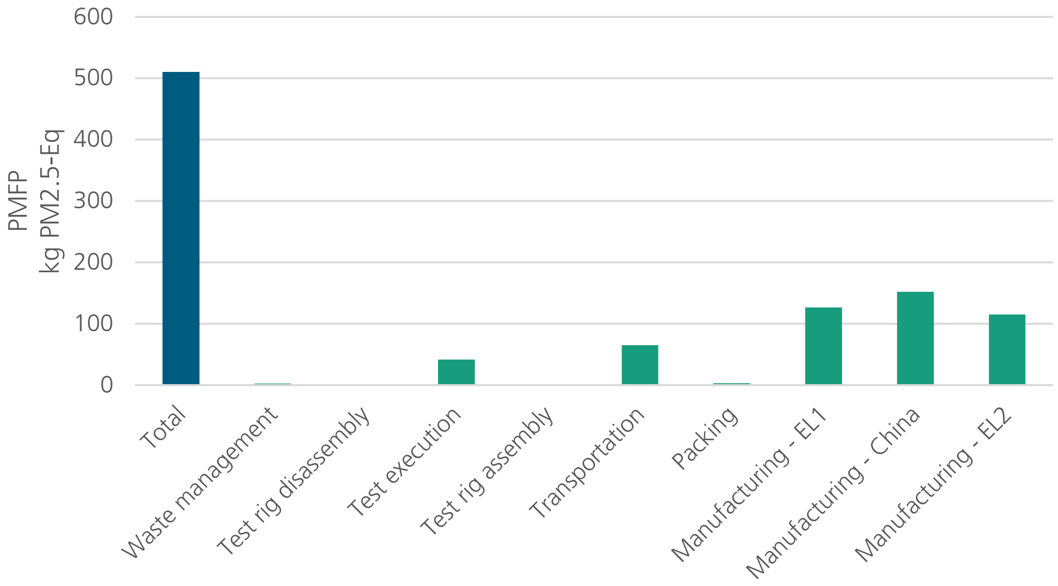

Figure 24. Contributions to particulate matter formation potential by process.

4.3.2.16 Photochemical Oxidant Formation Potential: Humans (HOFP)

As shown on Figure 25, the majority of the emissions of this impact category are concentrated in the manufacturing process (65.3%). Most of the emissions come from the steelmaking process. Transportation also plays an important role in this impact category, around 26.2% of the total contributions come from this process. These emissions are explained by the use of fossil fuels which release NO_x in the exhaust gases.

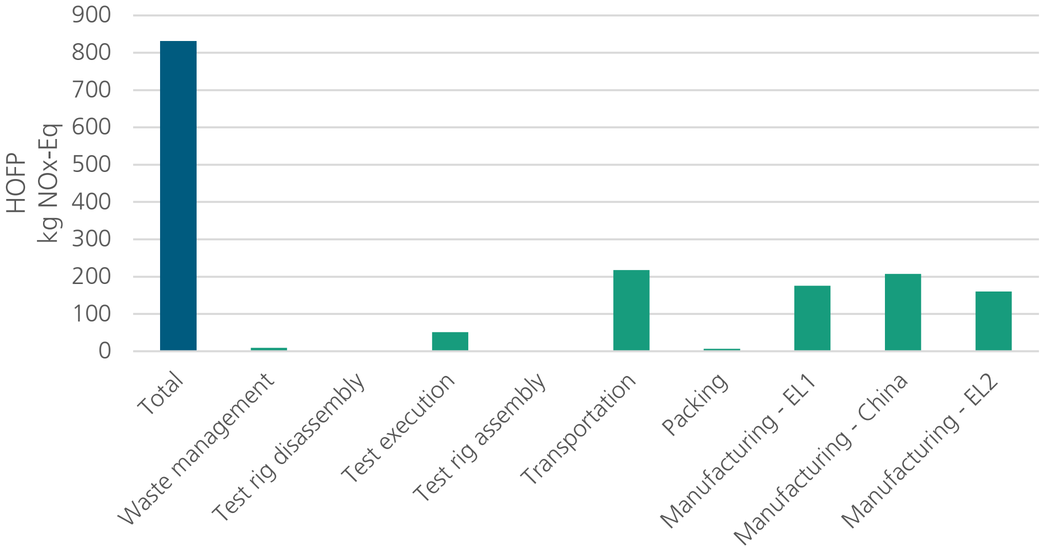

Figure 25. Contributions photochemical oxidant formation potential: humans, by process.

4.3.2.17 Photochemical Oxidant Formation Potential: Ecosystems (EOFP)

The distribution of emissions shown on Figure 26 is very alike the one from Figure 25. Most of the emissions come from the manufacturing process 65.7%, nevertheless the transportation process is also significant with around 25.5% of the total emissions of this impact category.

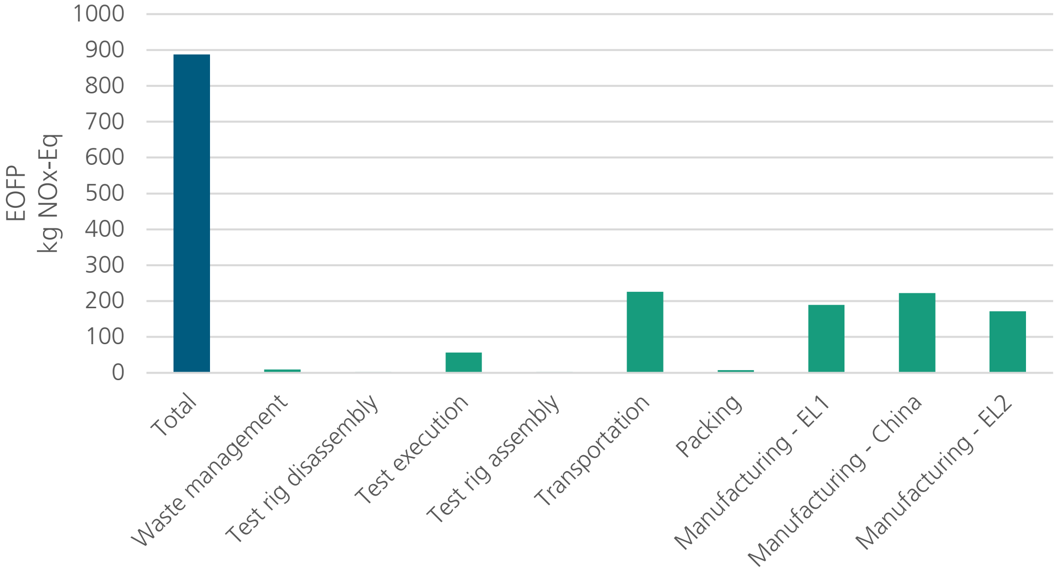

Figure 26. Contributions photochemical oxidant formation potential: ecosystems, by process.

4.3.2.18 Water Use - Water Consumption Potential (WCP)

As shown on Figure 27, almost all the contributions come from the manufacturing processes (around 81.7%). For the manufacturing, most of the contributions come from the steelmaking process, nevertheless the machining operations of drilling and milling also show to be significant (around 20% of the total contributions). The test execution contributes around 12.9% of the water consumption, most of which is linked to the photovoltaic modules production.

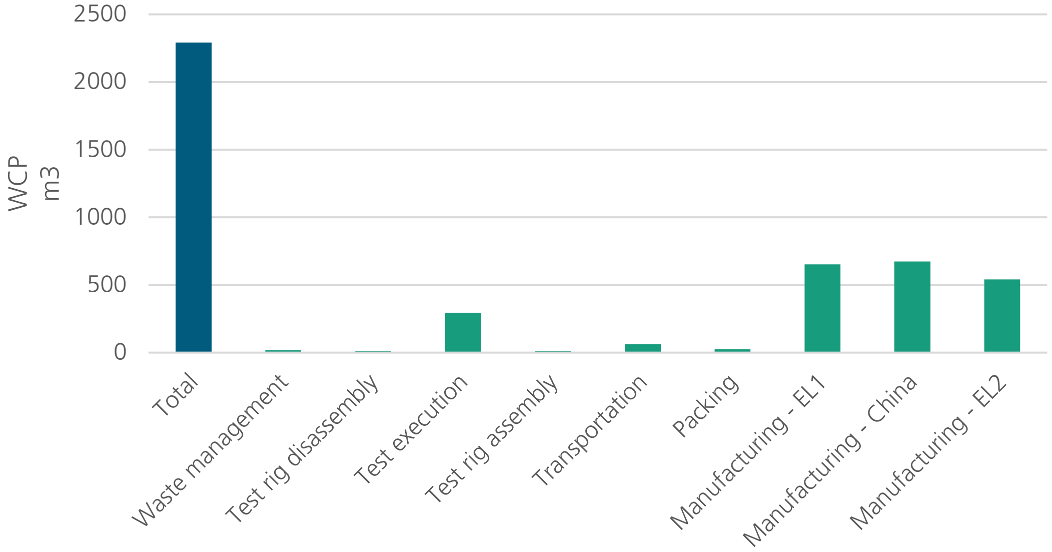

Figure 27. Contributions to water consumption potential, by process.

4.4 Interpretation

4.4.1 Life Cycle Impact Assessment Result

This section presents the interpretation of the environmental impacts results from one endurance test conducted with the BEAT 6.1 at the large bearing laboratory in Hamburg, Germany. The life cycle inventory has been modelled following the five accounting principles proposed by the greenhouse gas protocol and the cut-off criteria to ensure a high degree of data quality and representativeness of the testing activities.

The results presented in the impact assessment clearly show that the manufacturing of the machine elements dominate the contributions to almost all impact categories in the BAU scenario. In a deeper analysis, it can be seen that the contributions from steelmaking are much higher than those from the machining processes (steel milling, drilling, and welding). At this point, it is important to remark that these processes were modelled using the world market for steel supply, this dataset is available in ecoinvent 3.9.1 and provides a pondered average for different technologies and geographical location of suppliers. The mentioned dataset assumes that around 74.2% of the steel supplied in the global market is manufactured with Blast Furnace – Basic Oxygen Furnace (BF-BOF) technology and 25.8% with Electric Arc Furnace (EAF) technology. The most important difference between the two technologies is the raw material they use. While the BF-BOF technology uses mainly iron ore, the principal raw material for EAF is steel scrap. This brings up the question if reducing the total environmental impacts is possible by ensuring that the machine elements are manufactured using steel that has been produced using the EAF technology.

Despite the substantial electric energy consumption associated with the test execution, the results reveal that the environmental impacts associated with this process are less significant than initially expected. It is worth noting that the model contemplates a renewable electricity supply, therefore, to comprehensively evaluate the environmental implications this decision, a sensitivity analysis using Germany's electricity grid is to be conducted.

With regards to the electricity supply and the manufacturing processes, it is noted that the machining operations (from the machine elements suppliers) have been modelled using regional markets for electricity. While their environmental impacts are notably smaller than the ones coming from steelmaking, they are not negligible (for example, for GWP100, steelmaking represents around 59.5% of the total emissions, while machining processes share is close to 13.5%). Therefore, it becomes pertinent to investigate the potential environmental impact reduction resulting from a shift towards renewable energy sources by the suppliers responsible for manufacturing machine elements components that the LBL directly commissions.

The transportation process also shows a significant contribution to the overall environmental impacts of the analyzed system. While for some impact categories, such as marine and freshwater eutrophication (MEP and FEP) and ecotoxicity (METP and FETP), its contribution remains below 5%, there are other impact categories where its influence is notably higher. For instance, the contributions to the terrestrial ecotoxicity potential (TETP) accounts for around 30% of the total; the global warming potential (GWP100) close to 14% and the photochemical oxidant formation potential, in both human (HOFP) and ecosystems (EDFP), is around 26%. Notably, the contributions for TETP and WGP100 arise mainly from road transportation. Despite covering a distance seven times greater than road transportation, sea transportation exhibits relatively lower environmental impacts than road transportation in most of the impact categories, as an example, 11.9% of the emissions of GWP100 come from road transport while only 1.9% are emitted during sea transport. This observation paves the way for a comprehensive analysis of the transportation logistics for the machine elements. Exploring the potential for an alternative delivery route that leverages sea transportation from the manufacturing site to the port city of Hamburg, aiming to minimize the distance covered by road transportation and consequently, reducing the associated environmental impacts.

4.4.2 Sensitivity Analyses

The primary objective of the sensitivity analyses presented in this section is to pinpoint the repercussions of variations in the BAU process on the impact categories results that were outlined in the preceding section. These sensitivity analyses have been formulated through a rigorous analysis and interpretation of the results presented in the life cycle impact assessment chapter.

The scenarios to be analyzed and whose results are presented in this section include:

1. Ensuring the usage of steel produced in an electric arc furnace and proceeding from Europe in the manufacturing of machine elements that are directly commissioned by IWES.
2. Execution of endurance test using electricity sourced by the German electricity grid, instead of the renewable energy mix from the current provider.
3. Shifting the electricity supply from the grid to renewable energy sources of the suppliers of machine elements that are directly commissioned by IWES.
4. Exploring a new transportation logistic that minimizes the distance travelled by road.

4.4.2.1 Steel Produced with Electric Arc Furnace Technology in Europe.

As appreciated in the results shown on Figure 9, the contributions stemming from the manufacturing of the machine elements heavily dominate most of the impact categories analyzed in this study. It is worth noting that Fraunhofer IWES is only able to decide on the supply chain of some of the machine elements used for the test rig assembly, while other elements are provided by their counterparts. The machine elements that Fraunhofer IWES directly commissions account for 32% of the total mass of machine elements used for the studied testing project.

Table 9. Environmental impacts associated with endurance testing if machine elements commissioned by IWES are manufactured with steel produced through EAF technology in Europe.

Impact category	Reference unit	Business as usual scenario	Steel produced in Europe through EAF technology	Impact category variation
TAP	kg SO_2-Eq	909.6	776.5	-14.6%
GWP100	kg CO_2-Eq	304,910.2	262,142.5	-14.0%
FETP	kg 1.4-DCB-Eq	27,882.9	27,018.5	-3.1%
METP	kg 1.4-DCB-Eq	38,177.9	37,207.8	-2.5%
TETP	kg 1.4-DCB-Eq	2,412,322.8	2,113,695.6	-12.4%
FFP	kg oil-Eq	71,489.1	61,595.0	-13.8%
FEP	kg P-Eq	116.6	97.6	-16.3%
MEP	kg N-Eq	24.2	20.4	-15.6%
HTPc	kg 1.4-DCB-Eq	292,800.5	451,125.1	54.1%
HTPnc	kg 1.4-DCB-Eq	360,522.8	325,805.6	-9.6%
IRP	kBq Co-60-Eq	9,011.4	11,535.0	28.0%
LOP	m^2*a crop-Eq	18,523.8	17,823.4	-3.8%
SOP	kg Cu-Eq	61,992.6	45,710.9	-26.3%
ODPinfinite	kg CFC-11-Eq	0.1	0.1	-4.3%
PMFP	kg PM2.5-Eq	510.0	421.8	-17.3%
HOFP	kg NOx-Eq	831.3	711.7	-14.4%
EOFP	kg NOx-Eq	886.8	757.9	-14.5%
WCP	m^3	2,291.1	2,043.4	-10.8%

From the machine elements manufacturing phase, it was described in Section 4.3.2, that the steelmaking process is responsible for most of the emissions in almost all the environmental categories.

This sensitivity analysis focuses on determining the extent of variation on the environmental impacts that can be achieved if the machine elements that are directly commissioned by IWES are manufactured using steel that has been produced in Europe through EAF technology. Unlike the BF-BOF process which heavily relies on iron ore, EAF predominantly uses scrap steel as raw material.

Table 9 presents the results obtained for this scenario and compares them to the BAU scenario. The last column shows that the use of steel manufactured in Europe through EAF technology has a better performance in almost all impact categories (16/18).

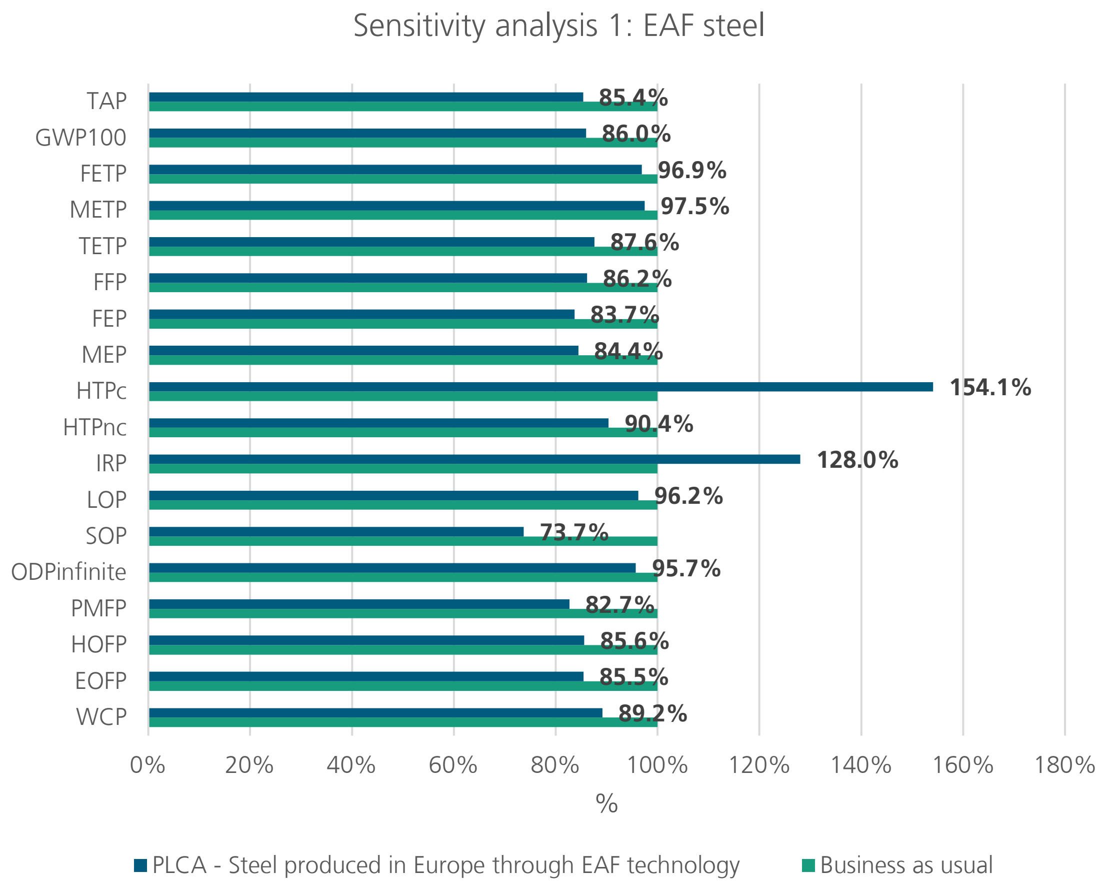

Figure 28. Variation in environmental impacts associated with endurance testing if machine elements commissioned by IWES are manufactured with steel produced in Europe through EAF technology.

It is worth noting that the reduction in the climate change indicator GWP100 is 14%, in other words, the reduction is nearly 43 ton of CO_2 equivalent; other noteworthy variations in the indicators are the reduction in non-renewable energy resources, also with 14%. Since this steel production process uses mainly recycled steel, the mineral resources indicator SOP also shows a much better performance with a reduction of 26% of its total contributions. These values seem even more relevant when compared to the share of steel mass to be analyzed in this sensitivity analysis (32%).

Figure 28 visually shows the variation in environmental impacts arising from the shift from world market for steel to steel produced in Europe through EAF as previously described. It can be clearly appreciated how most of the environmental impact categories show a significant reduction ranging from 10% to almost 27%; these results become more significant when noted that the machine elements considered in this scenario only account for 32% of the total mass of steel used for the manufacturing of all the machine elements used for the assembly of the test rig.

Nevertheless, not all the impact categories exhibit a positive behavior with this change. The human toxicity potential: carcinogenic (HTPc) shows a very significant increase of 54% when compared to the BAU scenario. The breakdown of the results obtained through the OpenLCA model attributes this increase to the slag waste that is produced in EAF steel manufacturing and subsequently landfilled. On the other hand, the study from Cappelletti et al. (2016), despite the limitations of a small control group, revealed a statistically significant increase of diabetes, cardiovascular diseases and death due to lung cancer in workers of an EAF steel mill and suggested that the outcome might be attributed to the numerous toxic and cancerogenic substances contained in the foundry dust/diffuse emissions released in the electric arc furnace.

4.4.2.2 Endurance Test Execution Using Electricity Coming from the Grid

As it was briefly explained in the interpretation of the life cycle assessment results, despite the substantial electric energy consumption associated with the test execution, results revealed that the environmental impacts associated with this process are less significant than initially expected. It is thought that these results might be the consequence of the renewable energy supply which was used in the model. Therefore, it is noteworthy to evaluate the effect of this electricity supply by conducting a sensitivity analysis using Germany’s electricity grid.

This sensitivity analysis has been conducted by modelling the processes that require electricity within the LBL (test rig assembly, test execution, and test rig disassembly) as they were supplied by Germany’s medium voltage electricity market, instead of the renewable energy mix that was modelled for the BAU scenario. The results obtained for this scenario are presented and contrasted with the BAU scenario in Table 10. The effects of the modification in electricity supply are evident and for most of the impact categories, a very significant increase in the emissions takes place; for example, the GWP100 increases in 48.8%, that represents a difference of nearly 149 ton of CO_2 equivalent. The non-renewable fossil fuel potential (FFP) also presents a similar result with an increase of around 55%, this is equivalent to an additional 39 ton of oil equivalent which would have to be burned to produce the required energy to execute the endurance test.

The highest variation happens on the ionizing radiation potential (IRP), with a percentual change of 469%; this happens because Germany’s electricity grid still made use of nuclear sources in the analyzed year, and the emissions analyzed in this impact category result from nuclear sources electricity production. The impact category with the second highest change is the freshwater eutrophication potential (FEP), with an increase of nearly 210% and it is explained due to the mining for lignite that is linked to Germany's electricity grid.

Table 10. Environmental impacts associated with endurance testing if the execution of the testing was done with electricity from Germany's electricity grid instead of renewable energy sources.

Impact category	Reference unit	Business as usual scenario	Test execution with electricity from Germany's grid	Impact category variation
TAP	kg SO_2-Eq	909.6	903.8	-0.6%
GWP100	kg CO_2-Eq	304,910.2	453721.1	48.8%
FETP	kg 1.4-DCB-Eq	27,882.9	32059.5	15.0%
METP	kg 1.4-DCB-Eq	38,177.9	44074.6	15.4%
TETP	kg 1.4-DCB-Eq	2,412,322.8	2261020.9	-6.3%
FFP	kg oil-Eq	71,489.1	110892.0	55.1%
FEP	kg P-Eq	116.6	360.7	209.3%
MEP	kg N-Eq	24.2	39.6	64.0%
HTPc	kg 1.4-DCB-Eq	292,800.5	302685.4	3.4%
HTPnc	kg 1.4-DCB-Eq	360,522.8	590903.7	63.9%
IRP	kBq Co-60-Eq	9,011.4	51340.2	469.7%
LOP	m^2*a crop-Eq	18,523.8	17247.0	-6.9%
SOP	kg Cu-Eq	61,992.6	61742.1	-0.4%
ODPinfinite	kg CFC-11-Eq	0.1	0.2	35.6%
PMFP	kg PM2.5-Eq	510.0	514.3	0.9%
HOFP	kg NOx-Eq	831.3	850.9	2.4%
EOFP	kg NOx-Eq	886.8	909.1	2.5%
WCP	m^3	2,291.1	2732.5	19.3%

On the other hand, there are some impact categories where the performance using the electricity grid is a little bit better than using renewable energy supply, but the variations are much smaller than the previously mentioned. For example, the agricultural land occupation (LOP) impact category shows a little bit worse performance under the renewable energy supply scenario, which arises from the agricultural lands whose usage is sometimes shifted to renewable energy installations.

The results presented on Table 10 and described in the previous paragraphs are shown graphically in Figure 29. There it can be appreciated that the scenario in which a renewable energy supply is assured performs significantly better in almost all the impact categories when compared to the scenario in which electricity coming from the German electricity grid is used.

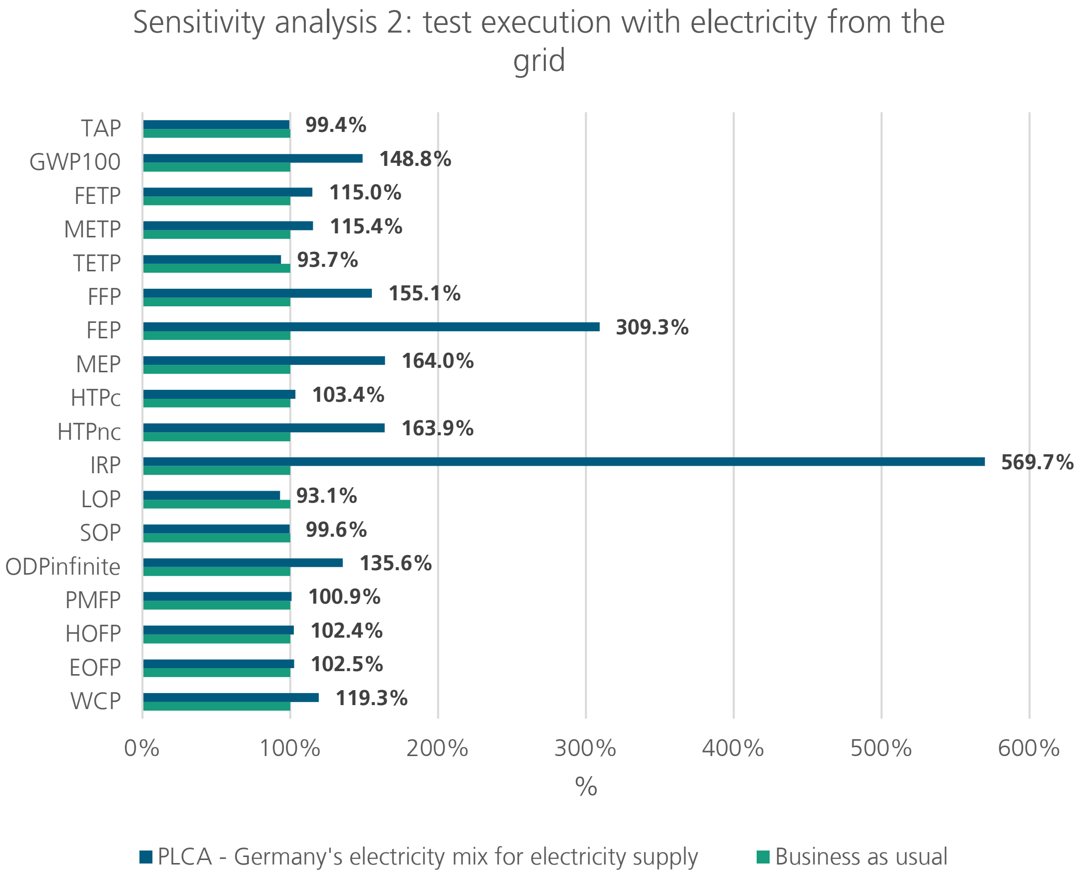

Figure 29. Variation in environmental impacts associated with endurance testing if the execution of the testing was done with electricity from Germany's electricity grid instead of renewable energy sources.

4.4.2.3 Shift to Renewable Energy Supply from Suppliers of Machine Elements Directly Commissioned by IWES.

As outlined in Section 4.4.1, the processes that show the greatest contribution to the total environmental impacts are related to the manufacturing of the machine elements. Among these processes, steelmaking has shown the greatest impact. However, the machining processes also play a not-negligible role. The results indicate that for some impact categories their contributions could be greater than 10% of the total emissions. For instance, in the case of GWP100, the machining processes are responsible for 13.5% of the total emissions.

With these findings in mind, the possible reduction in environmental impacts through an alternative electricity supply during the machining processes is addressed. For this sensitivity analysis, the manufacturing of the machine elements that are directly commissioned by Fraunhofer IWES (32% of the total machine elements mass) was modelled using a renewable energy supply; To simplify a little bit this scenario, it was assumed that the renewable energy matrix modelled for the BAU scenario could be employed for the milling, drilling, and welding processes.

Table 11. Environmental impacts associated with endurance testing if the manufacturing of the machine elements that are directly commissioned by IWES is done with renewable energy supply.

Impact category	Reference unit	Business as usual scenario	Machine elements manufacturing using electricity from renewable sources	Impact category variation
TAP	kg SO_2-Eq	909.6	906.4	-0.3%
GWP100	kg CO_2-Eq	304,910.2	303,529.2	-0.5%
FETP	kg 1.4-DCB-Eq	27,882.9	27,834.3	-0.2%
METP	kg 1.4-DCB-Eq	38,177.9	38,114.3	-0.2%
TETP	kg 1.4-DCB-Eq	2,412,322.8	2,410,684.3	-0.1%
FFP	kg oil-Eq	71,489.1	71,087.4	-0.6%
FEP	kg P-Eq	116.6	115.8	-0.7%
MEP	kg N-Eq	24.2	24.1	-0.2%
HTPc	kg 1.4-DCB-Eq	292,800.5	292,735.1	0.0%
HTPnc	kg 1.4-DCB-Eq	360,522.8	359,216.9	-0.4%
IRP	kBq Co-60-Eq	9,011.4	8642.3	-4.1%
LOP	m^2*a crop-Eq	18,523.8	18,525.3	0.0%
SOP	kg Cu-Eq	61,992.6	61,991.7	0.0%
ODPinfinite	kg CFC-11-Eq	0.1	0.1	0.0%
PMFP	kg PM2.5-Eq	510.0	507.8	-0.4%
HOFP	kg NOx-Eq	831.3	828.6	-0.3%
EOFP	kg NOx-Eq	886.8	884.1	-0.3%
WCP	m^3	2,291.1	2,281.1	-0.4%

Table 11 summarizes the results of the analyzed scenario and compares them with the BAU one. The results indicate that there is indeed a better performance in almost all the environmental impact categories, however, the observed improvement is very small to consider this a potential measure to reduce environmental impacts. Moreover, the observed reduction is too small and most likely would not justify the request to modify the process of the supplier. The only impact category where the variation in results is higher than 1% is the IRP, which is explained by the reduction in electricity generated through nuclear sources.

4.4.2.4 Transportation Logistic that Minimizes Road Transport

In Section 4.4.1, it was previously discussed that transportation is one of the three major categories of processes that have the highest impact on the total environmental footprint. The contributions from the transportation operations range between 5% to 26% in the BAU scenario. The analysis further revealed that, of the two used transportation methods, road transport had a significantly larger environmental impact than sea transportation.

This led to the proposal to set up a new transportation logistic which could minimize the distance covered by road and use more sea transportation instead. This is feasible, because both of the machine elements suppliers located in Europe have their facilities located in a city with access to a seaport.

Table 12. Environmental impacts associated with endurance testing with a transportation logistic that minimizes the distance covered by road.

Impact category	Reference unit	Business as usual scenario	Alternative transportation logistic	Impact category variation
TAP	kg SO_2-Eq	909.6	882.4	-3.0%
GWP100	kg CO_2-Eq	304,910.2	271,482.8	-11.0%
FETP	kg 1.4-DCB-Eq	27,882.9	27,022.8	-3.1%
METP	kg 1.4-DCB-Eq	38,177.9	36,648.1	-4.0%
TETP	kg 1.4-DCB-Eq	2,412,322.8	1,742,589.7	-27.8%
FFP	kg oil-Eq	71,489.1	60,864.1	-14.9%
FEP	kg P-Eq	116.6	114.3	-2.0%
MEP	kg N-Eq	24.2	23.2	-3.9%
HTPc	kg 1.4-DCB-Eq	292,800.5	291,126.9	-0.6%
HTPnc	kg 1.4-DCB-Eq	360,522.8	333,251.3	-7.6%
IRP	kBq Co-60-Eq	9,011.4	8,454.8	-6.2%
LOP	m^2*a crop-Eq	18,523.8	17,209.4	-7.1%
SOP	kg Cu-Eq	61,992.6	61,313.5	-1.1%
ODPinfinite	kg CFC-11-Eq	0.1	0.1	-14.1%
PMFP	kg PM2.5-Eq	510.0	491.5	-3.6%
HOFP	kg NOx-Eq	831.3	763.4	-8.2%
EOFP	kg NOx-Eq	886.8	812.0	-8.4%
WCP	m^3	2,291.1	2,236.2	-2.4%

Under the revised transportation scheme, machine elements that are manufactured in China, would still be received by IWES counterpart in a city in Europe, and then, all machine elements transported via water to Hamburg. From the port of Hamburg to the LBL, road transportation is to be used.

Table 12 presents the results obtained for the proposed transportation logistic designed to minimize the distance covered by road transportation. Notably, it reveals a significant reduction in all impact categories. The reductions in the total emissions range from 0.6% in the least affected category (HTPc) to 27.8% in the one with the highest variation (TETP). For this category, most of the contributions originally found their source in the treatment for brake wear emissions, hence the reduction. The GWP100 shows a reduction of 11% in the total CO_2 equivalent emissions, which translates to a decrease over 33 tons of CO_2 equivalent.

Figure 30 displays the variation in all environmental impacts. This graphic representation strongly showcases the substantial emissions reduction potential across all impact categories, thus underscoring the need for further analysis of the potential of this strategy.

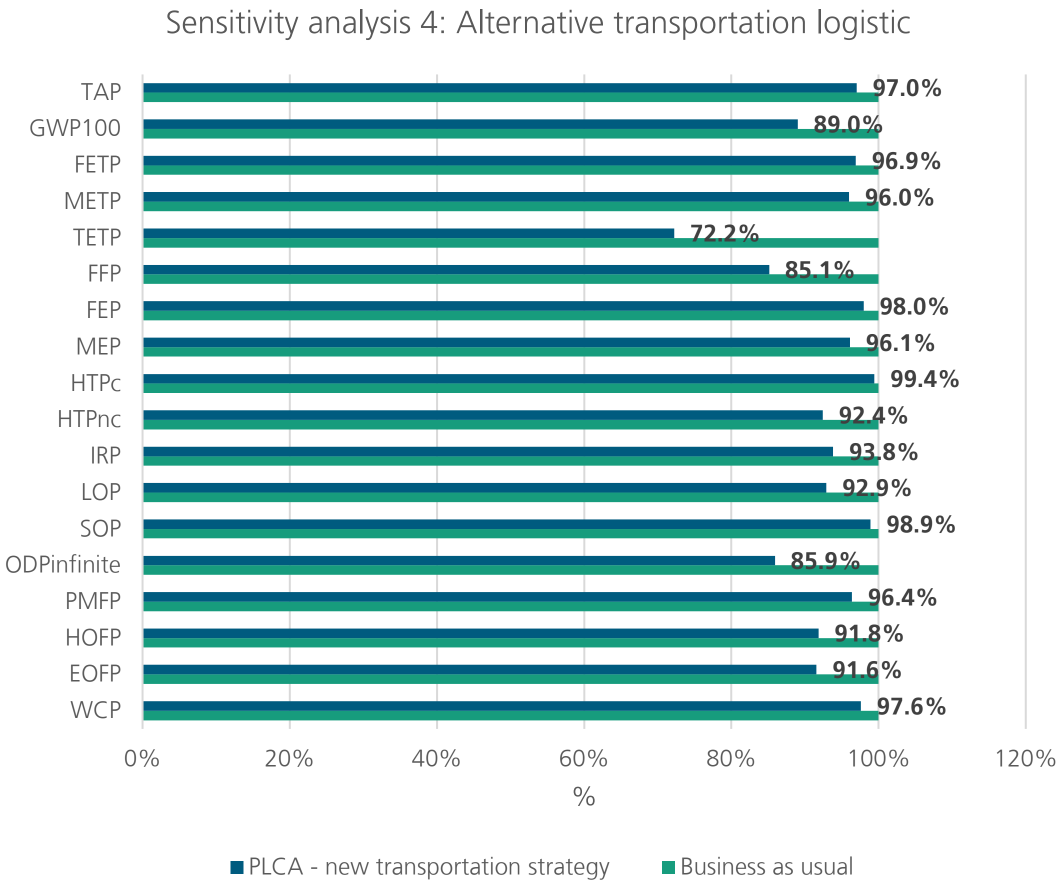

Figure 30. Variation in environmental impacts associated with endurance testing if a transportation logistic minimizing the distance covered by road is used.

4.4.3 Data Quality Checks

During the execution of this LCA, continuous checks for completeness, consistency and representativeness of the used data have been conducted throughout different stages of the study. All primary data provided by Fraunhofer IWES is representative for the analyzed project, the functional unit, and also for its period of execution (year 2020).

The following areas have been identified to have great influence on the environmental impacts and due to that reason, it is recommended that special attention to data quality is paid in future endurance testing LCA:

- Production datasets for low-alloyed steel
- Supply chain for low-alloyed steel
- Transportation logistic of all machine elements to the LBL
- Electricity supply for endurance testing

Fraunhofer IWES supplied a complete breakdown of the machine elements commissioned for this project, along with the respective suppliers. Additionally, they established an effective communication channel to facilitate information exchange and address inquiries from the LCA practitioner. The suppliers demonstrated willingness to respond to questions and provided available information, though certain details such as steel traceability were not possible to obtain.

It is worth emphasizing that the environmental contributions that have their origin in steelmaking for the machine elements manufacturing have a high impact. Therefore, it is highly recommended to make efforts to enhance the traceability in this regard, and if possible, to request the exclusive usage of steel manufactured through EAF technology. This study used ecoinvent 3.9.1 for steel production datasets.

Regarding transportation logistics, it was developed based on the geographical locations of the machine element suppliers and the LBL. To ensure the accuracy and representativeness of the real transportation process, project documentation was thoroughly examined, and inquiries were made to the project leader.

The electricity supply during the evaluated period could be analyzed based on electricity bills and historical data gathered with a power logger in the test hall. The same way as with transportation, all data used was carefully compared to the one presented in the project documentation and any remaining doubts were translated to the project leader.

Data used in the modelling of all the other processes (packaging, test rig assembly, test rig disassembly and waste management) followed a similar strategy, where information was first requested to the LBL team, and carefully contrasted with the official project documentation. For these processes, mass balances were also elaborated to ensure data completeness and consistency.

4.4.4 Conclusions

This study presents a detailed and representative assessment of the environmental impacts associated with the execution of an endurance test on pitch bearings for a period of 120 days at an average power of 120 KW. The life cycle assessment has been conducted in compliance with the norms ISO 14040:2006 and ISO 14044:2006; and as mentioned in the data quality check, it has been conducted following the five accounting principles proposed by the Greenhouse Gas protocol.

This study strongly suggests the effectiveness of previous measures in minimizing environmental impacts, particularly in ensuring a renewable energy supply for endurance testing. The results of this case study indicate that emissions across various impact categories would potentially be higher if an electricity supply from the German electricity grid were considered.

The BAU scenario results indicate that the way to reduce environmental impacts in the most significant way is to address the main raw material used for machine elements manufacturing, which is steel. The contributions from steelmaking constitute the most substantial fraction, exceeding half of the total project emissions in some impact categories. Furthermore, the sensitivity analysis emphasizes the feasibility of IWES suggesting their suppliers the adoption of steel produced through electric arc furnace (EAF) technology in Europe. While IWES may not have direct influence over all machine element suppliers, they can request this material choice from the specific supplier to whom they directly commission a significant portion of the machine elements, constituting 32% of the total mass. Implementing such change could result in substantial enhancements in the overall environmental performance, as highlighted by the sensitivity analysis.

Regarding transportation logistics, which results showed as one of the three most significant processes in terms of environmental impacts, road transportation was found to contribute a substantially higher share of environmental footprint compared to water transportation. Sensitivity analysis further revealed the potential for a new transportation strategy that could significantly reduce the environmental impacts of endurance test projects. This strategy involves minimizing the distance traveled by machine elements on the road and, instead, increase the distance traveled by water. This approach is feasible given the strategic locations of the LBL and European machine element suppliers in cities with access to ports. This situation seems promising because improvements in the results for all 18 analyzed impact categories are observed.

Finally, processes like packing, test rig assembly and disassembly, and waste management account for a minimal portion of the total environmental impacts. Thus, no specific short-term modifications to the business as usual scenario are proposed for these processes. However, the LCA practitioner recommends that LBL decision-makers continue their waste treatment strategies, which have proven effective in recycling waste steel and properly disposing of other waste materials, even if quantities are small.

5 Case study: Organizational Life Cycle Assessment (O-LCA)

5.1 Goal and scope Definition for the Organizational Life Cycle Assessment (O-LCA): Large Bearing Laboratory (LBL)

The present master thesis is an O-LCA and has been carried out by the practitioner Moises Guzman, an internal employee of Fraunhofer IWES, deployed at the Large Bearing Laboratory (LBL) in Hamburg. This study is to comply with the norms ISO 14040:2006, ISO 14044:2006 and TS/ISO 14072 (2014).

5.1.1 Goal

The present O-LCA is intended to analyze the complete operations of the Large Bearing Laboratory (LBL) for one year and to provide its personnel with guidelines to identify and understand the environmental hotspots of the organization, and to propose initial measures that could lead to an improvement in the environmental performance of the organization.

The Fraunhofer Gesellschaft has pledged for climate neutrality by 2030 (Fraunhofer-Gesellschaft e.V., 2021), therefore this study will significantly contribute to this goal by identifying opportunities to reduce environmental impact. At the moment, results are not intended to be published or shared with external stakeholders, nevertheless this could change during the development of the assessment. The present assessment is not intended to be used for comparative purposes with any other organization.

5.1.2 Scope

The Large Bearing Laboratory is a research facility belonging to the Fraunhofer-Institute for Wind Energy Systems (IWES), where pitch systems bearings for state-of-the-art wind turbines are tested (Fraunhofer IWES). A more comprehensive breakdown of this process can be found in the product life cycle assessment for endurance test for pitch bearing systems.

The reporting unit in this O-LCA is defined as 1 year of operation of the LBL (2020). This year has been chosen to be able to do an integration with the simultaneously conducted product LCA, which uses as a reference, a project done in the year 2020. It is worth noting that the Covid-19 pandemic resulted in some processes to be analyzed in this O-LCA to have a peculiar behavior, which might deviate from a business as usual year.

The present study is an O-LCA in which the complete operation of the LBL is analyzed and will include the following stages:

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

5.1.2.1 System Boundary

The system boundary of this study will consider the complete operation of the LBL for one year (2020), a cradle to grave approach is followed. A diagram of the system boundaries defined for this case study is presented in Figure 6. Basically, the system boundaries of the product LCA are expanded and adjusted to also include the operations of the LBL offices including data and IT services, and business travels.

It is worth noting that the reporting unit does not exactly match the testing period for the project analyzed in the product life cycle assessment, nevertheless, besides said project, during the year 2020, only minor testing activities, accounting for less than 5% of the test rig's electricity consumption were conducted, Therefore, these minor activities will be excluded from the system boundaries.

Conducting this organizational LCA requires the practitioner to gather information about all the machine elements that were acquired for testing in the analyzed year, the indirect upstream impacts from the raw materials, all the environmental impacts associated with the office's operation, electricity consumption, and information regarding business travels as well. Similar to the product life cycle assessment, this case study does not include the construction of the facilities where the testing activities are executed, the test rig foundations, and hydraulic system. This decision has been influenced by time constraints and the reasoning that their inclusion does not contribute to the main goal of this assessment. On top of that, these elements are not expected to be modified for future tests.

5.1.2.2 Cut-Off Criteria

A proportion of 1% (mass, energy, and environmental relevance) has been chosen as the cut-off criterion at system level. In addition, the portion to be cut off shall not exceed 5% per unit process.

5.1.2.3 Allocation Procedures

The system is already expanded enough to expect nearly no allocation complexities. Allocation revolving the endurance testing have already been addressed in the product LCA. For energy consumption, the electricity bills for the evaluated year are available, but they reflect the total consumption of the LBL facilities. Consumption for the test rig has been previously allocated.

Information regarding business trips carried out by car is only available for IWES as a whole, for this reason, an allocation based on the total number of employees will be made.

5.1.2.4 Modelling the Life Cycle Phases

The software OpenLCA and the database ecoinvent 3.9.1 are used to model the processes and the overall system; they have also been used to generate the life cycle inventories and impact assessment which are the base for the conclusions of this study. OpenLCA follows the approach of first modelling flows, which are followed by a process capable of generating said flow. Processes are gathered and used to simulate systems. When multiple systems are to be compared, they can be grouped in a project. OpenLCA allows the modelling of processes by using products and secondary processes which can be taken from the chosen databases, in this case ecoinvent. This database also allows the user to assign a geographic location to these processes, nevertheless there are several processes which have not yet been modelled for multiple locations.

For this assessment, the model elaborated for the product LCA is used for one of the two group of processes that make up this O-LCA, as described in Figure 31. Besides it, the processes needed for the operation of the offices are modeled. Likewise, waste generation and treatment associated with the offices is included in the model.

5.1.2.5 Impact Categories Selected and Methodology of Impact Assessment, and Subsequent Interpretation to be Used

This study follows an attributional, process based approach, which aims to quantify the relevant environmental flows related to LBL, based on physical and energy flows. In this case study, an initial model is created and called baseline, which serves as the business as usual (BAU) scenario. Sensitivity analyses are to be performed to evaluate the effect in environmental impacts that the modification of certain parameters could have.

The results of the inventories will be assigned to the impact categories which are shown on Figure 7, following the ReCiPe 2016 life cycle impact assessment (LCIA) method, which allows a harmonic way to characterize the impacts at midpoint and endpoint level (M.A.J. Huijbregts et al., 2016). Since Global Warming Potential (Carbon Footprint) is the impact category most relevant to the LBL team, The IMPACT 2002+ methodology, which offers a more straightforward and specific approach (Jolliet et al., 2003), has also been considered , nevertheless, the ReCiPe 2016 has gained a high degree of acceptance among LCA practitioners and it also benefits from recent data. A more detailed definition of the midpoint level impact categories assessed in this study is presented in Annex A. The assessment on this report limits itself to the midpoint categories shown on Figure 7; endpoint categories or damage pathways are not analyzed.

5.1.2.6 Data Requirements

This study follows the five accounting principles proposed by the Greenhouse Gas protocol (Greenhouse Gas Protocol, 2011) which are relevance, completeness, consistency, transparency and accuracy to ensure that the product inventory constitutes a true and fair representation of its environmental impacts.

To do so, high quality data is necessary, primary data is used for all processes under the ownership or control of the LBL. If primary data is not available or measurable, secondary data is used.

Among the data requirements that fall under the ownership or control of the LBL are:

- Electricity consumption during the analyzed year
- Manpower assigned to the LBL during the analyzed period
- End of Life (EoL) management strategy for projects outputs
- Waste generation and management procedures
- Electricity supply contract
- Office supplies and equipment bought during the analyzed year
- Historic data on business travels of the LBL employees
- Complete list of commissioned machine elements (including weight and material)

This study seeks to achieve a high level of data quality also for the machine element manufacturing processes that were commissioned for testing. Strategies to achieve this have been described in the product life cycle assessment study. Some of Information requested to suppliers is shown below:

- Composition of electricity supply
- Steel suppliers (Location, production technologies)
- Ratios of final product to raw materials
- Manufacturing technology

5.1.2.7 Assumptions

- For the modelling of the pitch bearing endurance test execution, all assumptions used in the Product LCA stand.
- Electricity bills are available, but they reflect the total consumption of the building including the offices and a server room. Constant monthly consumptions of 1280 KWh and 4000 KWh are allocated to the offices and server room respectively.
- Operations in the LBL were affected by the Covid-19 pandemic, for this reason, to model the commute to work process, it is assumed that personnel working at the LBL were in the offices an average of 1.5 days per week.
- Fraunhofer IWES documentation accounts for 17 employees at the LBL in the year 2020. In this study, it is assumed this number was constant throughout the year.
- Capital equipment is not included in the system boundaries of this study.
- Outsourced services as security and building maintenance services (including cleaning operations) are not included in the system boundaries.
- Business travel execution is limited to plane and car as transportation mode.

5.1.2.8 Limitations

- As mentioned in the assumption, operations in the LBL were highly affected by the Covid-19 pandemic, for this reason, the electricity consumption in the offices might have been smaller than under normal conditions, nevertheless this study limits itself to the available data.
- Information about business trips that Fraunhofer IWES employees performed by train is not available.
- Tracing machine elements supply chain specifications.

5.1.2.9 Type and Format of the Report Required for the Study

The reporting format will follow the regulations stated in the ISO 14044: 2006b in Sections 5.1 and 5.2 and the TS/ISO 14072: (2014).

5.2 Inventory analysis

5.2.1 Large Bearing Laboratory Organizational Operation

The flow diagram for the analyzed organization is shown on Figure 31. The analysis basically segments the organization into two different sections; the first one is the execution of pitch bearings endurance testing, which was studied in the product LCA, and the second one is the operation of the offices. For the description of the processes that make up the execution of the pitch bearings endurance testing, please see the product LCA study case. In this section, the processes that are modelled for the office's operations are described. The data presented has been obtained through Fraunhofer IWES reports, inquiries to employees, and some assumptions. A validation process using mass and energy balances has been conducted to assess the data quality gathered by the LCA practitioner.

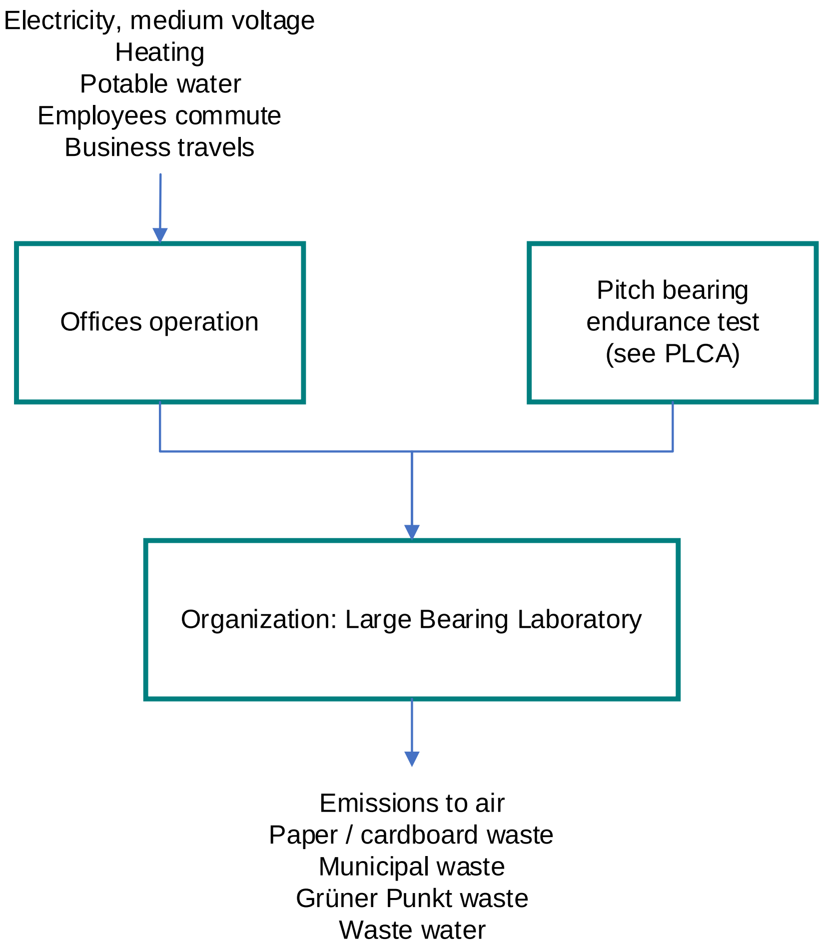

Figure 31. Flow diagram for the analyzed organization

5.2.1.1 Office's Services

This process takes into consideration the basic services that the LBL offices require to operate (electricity, potable water, and heating). Data for the electricity consumption has been obtained through allocation based on the electricity bills and the consumption of the test rig which was measured with a power logger. For potable water and heating, information was obtained directly from Fraunhofer IWES internal reports, in this case, no allocation was made. A summary is presented in Table 13.

Table 13. Summary of the basic services required for the operation of the LBL offices (2020)

Flow	Unit	Amount
Electricity	kWh	15411
Potable water	m^3	30
Heating	kWh	52968

5.2.1.2 Commute of Employees to the LBL

As previously mentioned, the year 2020 was very particular due to the Covid-19 pandemic. A lockdown was in place for a significant portion of the year; therefore, remote work saw a substantial increase and employees commuted less to the workplace. For this study, it is estimated that on average, each employee worked for 1.5 days per week in the LBL offices for 47 working weeks. Total commuting distances assumed for this study are presented in Table 14.

Data about the employees' commuting patterns was obtained through conversations with a group of individuals. Based on the obtained information, it is assumed that out of the 17 employees assigned to the LBL, 15 used public transportation for their commute to their workplace; for these cases, an estimated distance of 20 km between Hamburg city center and the LBL was considered in the model. Train transportation was used for the simulation of this process. For the employees who opted for car travel, a distance of 15 km is assumed for each of their commutes.

Table 14. Total commuting distances included in the model.

Commuting method	Flow	Units	Amount
Public transportation	Number of employees	employee	15
	Distance travelled per commute	km / commute	20
	Number of commutes	commute / employee	140
	Total distance travelled	**km**	**42,000**
Private car	Number of employees	employee	2
	Distance travelled per commute	km / commute	15
	Number of commutes	commute / employee	140
	Total distance travelled	**km**	**4,200**

5.2.1.3 IT and Data Services (Server Room)

The LBL has a server room which requires a cooling system to operate properly. The power consumption has not been measured but it has been assumed and allocated from the total electricity consumption of the facilities. It is assumed that 4000 kWh are needed per month to run the server room, accounting for a total of 48000 kWh in total during the analyzed year.

5.2.1.4 Office Supplies

This section considers the technological office supplies that Fraunhofer IWES provided to the LBL in the year 2020 to guarantee their employees had all the necessary tools to perform their tasks. The information regarding the list of equipment was provided by the IT department from Fraunhofer IWES and is shown on Table 15. It is important to mention that end of life management for this equipment has been included in the modeling of this process.

Table 15. IT supplies provided to the LBL in year 2020

Flow	Units	Amount
Laptop computer	Unit	15
Desktop computer	Unit	3
Mouse	Unit	5
Keyboard	Unit	5
Connection cable	Unit	12
Wi-Fi access point	Unit	2
USB flash drive	Unit	4
Docking station	Unit	14

5.2.1.5 Business Travel

In a typical year, some of the LBL employees conduct business trips, which are normally related to attendance to conferences, visits to clients or machine elements suppliers, or travelling to other IWES locations. These activities might include different ways of transportation such as long distance train, car, or plane.

Since 2022, Fraunhofer IWES increased its efforts to monitor information regarding plane travel, since it is considered to be the transportation mode associated with the highest environmental impacts, nevertheless there is no official report on plane travels for the year 2020. However, 2020 stands out as an anomaly due to the Covid-19 pandemic, and according to the employees deployed at the LBL, no business trip involving plane travel were executed that year.

Fraunhofer IWES provided data regarding the total distance covered by car during business trips for the analyzed year, nevertheless the information is not broken down for different IWES locations. An approximate distance of 3600 km was allocated to the LBL based on the total distance covered by car, and the percentage of IWES employees deployed at this location. Unfortunately, information regarding long distance train travel has not been monitored and therefore it is not considered in this study. In this study, business travel does not consider environmental emissions related to accommodation, only mobility.

5.2.1.6 Waste Management

The operation of the LBL offices directly contributes to the generation of different kind of waste, which are summarized in Table 16. This information has been obtained from Fraunhofer IWES internal reports for the year 2020 and is expected to be accurate. It is assumed that all potable water used in the building is also disposed as wastewater.

Table 16. Summary of waste generated by the LBL in the analyzed period.

Flow	Unit	Amount	EoL management
Paper waste	kg	3340	Recycled
Various packaging	kg	408	Collected by Grüner Punkt
Municipal waste	kg	460	Market for municipal waste
Wastewater	m3	30	Wastewater treatment

5.3 Impact Assessment

5.3.1 Summary of Results

An overview of the environmental impacts associated with the large bearing laboratory as an organization is presented in Table 17. As it was mentioned in Section 5.2.1, the processes analyzed in this study can be grouped in two groups, the processes corresponding to the endurance test and those related to the operation of the offices. Table 17 also presents the contribution from each of those processes' groups. It can be appreciated in the last two columns that the contributions arising from the endurance testing are much higher than those from the office operations. Results have been obtained using the software OpenLCA and the system has been modelled making use of the ecoinvent 3.9.1 cut-off database. The impact categories presented correspond to the LCIA method ReCiPe 2016, midpoint (H). The (H) makes reference to a hierarchist time horizon, which considers the environmental impacts for 100 years. The midpoint impact categories definition is available in Annex A. A more detailed presentation of the results comes in the following section.

Table 17. ReCiPe 2016 midpoint impact results for the LBL as an organization (O-LCA) and its two corresponding group of processes; endurance test execution (PLCA) and office operation.

Impact category	Unit	Large Bearing Laboratory	Endurance test execution	Office operation
TAP	kg SO_2-Eq	959.9	909.6	50.4
GWP100	kg CO_2-Eq	333,900.0	304,910.2	28,989.8
FETP	kg 1.4-DCB-Eq	31,247.7	27,882.9	3,364.8
METP	kg 1.4-DCB-Eq	42,534.9	38,177.9	4,357.0
TETP	kg 1.4-DCB-Eq	2,555,368.6	2,412,322.8	143,045.8
FFP	kg oil-Eq	79,265.4	71,489.1	7,776.3
FEP	kg P-Eq	123.2	116.6	6.6
MEP	kg N-Eq	25.5	24.2	1.3
HTPc	kg 1.4-DCB-Eq	294,901.6	292,800.5	2,101.0
HTPnc	kg 1.4-DCB-Eq	404,739.7	360,522.8	44,216.8
IRP	kBq Co-60-Eq	11,730.0	9,011.4	2,718.6
LOP	m^2*a crop-Eq	19,582.8	18,523.8	1,059.0
SOP	kg Cu-Eq	62,609.1	61,992.6	616.5
ODPinfinite	kg CFC-11-Eq	0.1	0.1	0.0
PMFP	kg PM2.5-Eq	531.5	510.0	21.6
HOFP	kg NOx-Eq	869.3	831.3	38.0
EOFP	kg NOx-Eq	927.9	886.8	41.1
WCP	m^3	2,417.5	2,291.1	126.3

Figure 32 and Figure 33 present in a visual way the results shown on Table 17; While Figure 32 depicts a comparison in percentages, Figure 33 displays the absolute values of the contributions to each environmental impact category in absolute values. It can be clearly appreciated that the analyzed impact categories are more affected by the contributions coming from the endurance test execution; group of processes which have been carefully analyzed in the product LCA study case. Even though the results for each impact category will be analyzed deeper in the following sections, it is worth noting some significant results.

Figure 32. Overview of each group of processes to the total organizational environmental impacts.

For the GWP100, 91.3% of the $CO_{2=eq}$ contributions come from the endurance testing, while only 8.7% come from the office operations. Some other remarkable impact categories, for which the contribution from the office's operation is below 10% are the non-renewable fossil fuel potential, agricultural land use, material resources or mineral ore potential, and water consumption potential.

The breakdown of the contributions arising from each of the processes that belong to the endurance test execution has been presented and analyzed in the product LCA study case. While the contributions for the processes grouped in the office operation are to be analyzed in the following section, even if their total share is much smaller than the analyzed product. An initial breakdown of the contributions of these processes into each environmental impact category is presented in Figure 34.

At a first glance, it can be noted that there is no process that dominates the contributions to all impact categories (in contrast to the product LCA, which was heavily dominated by the manufacturing of machine elements). To start the analysis, it could be mentioned that under the operational circumstances of the reporting unit (year 2020), business travel and waste management have the lowest contributions in almost all impact categories. The process modelling the employees' commute to the workplace also has low overall contributions, with the exception of the ionizing radiation potential (IRP) impact category, which is dominated by this process.

Figure 33. Comparison of the environmental impact contributions between the endurance testing processes and the office operation processes in absolute values.

On the other hand, the three processes that seem to dominate the contribution shares of the total environmental impacts are the office's basic services, data server operation and office supplies. In the case of the first two mentioned, this could be explained due to the high energy requirements from these processes. The office supplies could be linked to the environmental impacts arising from the manufacturing and waste management of the IT equipment.

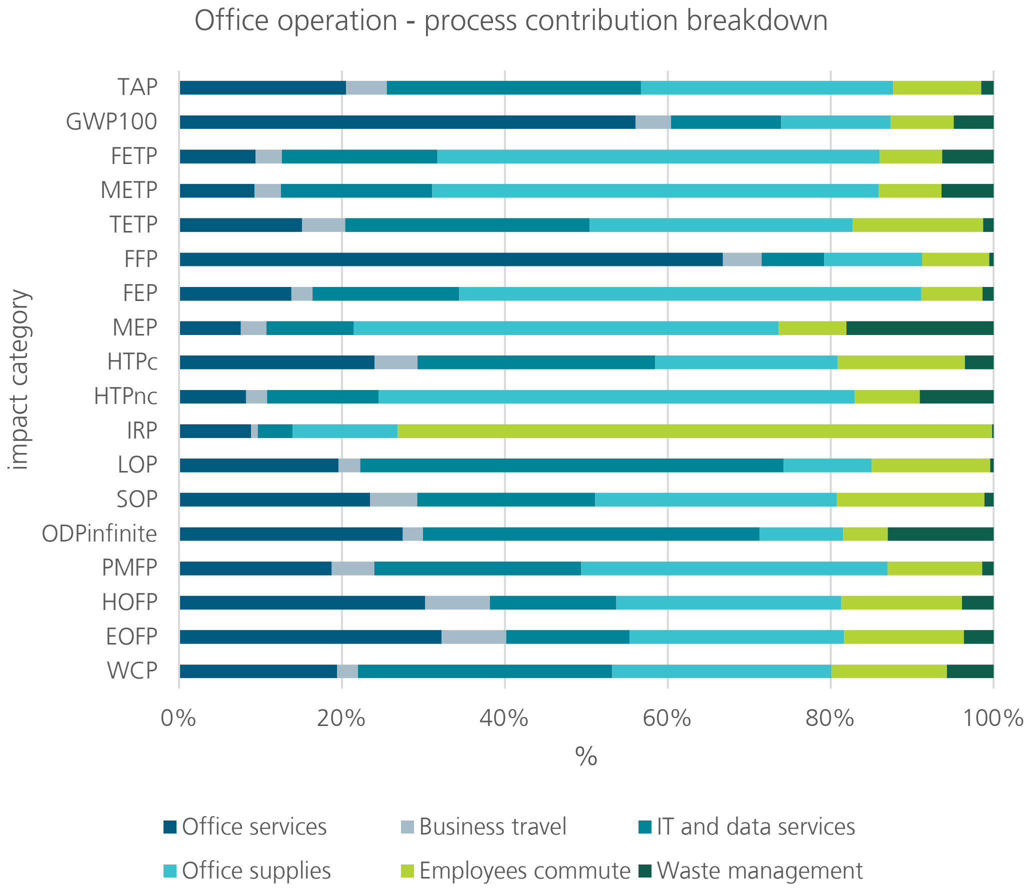

Figure 34. Breakdown of the environmental contributions for the processes that have been grouped in the office operations.

5.3.2 Impact Categories Results Analysis

5.3.2.1 Acidification: Terrestrial - Terrestrial Acidification Potential (TAP)

Figure 33 presented the absolute contributions that each of the analyzed group of processes have into the total terrestrial acidification potential impact category. There is appreciated that the execution of the endurance test has a much more significant impact than the offices operation (94.8% versus 5.2%). The breakdown for the processes that have been grouped in the endurance test execution have already been analyzed and can be found in the product LCA study case. For the group of office operation, office supplies and IT and data services are the processes with the highest contributions to this impact category, as appreciated in Figure 35. This can be explained due to the high amount of energy that the server room needs to operate and from the manufacturing of the technological equipment.

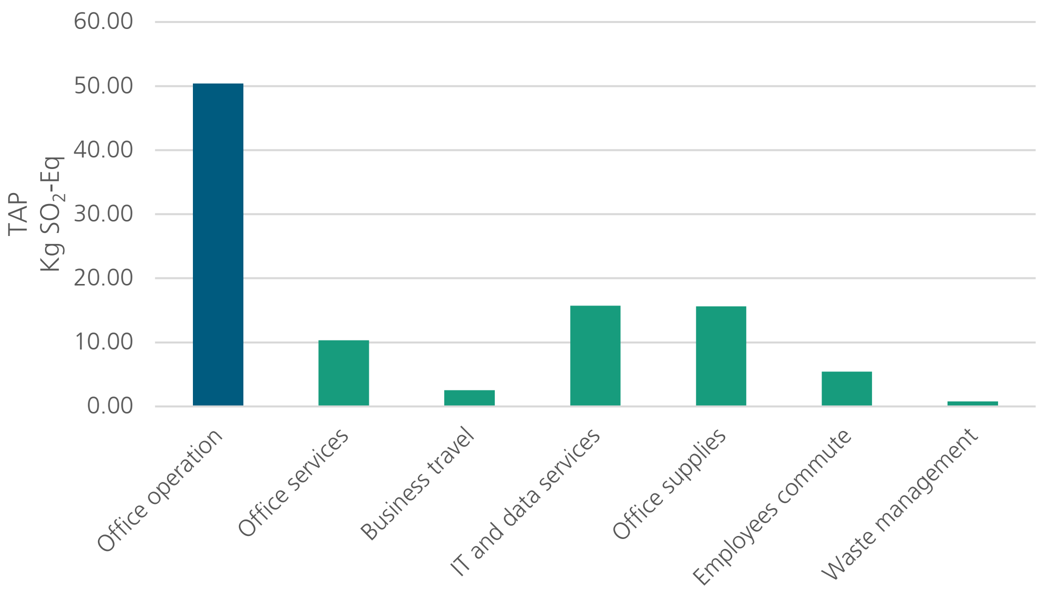

Figure 35. Contributions to terrestrial acidification potential, breakdown for each office operation process.

5.3.2.2 Climate Change - Global Warming Potential (GWP100)

The $CO_{2=eq}$ emissions arising from the office operations account for 8.7% of the organizational carbon footprint for the year 2020, while the emissions coming from the endurance test execution represent 91.3% as shown on Figure 32 and Figure 33. For the analysis of the breakdown of the processes grouped in the endurance test execution, proceed to the product LCA study case. Even if the emissions arising from the office operations are much smaller, it is worth analyzing the distribution of the contributions of each of its processes.

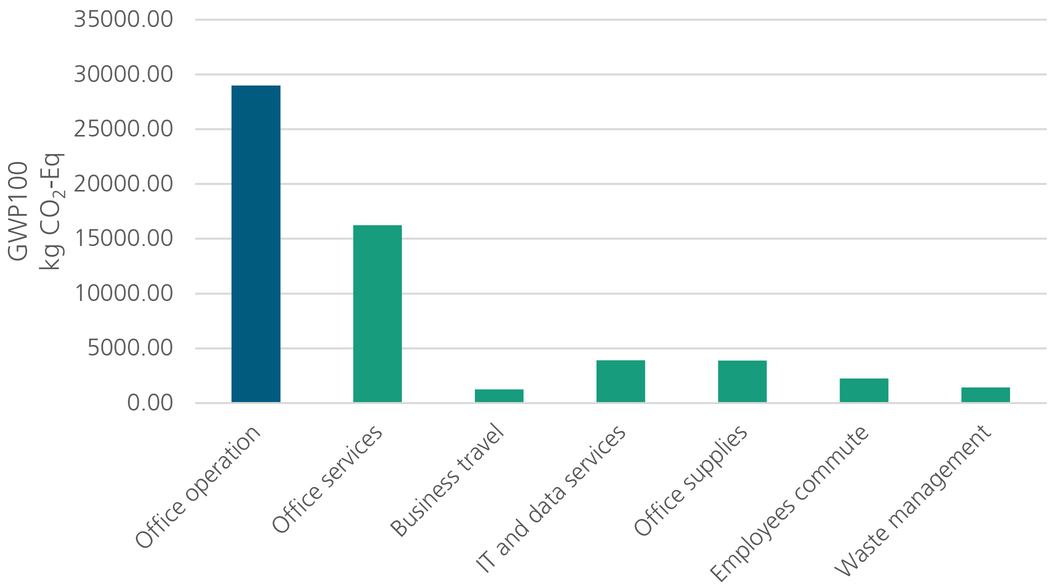

Figure 36. Contributions to GWP100, breakdown for each office operation process.

In Figure 36 can be observed that more than 50% of the total $CO_{2=eq}$ emissions originate from the office's basic services. A deeper analysis shows that the heating supply is responsible for most of the mentioned emissions. IT and data services account for 13.5% of the total contributions to this category, which is linked to the high amount of energy consumed by the server. Under the analyzed conditions, the contributions from business travel are very low (4.3%), but this might have been different if Covid-19 had not caused business travel to be reduced as significantly as it did.

5.3.2.3 Ecotoxicity: Freshwater Ecotoxicity Potential (FETP)

For this category, the contributions originating from the office operations add up to 10.8%, while the 89.2% remaining comes from the group of processes corresponding to the execution of the endurance tests as seem in Figure 33. The breakdown and analysis of the contributions arising from the endurance test execution can be found in the product LCA study case.

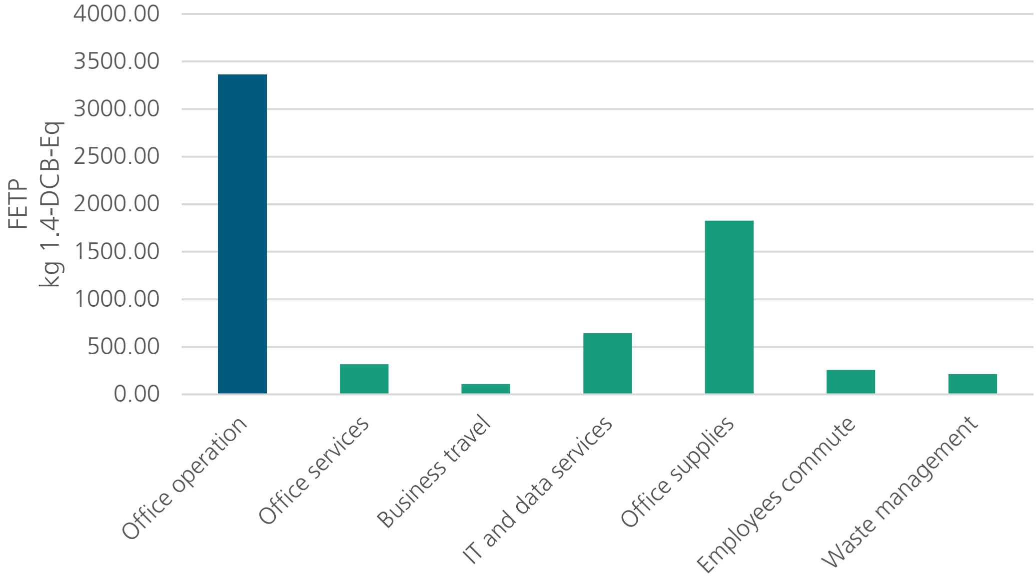

Figure 37. Contributions to FETP, breakdown for each office operation process.

Figure 37 presents the contributions of the processes that have been grouped into the office operation. It can be appreciated that most of the contributions in this category find their origin in the office supplies (54%), what is explained by the manufacturing processes of computers and laptops. Besides IT and data services (19.1%), all other processes have a contribution lower than 10% of the total FETP.

5.3.2.4 Ecotoxicity: Marine Ecotoxicity Potential (METP)

The comparison of the absolute contributions between the two group of processes (endurance test and office operation) to the marine ecotoxicity potential is shown on Figure 33. It can be appreciated that the distribution is also very similar to the previous category (FETP), with 10.2% of the total emission originating from the office operations and around 90% in the endurance test group of processes.

The breakdown and analysis of the processes that belong to the endurance test group can be found in the product life cycle assessment study case; while Figure 38 presents the contributions from the processes that have been grouped into the office operation. It can be observed once again that the distribution is very likely to the FETP, with 54.8% of the total contributions coming from the office supplies process. IT and data services account for 18.6% and all of the other processes contribute less than 10% each.

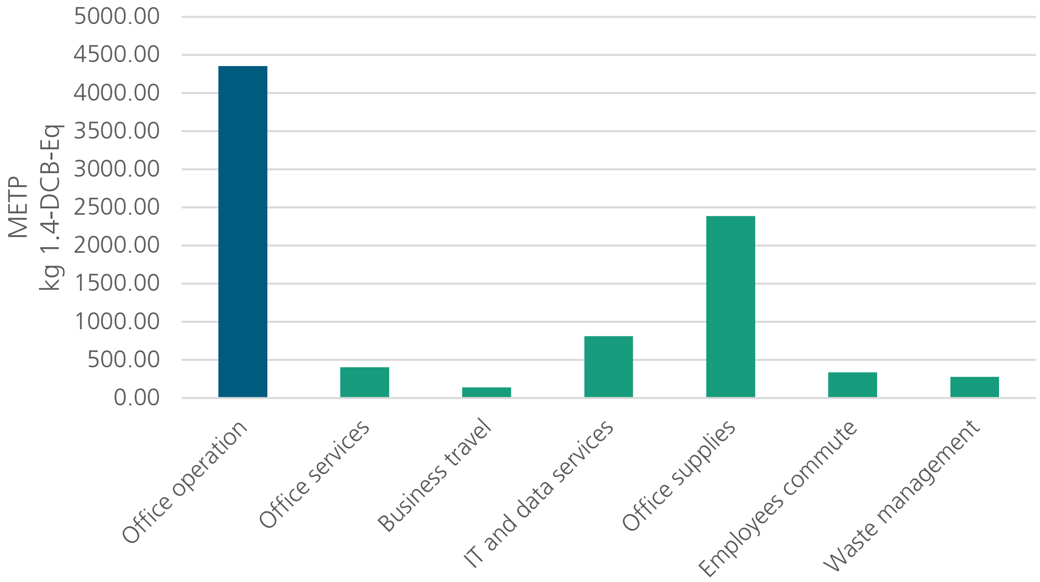

Figure 38. Contributions to METP, breakdown for each office operation process.

5.3.2.5 Ecotoxicity: Terrestrial Ecotoxicity Potential (TETP)

Figure 33 presents the comparison between the absolute contributions to the impact category TETP from the endurance test execution group of processes and the office operation group of processes. It can be noted that the first one is much higher than the second one (94.4% versus 5.6%). The breakdown and analysis for the contribution of the processes belonging to the endurance test execution have been discussed and analyzed in the product LCA study case.

Processes that have been grouped in the office operation seem to have a more balanced distribution of contributions in this impact category. IT and data services, and office supplies have a contribution of a little over 30% each. Office's services and employee commute have a contribution of 15% each as shown on Figure 39. Waste management and business travel present the smallest contribution in this impact category with 5.3% and 1.3% respectively.

5.3.2.6 Energy Resources: Non-Renewable, Fossil Fuel Potential (FFP)

As shown in Figure 33, the contributions to the organizational FFP arising from the office operation are much smaller (9.8%) than those originating from the endurance test execution (90.2%). The FFP pattern from the endurance test execution has been broken down and analyzed in the product LCA study case. The one for the office operation is shown below in Figure 40.

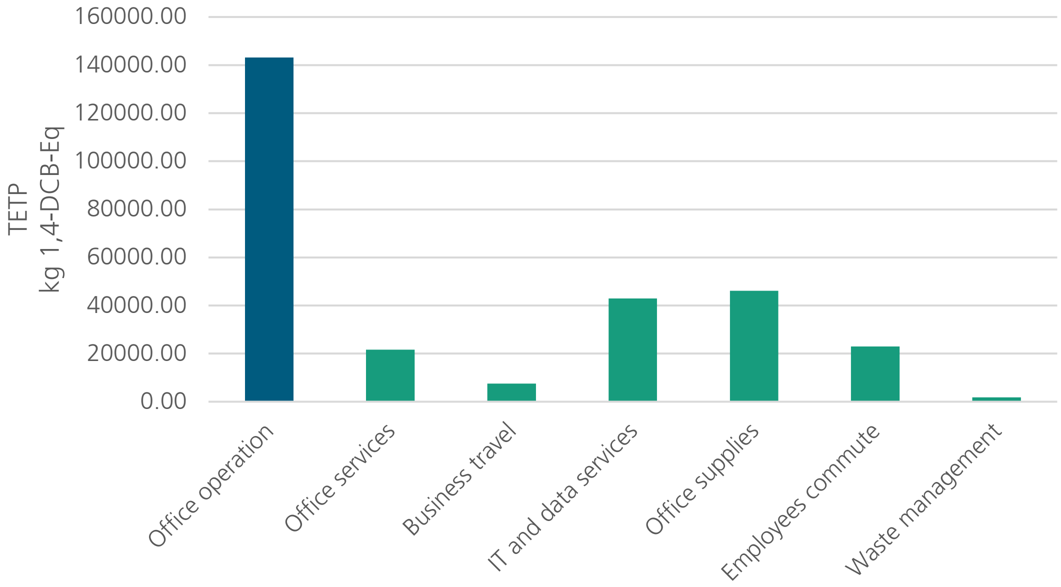

Figure 39. Contributions to TETP, breakdown for each office operation process.

When the emissions arising from the office operations are analyzed, it can be noted that most of them come from the offices' basic services, from which the heating supply is responsible for almost all of them. It is important to mention that the electricity supply used in the LBL comes from renewable sources, while the heating is supplied through natural gas. All the other processes have a contribution below 10%, with the exception of the process corresponding to the office supplies (12%).

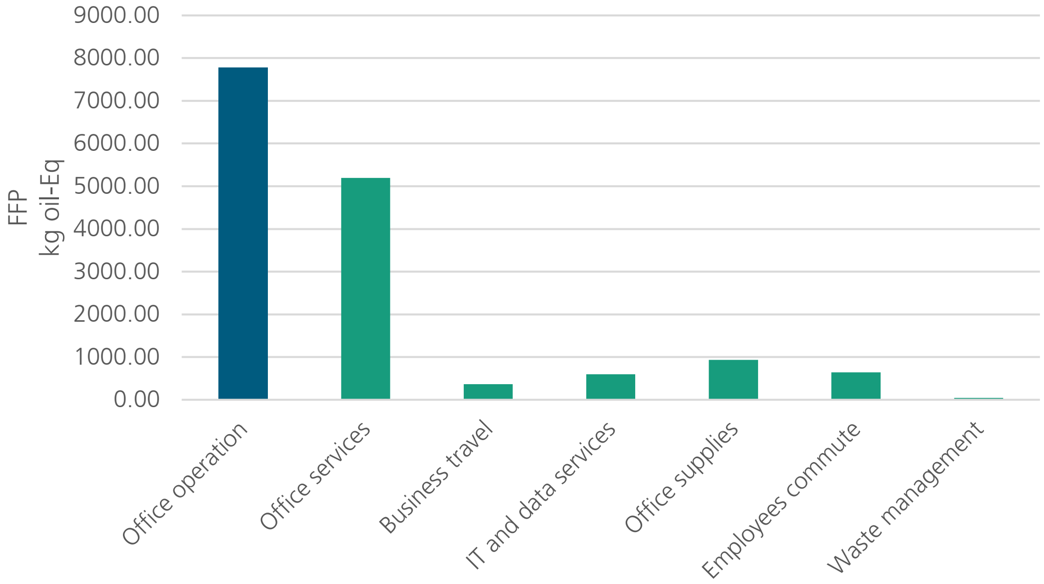

Figure 40. Contributions to FFP, breakdown for each office operation process.

5.3.2.7 Eutrophication: Freshwater Eutrophication Potential (FEP)

Figure 33 presents a comparison between the absolute contributions to the FEP arising from the endurance test execution and office operation groups of activities; it can be noted that the difference is really significant, with the first group providing close to 95% of the total emissions of this category against 5% originating from the office operation activities.

The complete breakdown for the activities belonging to the first group can be found in the product LCA study case, while the description for the group of activities from the second group can be seem in Figure 41. It can be noted that the process with the highest contribution from this group is the office supplies, which is explained by the components needed for the manufacturing of the IT equipment.

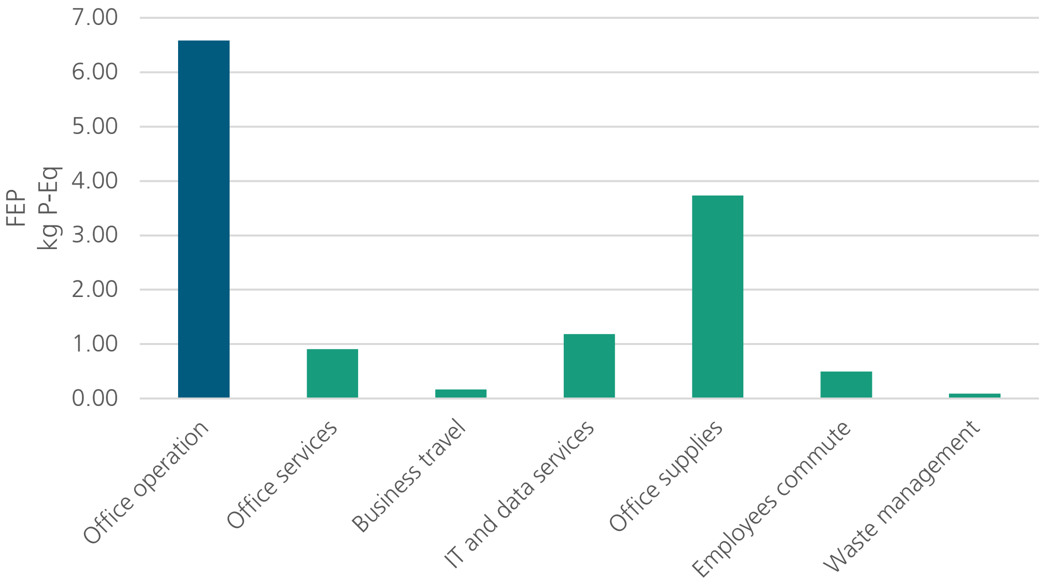

Figure 41. Contributions to FEP, breakdown for each office operation process.

5.3.2.8 Eutrophication: Marine Eutrophication Potential (MEP)

Similarly, to the other Eutrophication category, FEP, the distribution of contributions between the endurance test execution group of activities and the office operation group is very similar for FEP. The first group is responsible for almost 95% of the total emissions in this category while the second one accounts for only 5% (Figure 33).

The contribution of each process grouped in the office operation is again very similar to the FEP impact category. The process with the highest emissions in this group is the office supplies as it can be seemed in Figure 42.

5.3.2.9 Human Toxicity: Carcinogenic - Human Toxicity Potential (HTPc)

This is the impact category for which the contributions arising from the office operation group are the most neglectable. The total emissions accounted for this group of processes is lower than 1% while the rest (over 99%) originates from the endurance test execution group of activities, as it can be seen in Figure 33.

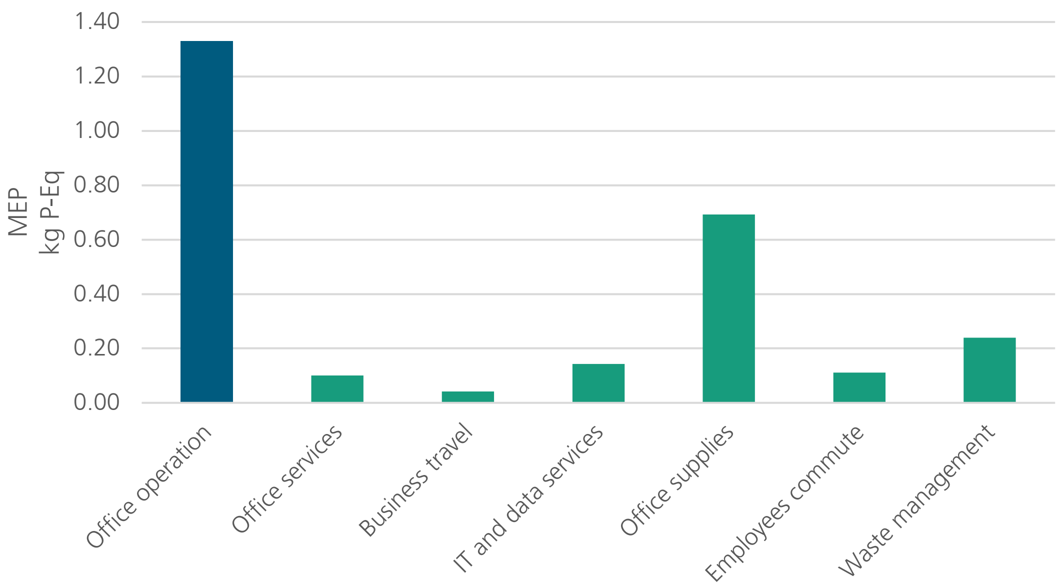

Figure 42. Contributions to MEP, breakdown for each office operation process.

It is also worth mentioning that the distribution for the office operation group of activities is relatively balanced, with 4 processes with contributions ranging from 15 to 30%. Waste management and business travel account for less than 5% of the total emissions in this impact category (Figure 43).

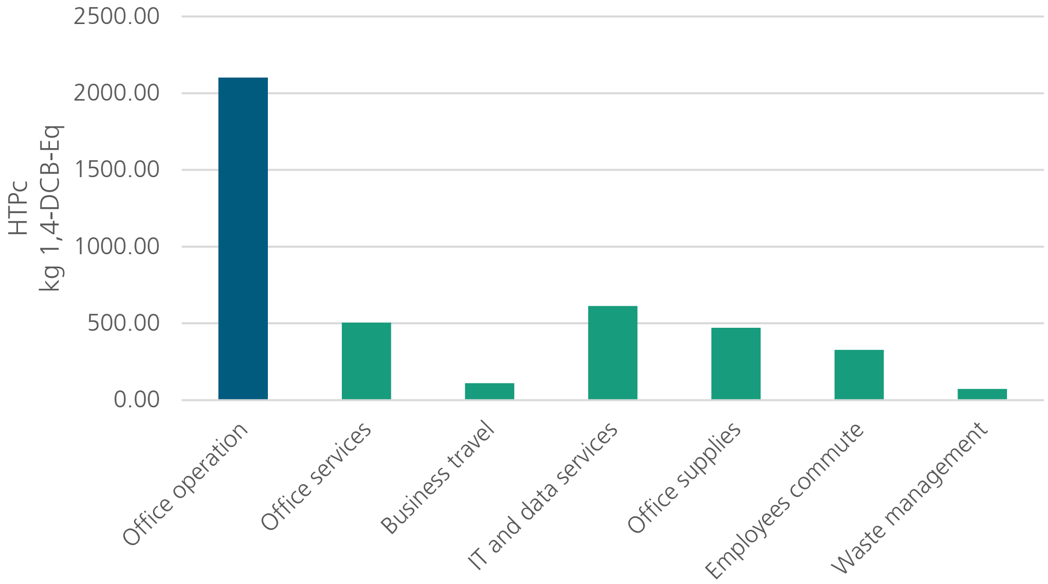

Figure 43. Contributions to HTPc, breakdown for each office operation process.

5.3.2.10 Human Toxicity: Non-Carcinogenic - Human Toxicity Potential (HTPnc)

Contrasting with the other human toxicity potential impact category, the contributions originating from the office operations processes are not so small for this impact category (HTPnc). Its emissions account for almost 11% of the total emissions, while the endurance test execution group provides around 89%, as presented in Figure 33.

The breakdown of the contributions originating from the endurance test execution can be found in the product LCA study case, while the details for the office operation group is shown on Figure 44. Most of the emissions come from the office supply process, which can be further explained with the requirement for technological equipment.

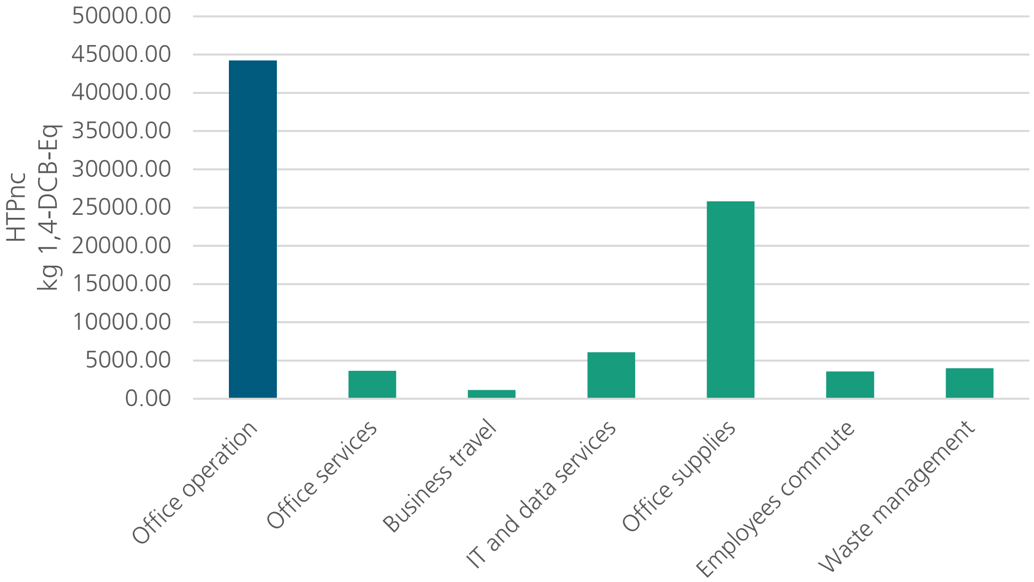

Figure 44. Contributions to HTPnc, breakdown for each office operation process.

5.3.2.11 Ionising Radiation - Ionising Radiation Potential (IRP)

In Figure 33 can be appreciated that the contributions from the group of activities of office operation are significant, especially when it is compared to the other impact categories. Office operation accounts for 23.2% of the total emissions for IRP, while the endurance test execution (whose breakdown has been presented in the product LCA study case) accounts for 76.8%.

Figure 45 presents the detailed contributions for the office operation group of processes. It is clear that most of the emissions in this group find an origin in the employees' commuting activities. The breakdown of the results of the OpenLCA model showed that most of the emissions come from the train use as commuting method.

5.3.2.12 Land Use - Agricultural Land Occupation (LOP)

Figure 33 present the contrast between the total contributions to the organization arising from the two analyzed groups of processes. It can be appreciated that the endurance test execution group has a much higher m^2 annual crop equivalents than the office operations group. The breakdown and analysis for the first one is presented in the product life cycle assessment case study. While the office's operation is shown on Figure 46.

It can be noted that the process most significant in the office operation is the IT and data services process, this is explained due to the amount of electric energy required in this process, which takes into consideration the shift of agricultural lands to photovoltaic installations land.

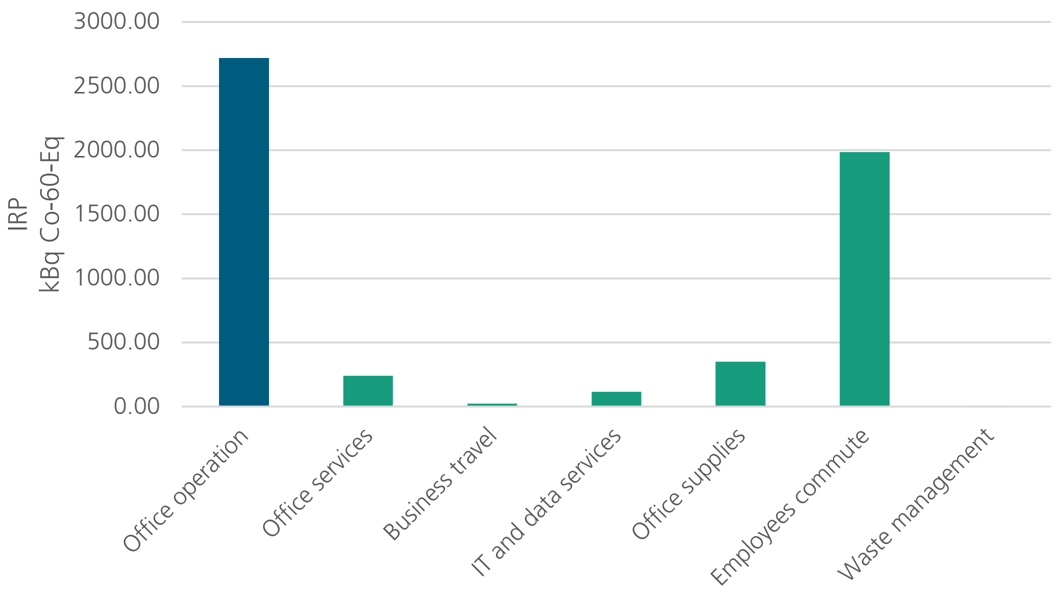

Figure 45. Contributions to IRP, breakdown for each office operation process.

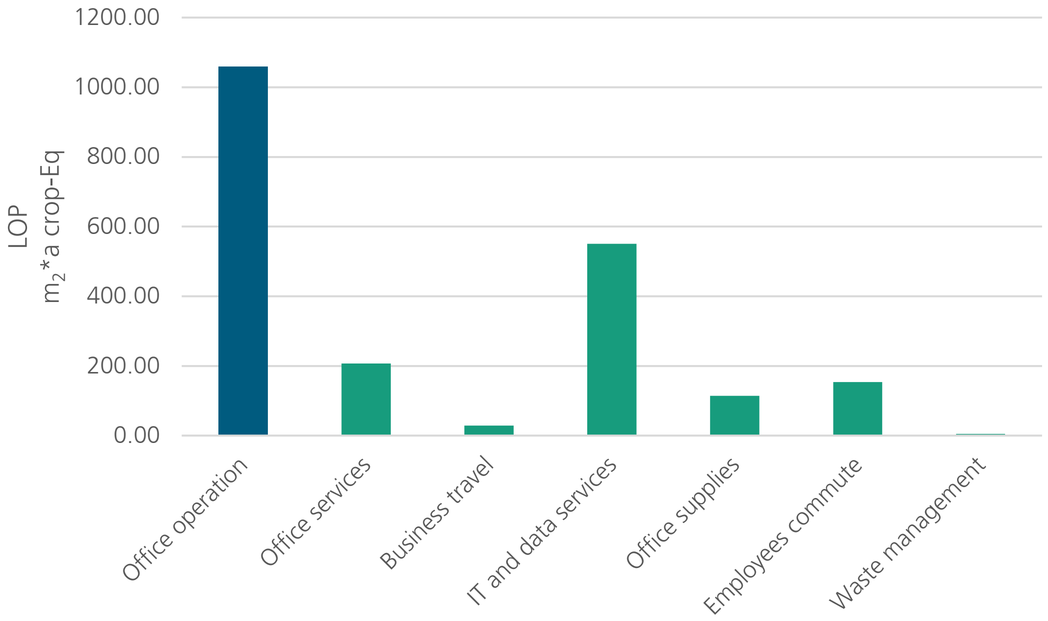

Figure 46. Contributions to LOP, breakdown for each office operation process.

5.3.2.13 Material Resources: Metals/Minerals - Surplus Ore Potential (SOP)

The contrast between the absolute contribution level of the endurance test execution test and the office operation groups of processes is shown on Figure 33. It can be clearly noted that the first group of processes clearly dominates with 99% of the total emissions. The group of processes of the office operation is responsible for only 1% of the contributions. The analysis and breakdown for the processes belonging to the endurance test execution is presented in the product LCA study case and are very high due to the machine elements manufacturing.

Figure 47 presents the breakdown of the contributions arising from the office operations group of activities. It can be appreciated that there is no process that clearly dominates the emissions levels. 4 processes' contributions range from 15 to 30%.

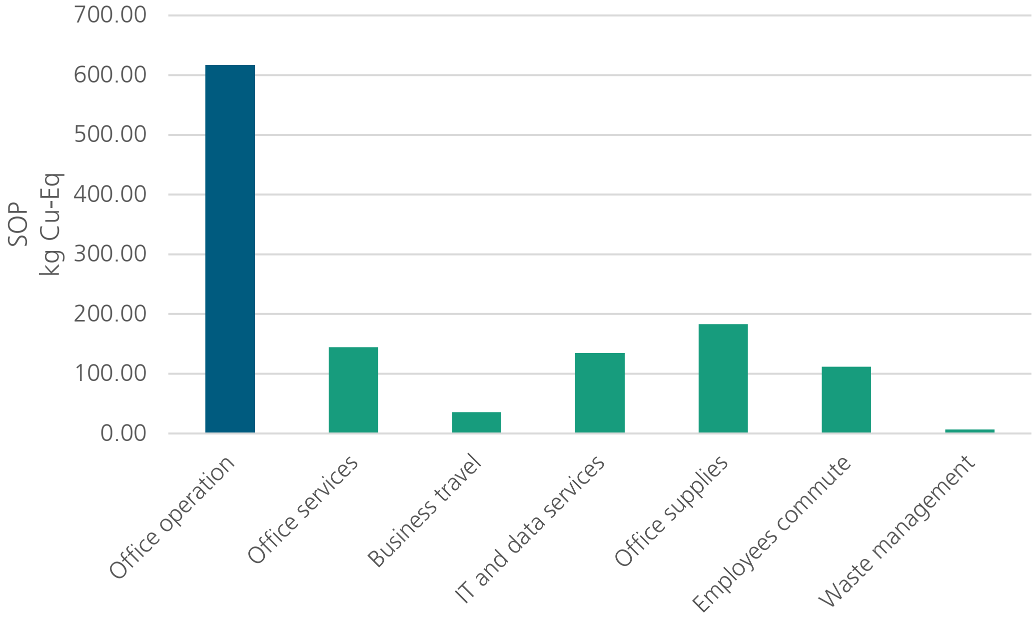

Figure 47. Contributions to SOP, breakdown for each office operation process.

5.3.2.14 Ozone Depletion - Ozone Depletion Potential (ODPinfinite)

The share of emissions into the ODPinfinite impact category originating from the two analyzed group of processes is displayed in Figure 33. It can be noted that the contributions from the endurance test execution processes are much higher than the office operation group (87.5% vs 12.5%). The analysis of the contributions from each process in the endurance test execution group is presented in the product LCA case study.

Figure 48 presents the breakdown of the contributions to this impact category from each of the processes that belongs in the office operation group. It can be noted that IT and data services, whose emissions are explained by the share of electricity that comes from biogas generation.

5.3.2.15 Particulate Matter Formation Potential (PMFP)

In Figure 33 it can be appreciated the absolute contributions to the organizational emissions in the PMFP category. Office operation group of processes accounts for 4.1% of the total impacts, while the group of activities related to the endurance test execution is responsible for 95.9% of the total emissions. The breakdown and analysis for the group of processes related to the endurance test execution can be seen in the product LCA study case.

The analysis for the contributions originating in the office operation can be seen in Figure 49. The contributions seem to be little balanced between IT and data services, office supplies and office services, with 25.4%, 37.7% and 18.7% respectively.

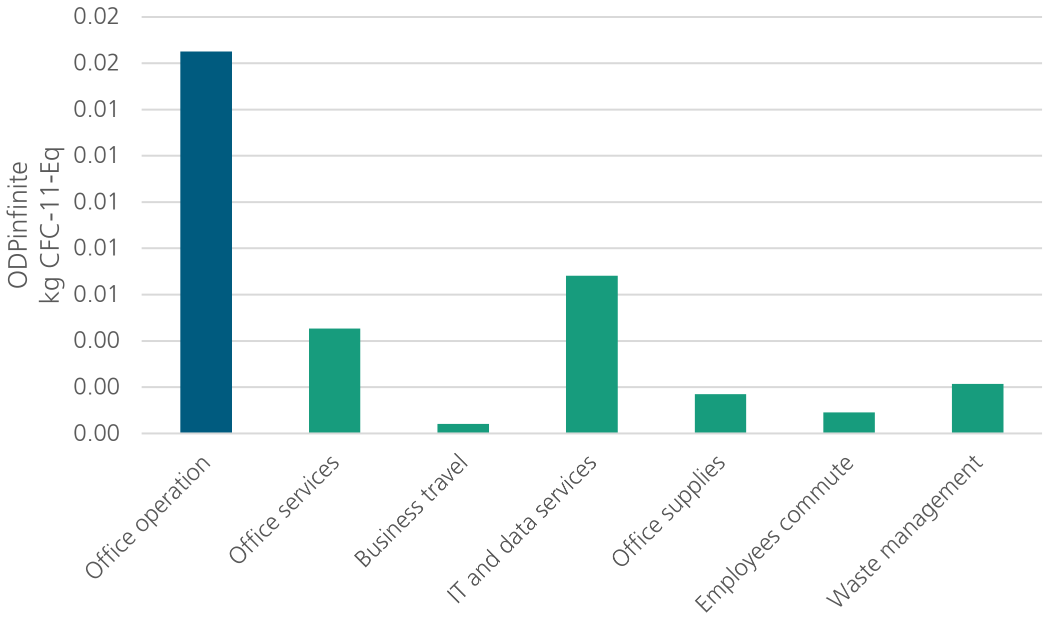

Figure 48. Contributions to ODPinfinite, breakdown for each office operation process.

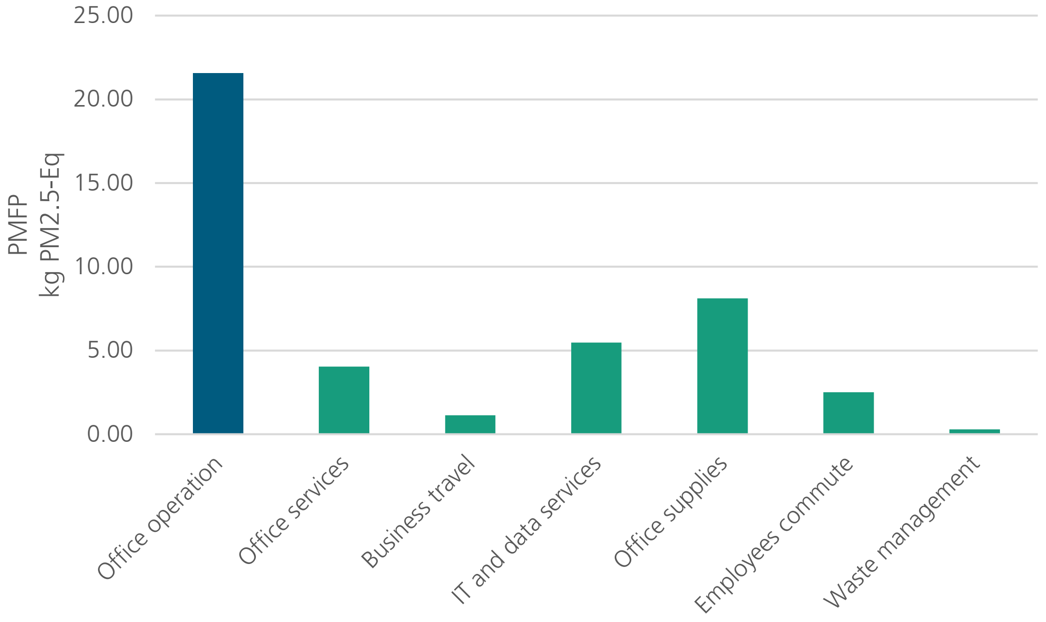

Figure 49. Contributions to PMFP, breakdown for each office operation process.

5.3.2.16 Photochemical Oxidant Formation Potential: Humans (HOFP)

Similar to the last impact category, the group of processes corresponding to the test execution account for a little over 95% of the total contributions, while the office operation processes account for 4.4%, as shown on Figure 33. The breakdown and analysis of the processes belonging to the endurance test execution group has been presented in the product LCA case study.

From the emissions that originate in the office operation processes, the highest impacts come from the office services and from the office supplies (around 30% and 28% approximately), as shown on Figure 50.

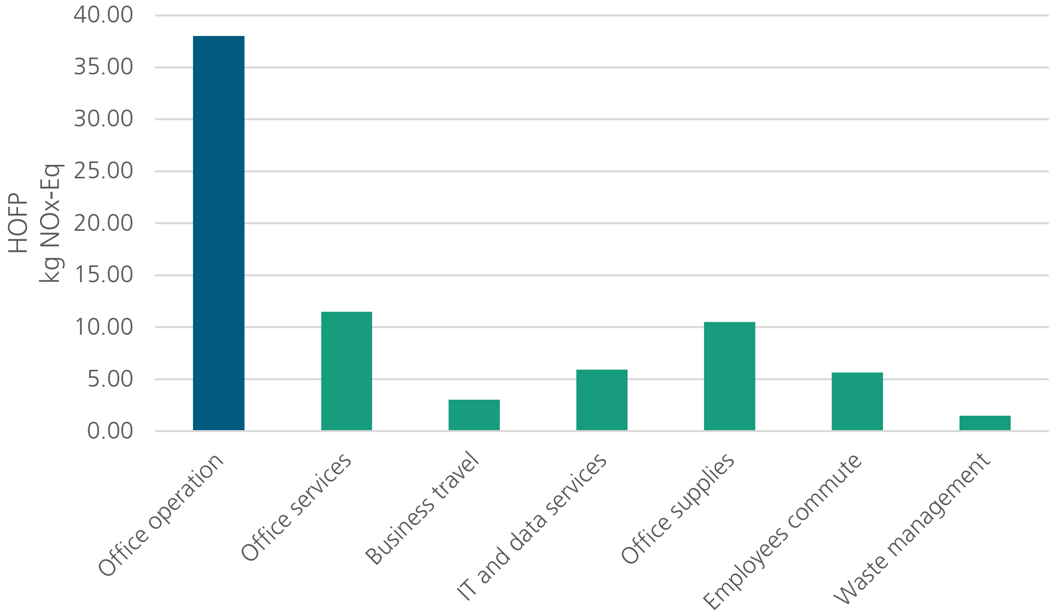

Figure 50. Contributions to HOFP, breakdown for each office operation process.

5.3.2.17 Photochemical Oxidant Formation Potential: Ecosystems (EOFP)

The distribution of the contributions arising from the analyzed groups is exactly the same as the previous impact category (HOFP), the group of processes corresponding to the test execution account for a little over 95% of the total contributions, while the office operation processes account for 4.4%, as shown on Figure 33.

The percentage of impacts coming from each process analyzed in the office operation group is also very similar to the previous category (HOFP). The two processes with the highest impact are the office services and office supplies with 32% and 26% as presented in Figure 51.

5.3.2.18 Water Use - Water Consumption Potential (WCP)

As presented Figure 33, the contributions from the group of processes belonging to the office operation is much smaller than the group that considers the endurance test execution (5% vs 95% respectively). The analysis of the contributions that each process of the endurance test has, is presented in the product LCA study case.

Figure 52 presents how to total WCP for the office operation is divided between its different processes. It can be noted that the processes with the highest relevance are IT and data services, office supplies, and office services. The contributions to this impact category are mostly related to the manufacturing of the equipment needed in each process (technological equipment of energy generation machinery for electricity supply).

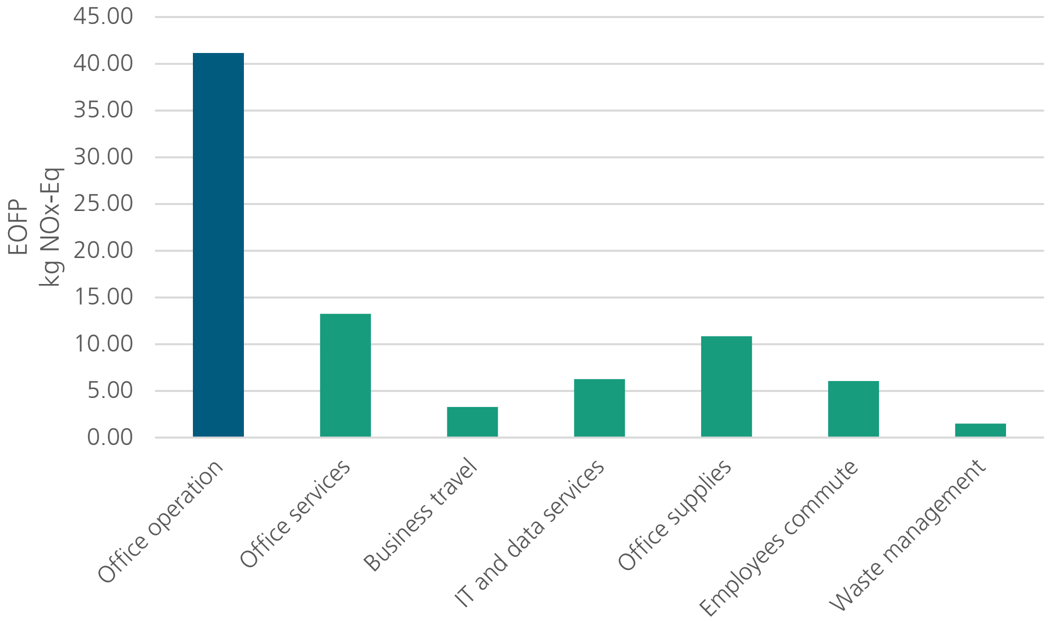

Figure 51. Contributions to EOFP, breakdown for each office operation process.

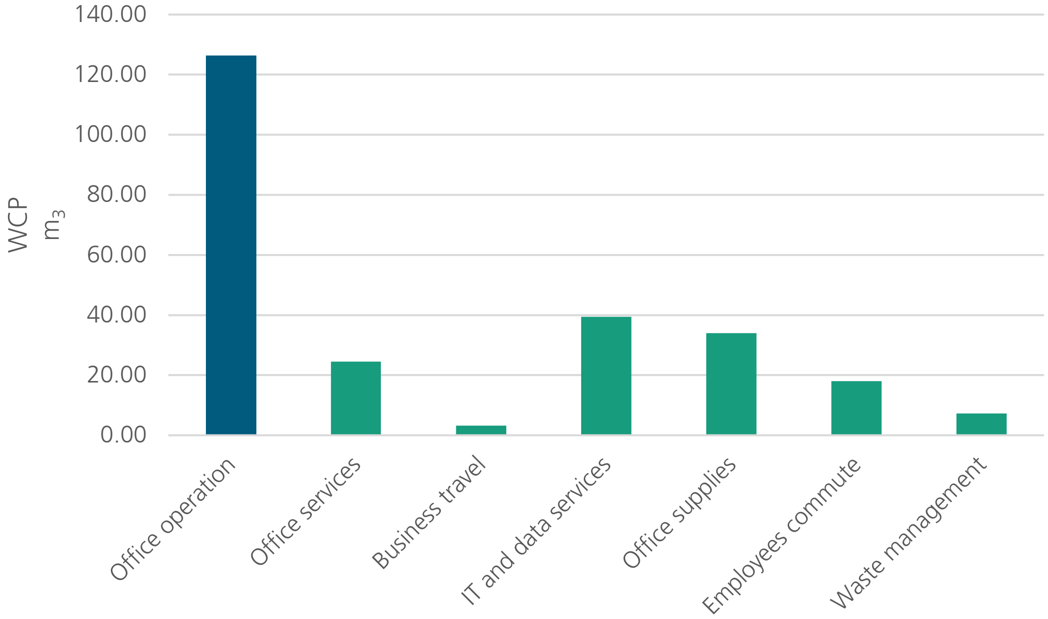

Figure 52. Contributions to WCP, breakdown for each office operation process.

5.4 Interpretation

5.4.1 Life Cycle Impact Assessment Result

This section describes the environmental impacts resulting from Fraunhofer IWES's Large Bearing Laboratory (LBL) operations during the reporting unit (2020). The life cycle inventory has been modelled following the five accounting principles proposed by the greenhouse gas protocol and the cut-off criteria to ensure a high degree of data quality and representativeness of the research facilities operations.

The analysis of the organization has been conducted by grouping all the relevant processes into two categories; the processes belonging to the execution of the pitch bearing endurance test in one group and those related to the operation of the offices in a second group. The first group of processes had been previously assessed in the product LCA, reason why it is taken as a basis for this study and often referred to. In the summary of results, from the Impact Assessment Chapter, it is clearly presented that the group of processes corresponding to the execution of the endurance test have a significant higher environmental impact in all the analyzed categories under the operational conditions in the year 2020. It is worth noting that the study year was particular operationally speaking due to the Covid-19 pandemic, and under differences circumstances, some processes might have presented a different behavior, nevertheless, the test rig activities were also smaller. In this study, it is assumed that only the product life cycle assessment reference project was executed in the study year, while in a normal operation year, two projects could be executed and a third might even be started.

Certain impact categories results that prove relevant are described below. The GWP100 stands out with a significant 91.3% of the total contributions linked to the execution of the endurance test, while only 8.7% of them are linked to the operation of the office. When considering material resources (SOP), a remarkable 99% of the contributions originate from the endurance test execution because of the high amounts of steel that is required for the machine elements manufacturing. Additionally, some impact categories like water consumption (WCP), land use (LOP) and terrestrial acidification (TAP) present very similar results, with around 5% of their total emissions arising from the office operation, while the remaining 95% comes from the endurance test execution.

The results presented in the product LCA study case clearly stated that the manufacturing of the machine elements dominate the contributions to almost all impact categories in the business as usual (BAU) scenario. In a deeper analysis, it was discovered that the contributions from steelmaking process significantly outweigh the other subprocesses analyzed in the machine elements manufacturing (steel milling, drilling, and welding). On top of that, the product LCA sensitivity analysis hinted that a shift to steel produced in Europe through EAF technology could represent a significant improvement across almost all the analyzed impact categories, for this reason, it is important to also analyze the benefits of this technology change to the global organizational environmental footprint.

The analysis of the results for each impact category, presented in Section 5.3.2, also revealed that the electricity supply plays an important role, not only for the endurance test execution but also for the office operation processes. As previously mentioned, the baseline of this study takes into consideration previous actions taken by the LBL decision makers and considers a renewable energy electricity supply. Simulations considering the use of Germany's electricity mix showed that this measure potentially helped in lowering emissions across various impact categories. It is therefore crucial to also examine the influence of this measure in the overall organization environmental footprint.

Given the uniqueness of the reference year, it might be valuable to model certain processes to simulate a scenario that represents more closely the typical operational conditions, for example, the business trips process, which was significantly different that year, did not represent more than 8% of the total office contributions for any analyzed impact category.

5.4.2 Sensitivity Analyses

The primary objective of the sensitivity analyses presented in this section is to pinpoint the repercussions of variations in the organization processes on the impact categories results that were outlined in the preceding section. These sensitivity analyses have been formulated through a rigorous analysis and interpretation of the results presented in the life cycle impact assessment chapter.

The scenarios to be analyzed and whose results are presented in this section include:

5. Ensuring the usage of steel produced in an electric arc furnace (EAF) and proceeding from Europe in the manufacturing of machine elements that are directly commissioned by IWES.
6. Electricity supply to the LBL from the German electricity grid, instead of the renewable energy mix from the current provider.
7. Business travels modelled to resemble a normal operation year.
8. Transportation logistic that minimizes distance travelled by road.

5.4.2.1 Steel Produced with Electric Arc Furnace Technology in Europe.

As presented in the results of the product LCA study case, the contributions stemming from the manufacturing of the machine elements heavily dominate most of the impact categories for the group of processes associated with the endurance test execution. It was then described by the discoveries in this study that most of the contributions in all analyzed impact categories are significantly dominated by the mentioned group of processes, as shown in Figure 32. It is because of these reasons that this sensitivity analysis is proposed.

It is worth noting that Fraunhofer IWES is only able to decide on the supply chain of some of the machine elements used for the test rig assembly, while other elements are provided by their counterparts whose devices are tested. The machine elements that Fraunhofer IWES directly commissions account for 32% of the total mass of machine elements used for the reference project. The proposed model focuses on determining the extent of variation on the environmental impacts that can be achieved if the machine elements that are directly commissioned by IWES are manufactured using steel that has been produced in Europe through EAF technology. Unlike the BF-BOF process which heavily relies on iron ore, EAF predominantly uses scrap steel as raw material.

Table 18. Environmental impacts associated with the LBL as an organization if machine elements commissioned by IWES are manufactured with steel produced through EAF technology in Europe.

Impact category	Reference unit	Business as usual scenario	EAF steel produced in Europe	Impact category variation
TAP	kg SO_2-Eq	959.9	826.9	-13.9%
GWP100	kg CO_2-Eq	333,900.0	291,132.3	-12.8%
FETP	kg 1.4-DCB-Eq	31,247.7	30,383.4	-2.8%
METP	kg 1.4-DCB-Eq	42,534.9	41,564.8	-2.3%
TETP	kg 1.4-DCB-Eq	2,555,368.6	2,256,741.3	-11.7%
FFP	kg oil-Eq	79,265.4	69,371.3	-12.5%
FEP	kg P-Eq	123.2	104.2	-15.4%
MEP	kg N-Eq	25.5	21.7	-14.8%
HTPc	kg 1.4-DCB-Eq	294,901.6	453,226.1	53.7%
HTPnc	kg 1.4-DCB-Eq	404,739.7	370,022.4	-8.6%
IRP	kBq Co-60-Eq	11,730.0	14,253.6	21.5%
LOP	m^2*a crop-Eq	19,582.8	18,882.4	-3.6%
SOP	kg Cu-Eq	62,609.1	46,327.5	-26.0%
ODPinfinite	kg CFC-11-Eq	0.1	0.1	-3.7%
PMFP	kg PM2.5-Eq	531.5	443.4	-16.6%
HOFP	kg NOx-Eq	869.3	749.7	-13.8%
EOFP	kg NOx-Eq	927.9	799.1	-13.9%
WCP	m3	2,417.5	2,169.7	-10.2%

The results obtained for this sensitivity analysis and its comparison to the BAU scenario are presented in Table 18. It can be clearly seen that the use of steel manufactured in Europe through EAF technology results in a better performance of the system in almost all impact categories (16/18). The reduction in GWP100 is close to 43 ton of CO_2 equivalent, or 12.8% of the total organizational carbon footprint. Other relevant variations in the indicators are the reduction in non-renewable energy resources, also with 12.5%. Since this steel production process uses mainly recycled steel, the mineral resources indicator SOP also shows a much better performance with a reduction of 26% of its total contributions. These values seem even more relevant when compared to the share of steel mass to be analyzed in this sensitivity analysis (32%).

Figure 53 graphically presents the variation in environmental impacts arising from the shift from world market for steel to steel produced in Europe through EAF as previously described. It can be clearly appreciated how most of the environmental impact categories show a significant reduction ranging from 10% to almost 26%; these results become more relevant when noted that the machine elements considered in this scenario only account for 32% of the total mass of steel used for the manufacturing of all the machine elements used for the assembly of the test rig.

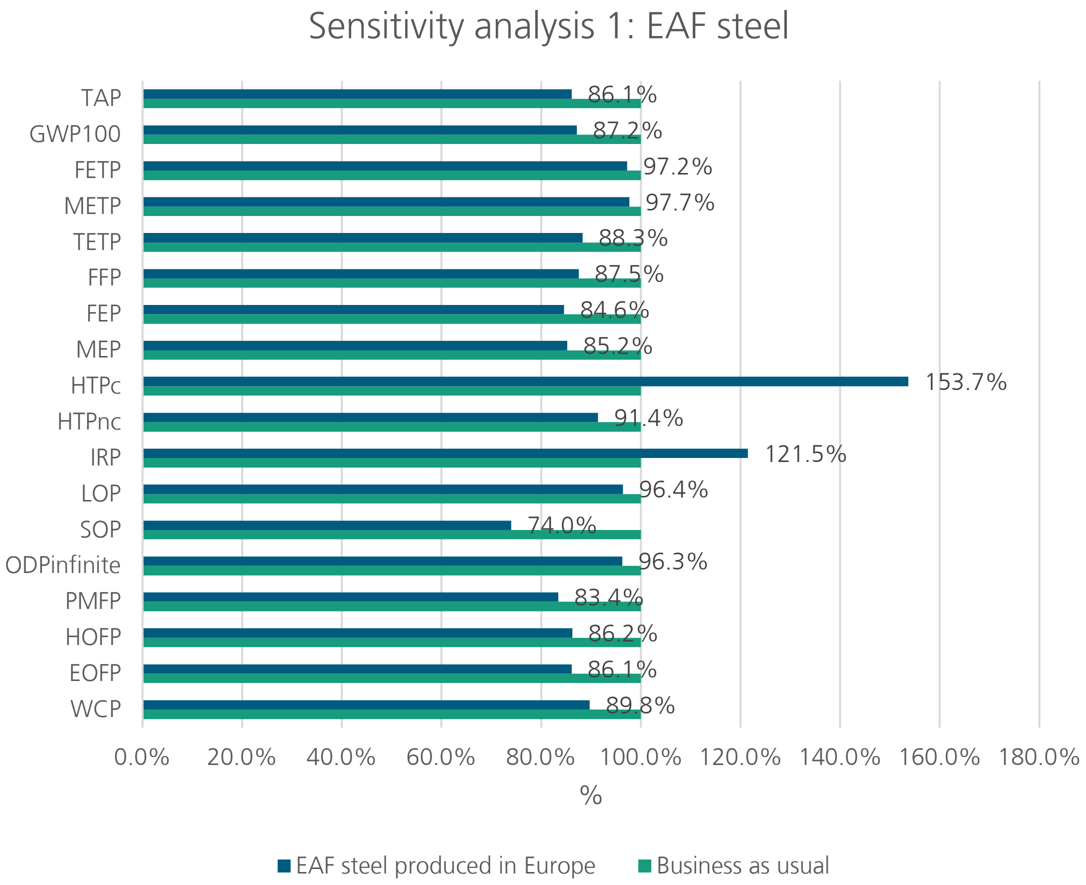

Figure 53. Variation in environmental impacts associated to the LBL as an organization if machine elements commissioned by IWES are manufactured with steel produced in Europe through EAF technology.

5.4.2.2 LBL's Electricity Supply Coming from the Grid

As it was briefly explained in the interpretation of the life cycle assessment results, this model contemplates a renewable energy supply for the operations of the LBL, which is in line with previous efforts from Fraunhofer IWES to reduce its environmental footprint. It is noteworthy to evaluate the effect that this measure could have had.

This sensitivity analysis has been conducted by modelling the processes that require electricity within the LBL (test rig assembly, test execution, test rig disassembly, IT and data room operation, and office services) as they were supplied by Germany's medium voltage electricity market, instead of the renewable energy mix that was modelled for the BAU scenario. The results for this sensitivity analysis are presented and compared to the BAU scenario in Table 19. The effects of the modification in electricity supply are evident and for most of the impact categories, a very significant increase in the emissions takes place; for example, the GWP100 increases in 52.1%, which translate to a difference of nearly 174 ton of CO_2 equivalent. The non-renewable fossil fuel potential (FFP) also presents a similar result with an increase of around 58%, this is equivalent to an additional 46 ton of oil equivalent which would have to be burnt to produce the required energy to supply the LBL operations and testing activities.

The highest variation happens on the ionizing radiation potential (IRP), with a percentual change of approx. 422%; this happens because Germany's electricity grid still made use of nuclear sources in the analyzed year, and the emissions analyzed in this impact category result from nuclear sources electricity production. The impact category with the second highest change is the freshwater eutrophication potential (FEP), with an increase of nearly 232% and it is explained due to the mining for lignite that is linked to Germany's electricity grid. On the other hand, there are some impact categories where the performance using the electricity grid is a little bit better than using renewable energy supply, but the variations are much smaller than the previously mentioned. For example, the agricultural land occupation (LOP) impact category shows a little bit worse performance under the renewable energy supply scenario, which arises from the agricultural lands whose usage is sometimes shifted to renewable energy installations.

Table 19. Environmental impacts associated with the LBL as an organization with electricity supply from Germany's electricity grid instead of renewable energy sources.

Impact category	Reference unit	Business as usual scenario	Electricity supply from Germany's grid	Impact category variation
TAP	kg SO_2-Eq	959.9	953.3	-0.7%
GWP100	kg CO_2-Eq	333,900.0	507,834.0	52.1%
FETP	kg 1.4-DCB-Eq	31,247.7	36,129.4	15.6%
METP	kg 1.4-DCB-Eq	42,534.9	49,427.1	16.2%
TETP	kg 1.4-DCB-Eq	2,555,368.6	2,378,522.9	-6.9%
FFP	kg oil-Eq	79,265.4	125,320.6	58.1%
FEP	kg P-Eq	123.2	408.5	231.5%
MEP	kg N-Eq	25.5	43.5	70.9%
HTPc	kg 1.4-DCB-Eq	294,901.6	306,455.3	3.9%
HTPnc	kg 1.4-DCB-Eq	404,739.7	674,014.8	66.5%
IRP	kBq Co-60-Eq	11,730.0	61,205.0	421.8%
LOP	m^2*a crop-Eq	19,582.8	18,090.4	-7.6%
SOP	kg Cu-Eq	62,609.1	62,316.3	-0.5%
ODPinfinite	kg CFC-11-Eq	0.1	0.2	36.4%
PMFP	kg PM2.5-Eq	531.5	536.6	1.0%
HOFP	kg NOx-Eq	869.3	892.3	2.6%
EOFP	kg NOx-Eq	927.9	954.0	2.8%
WCP	m3	2,417.5	2,933.3	21.3%

The results presented on Table 19 and described in the previous paragraphs are shown graphically in Figure 54. There it can easily be appreciated that the scenario in which a renewable energy supply is assured performs significantly better in almost all the impact categories compared to the scenario in which electricity coming from the German electricity grid is used.

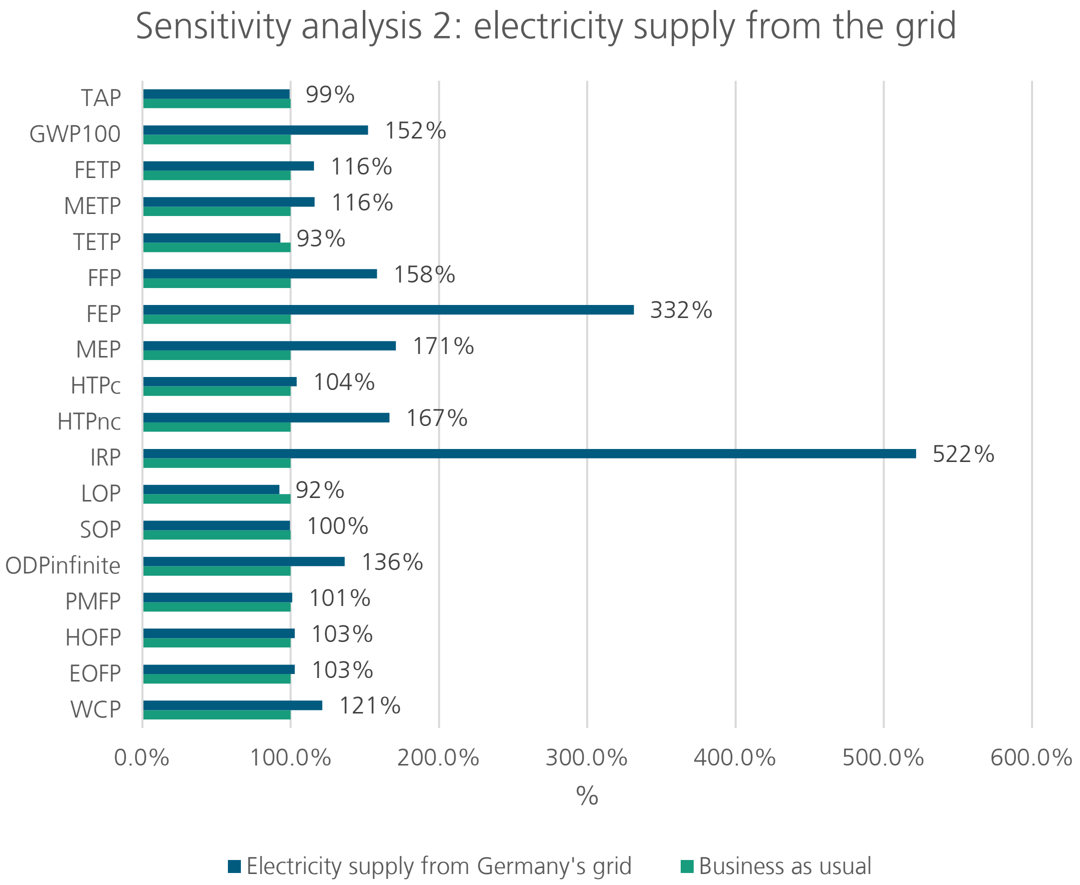

Figure 54. Variation in environmental impacts associated the LBL as an organization with electricity supply from Germany's electricity grid instead of renewable energy sources.

5.4.2.3 Business Travels Resembling a Normal Operating Year.

Due to the Covid-19 pandemic, during the analyzed year no business trips involving plane as a transportation mode were executed, on the BAU scenario, only 3600 km of road transportation via car were modelled. In Section 5.2.1.5, it was mentioned that in recent years, Fraunhofer IWES started to closely monitor the business trips that have been executed by air. By making use of this registry, it is possible to model a business trips process that better resembles a normal operation year. In this sensitivity analysis, 72579 km, which corresponds to the distance covered by plane by LBL employees in the year 2022, were simulated. The distance travelled by car is not modified in this analysis. Unfortunately, there is no historical data regarding business trips done by long distance train, therefore, it is still not considered in the analysis.

Table 20 presents the results of the LBL organizational environmental impacts under the proposed business travel scenario and compares it to the reference year scenario. It can be observed that almost all impact categories could have an increase in their absolute emissions which could be as high as 4.3% of the total of the organization. Some notable results are the increase in the GWP100 with around 2.6% of the total $CO_{2=eq}$ emissions or around 9 ton of $CO_{2=eq}$, the increase in FFP with an additional 2.6 ton of oil equivalent (an increase of 3.3%) that needs to be burned to fuel the modelled plane business trips. These results are even more significant when they are compared only to the processes corresponding to the office operations, that means, leaving out the processes that correspond to the execution of the endurance test. In that case, the increase in GWP100 is 30% and the increase of PFF is 33%.

The results of this sensitivity analysis are presented graphically in Figure 55. The emissions in all impact categories experience an increase in their total values due to the inclusion of plane flights for business trips. Even though the increase seems to be small, their impacts become more substantial when the comparison is made only with the processes that correspond to the office operation.

5.4.2.4 Transportation Logistic that Minimizes Road Transport

In the product LCA, it has been assessed that transportation of the machine elements to the LBL is one of the three processes that has the most significant environmental impacts on the endurance testing group of processes, with its contributions ranging from 5% to 26% of the emissions for each impact category within that group of processes. The analysis of the results breakdown further revealed that, of the two used transportation methods, road transport had a significantly larger environmental impact than sea transportation.

This led to the proposal to set up a new transportation logistic which could minimize the distance covered by road and use more sea transportation instead. This is feasible, because both of the machine elements suppliers located in Europe have their facilities located in a city with access to a seaport.

Under the revised transportation scheme, machine elements that are manufactured in China, would still be received by IWES counterpart in a city in Europe, and then, all machine elements transported via water to Hamburg. From the port of Hamburg to the LBL, road transportation is to be used.

It is worth noting that the implementation of an alternative transportation logistic had already been assessed in the product LCA, since the transportation of the machine elements to the LBL is a process exclusively affecting the forementioned group of processes. The results of the environmental impacts for the LBL under this new proposed transportation logistic, and the total variation in comparison to the business as usual scenario are shown on

Table 21. Notably, it reveals a potential significant reduction in all impact categories. The reductions in the total emissions could range from 0.6% in the least affected category (HTPc) to 26.2% in the one with the highest variation (TETP). For this category, most of the contributions originally found their source in the treatment for brake wear emissions, hence the reduction. The GWP100 presents a potential reduction of around 10% in the total CO_2 equivalent emissions, which could translates to a decrease of over 33 tons of CO_2 equivalent.

Figure 56 presents the variation in all impact categories; the graphical representation helps to easily visualize the substantial improvement in the performance for all categories. Results strongly suggest that this strategy should be further evaluated.

Table 20. Environmental impacts associated with the LBL as an organization if a business travels are modelled as a regular operating year.

Impact category	Reference unit	Reference year scenario	Business travel as regular	Impact category variation
TAP	kg SO_2-Eq	959.9	980.0	2.1%
GWP100	kg CO_2-Eq	333,900.0	342,551.2	2.6%
FETP	kg 1.4-DCB-Eq	31,247.7	31,288.5	0.1%
METP	kg 1.4-DCB-Eq	42,534.9	42,600.3	0.2%
TETP	kg 1.4-DCB-Eq	2,555,368.6	2,573,581.1	0.7%
FFP	kg oil-Eq	79,265.4	81,862.0	3.3%
FEP	kg P-Eq	123.2	123.5	0.2%
MEP	kg N-Eq	25.5	25.7	0.7%
HTPc	kg 1.4-DCB-Eq	294,901.6	294,988.9	0.0%
HTPnc	kg 1.4-DCB-Eq	404,739.7	407,150.4	0.6%
IRP	kBq Co-60-Eq	11,730.0	11,795.5	0.6%
LOP	m^2*a crop-Eq	19,582.8	19,623.8	0.2%
SOP	kg Cu-Eq	62,609.1	62,649.5	0.1%
ODPinfinite	kg CFC-11-Eq	0.1	0.1	0.4%
PMFP	kg PM2.5-Eq	531.5	538.6	1.3%
HOFP	kg NOx-Eq	869.3	906.9	4.3%
EOFP	kg NOx-Eq	927.9	966.9	4.2%
WCP	m3	2,417.5	2,423.4	0.2%

Table 21. Environmental impacts associated with the LBL as an organization if an alternative transportation logistic minimizing road transportation is implemented.

Impact category	Reference unit	Business as usual scenario	Alternative transportation logistic	Impact category variation
TAP	kg SO_2-Eq	959.9	932.8	-2.8%
GWP100	kg CO_2-Eq	333,900.0	300,472.5	-10.0%
FETP	kg 1.4-DCB-Eq	31,247.7	30,387.6	-2.8%
METP	kg 1.4-DCB-Eq	42,534.9	41,005.1	-3.6%
TETP	kg 1.4-DCB-Eq	2,555,368.6	1,885,635.4	-26.2%
FFP	kg oil-Eq	79,265.4	68,640.4	-13.4%
FEP	kg P-Eq	123.2	120.9	-1.9%
MEP	kg N-Eq	25.5	24.5	-3.7%
HTPc	kg 1.4-DCB-Eq	294,901.6	293,228.0	-0.6%
HTPnc	kg 1.4-DCB-Eq	404,739.7	377,468.1	-6.7%
IRP	kBq Co-60-Eq	11,730.0	11,173.4	-4.7%
LOP	m^2*a crop-Eq	19,582.8	18,268.4	-6.7%
SOP	kg Cu-Eq	62,609.1	61,930.0	-1.1%
ODPinfinite	kg CFC-11-Eq	0.1	0.1	-12.3%
PMFP	kg PM2.5-Eq	531.5	513.1	-3.5%
HOFP	kg NOx-Eq	869.3	801.4	-7.8%
EOFP	kg NOx-Eq	927.9	853.1	-8.1%
WCP	m3	2,417.5	2,362.6	-2.3%

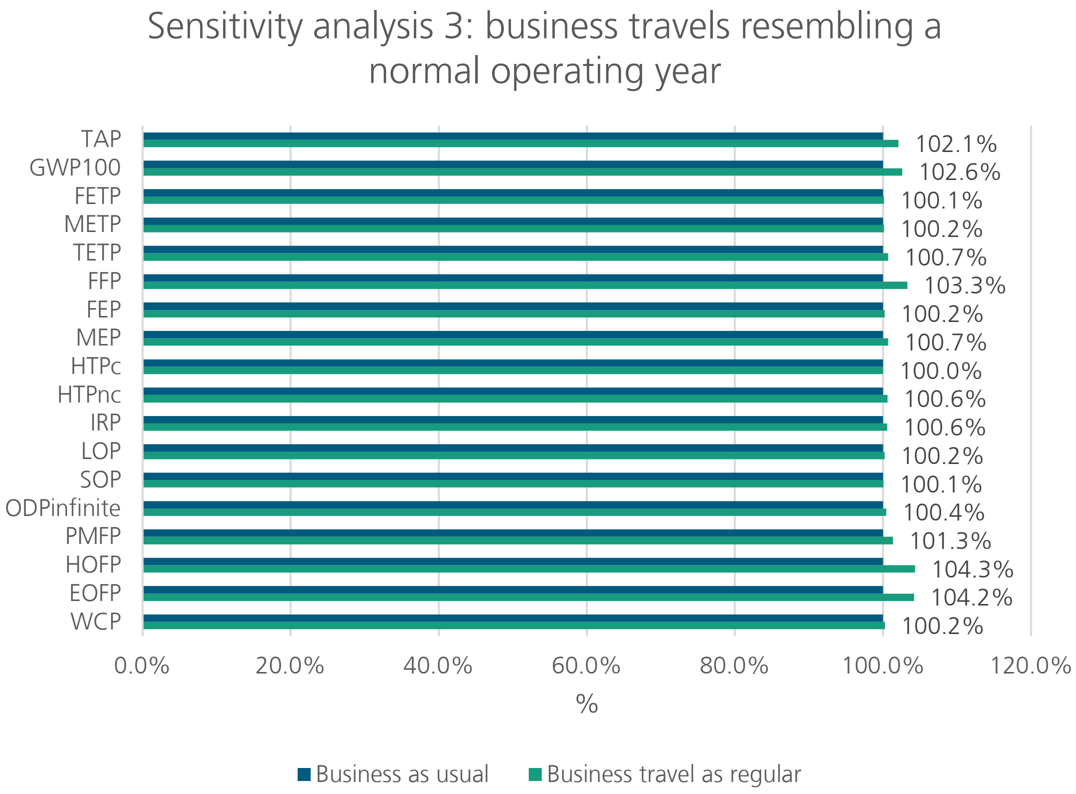

Figure 55. Variation in the environmental impacts associated with the LBL as an organization if a business travels are modelled as a regular operating year.

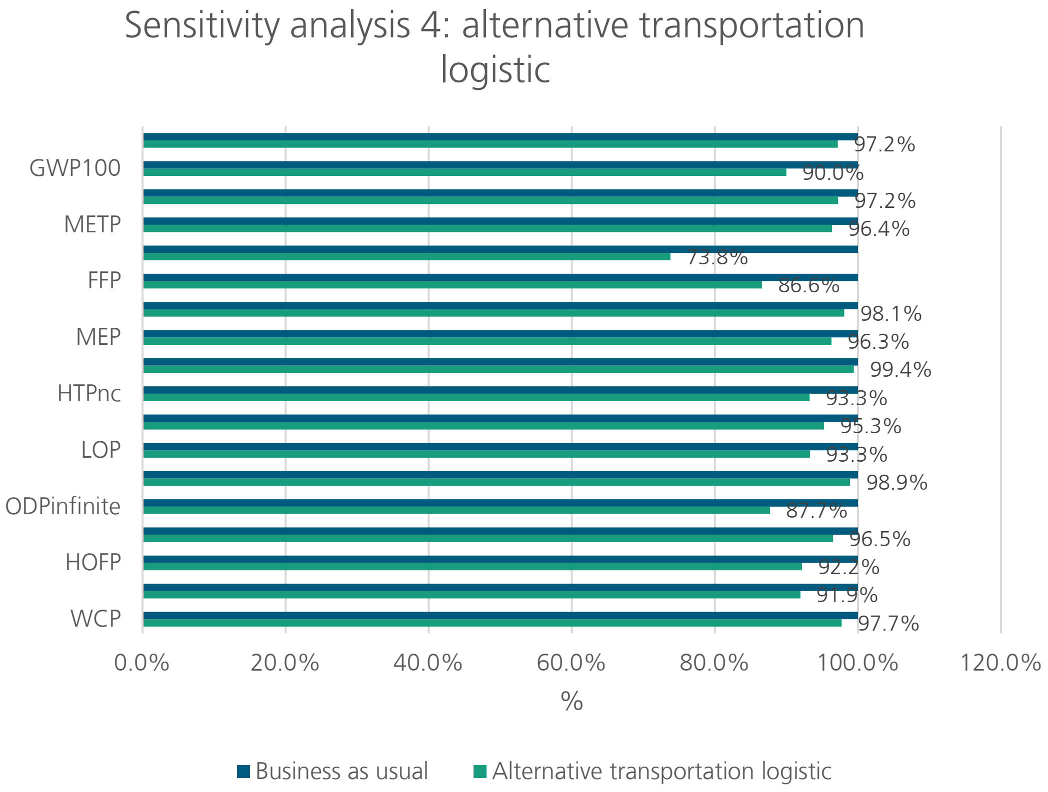

Figure 56. Variation in the environmental impacts associated with the LBL as an organization implementing an alternative transportation logistic minimizing road.

5.4.3 Data Quality Checks

During the execution of this O-LCA, continuous checks for completeness, consistency and representativeness of the used data have been conducted throughout different stages of the study. All primary data provided by Fraunhofer IWES is representative for the reporting unit (year 2020).

The following areas have been identified to have significant influence on the environmental impacts arising from the organization and due to that reason, it is recommended that special attention to data quality is paid in future organizational LCA.

- Production datasets for low-alloyed steel
- Supply chain for low-alloyed steel
- Electricity supply to the LBL
- Business travel conducted by LBL employees
- Transportation logistic of all machine elements to the LBL

Fraunhofer IWES supplied a complete breakdown of the machine elements commissioned for the project executed in the analyzed year, along with the respective suppliers. Additionally, they established an effective communication channel to facilitate information exchange and address inquiries from the LCA practitioner. The suppliers demonstrated willingness to respond to questions and provided available information, though certain details such as steel traceability were not possible to obtain.

It is worth emphasizing that the environmental contributions that have their origin in steelmaking for the machine elements manufacturing have a high impact. Therefore, it is highly recommended to make efforts to enhance the traceability in this regard, and if possible, to request the exclusive usage of steel manufactured through EAF technology. This study used ecoinvent 3.9.1 for steel production datasets.

Regarding transportation logistics, it was developed based on the geographical locations of the machine element suppliers and the LBL. To ensure the accuracy and representativeness of the real transportation process, project documentation was thoroughly examined, and inquiries were made to the LBL personnel in charge of the project execution.

As it has been described in this study, the processes with the highest environmental impacts are those related to the execution of the endurance test, while the office operation contributes with only a significant smaller portion of them; nonetheless, the efforts to achieve a high degree of data quality for said processes were maintained to the same standards as the ones previously mentioned.

The electricity supply and other basic services during the reporting unit period could be analyzed based on supplier bills, historical data gathered with a power logger in the test hall, and Fraunhofer IWES internal reports for the year 2020. The same way as with transportation, all data used was carefully compared to the one presented in project documentation and any remaining doubts were translated to the project leader. One aspect that could be improved for future assessments is the electricity consumption from the IT and data services (server room); the consumption of it was allocated based on the size of the servers, nonetheless, the allocation was an assumption. It is recommended that a power logger is used to measure the electricity consumption of the server room.

The commute of employees to the LBL was modelled based on assumptions reached through inquiries to the LBL staff. Preliminary simulations were performed to assess the magnitude of their contributions. Upon finding that the results of this process were not so high when compared to others, the stated assumptions were accepted.

Finally, the business travel process was simulated based on the information available for the reported period. Covid-19 made the business trip list very short for the mentioned year, an aspect that helped achieve a high degree of accuracy through inquiries to the LBL staff (no official reports from Fraunhofer IWES for that year were available to gather this data). Fraunhofer IWES started monitoring distance covered by plane in business trips, information that will allow better data quality for future assessment. The LCA practitioner recommends also tracking the information of business trips executed by long distance trains.

5.4.4 Conclusions

This organizational life cycle assessment presents a detailed and representative study of the environmental impacts associated with the large bearing laboratory during the year 2020, which was used as reporting unit in this report. The O-LCA has been conducted in order to comply with the norms ISO 14040:2006, ISO 14044:2006, and TS/ISO 14072 (2014); and as mentioned in the data quality check, it has been conducted following the five accounting principles proposed by the Greenhouse Gas protocol.

The results of the study indicate that the environmental impacts arising from the large bearing laboratory originate mostly from the group of processes that are directly linked to the endurance testing activities, while only a smaller portion of the contributions find their origin in the group linked to the operation of the offices. The results also strongly suggest the effectiveness of previous measures in minimizing environmental impacts, particularly in ensuring a renewable energy supply for the large bearing laboratory operation. The results of this case study indicate that emissions across various impact categories would potentially be higher if an electricity supply from the German electricity grid were considered.

Regarding the BAU scenario, results indicate that the way to reduce environmental impacts in the most significant way is to address the main raw material used for machine elements manufacturing, which is steel. The contributions from steelmaking constitute the most substantial fraction, exceeding half of the total organizational emissions in some impact categories. Furthermore, the sensitivity analysis emphasizes the feasibility of IWES suggesting their suppliers the adoption of steel produced through electric arc furnace (EAF) technology in Europe. While IWES may not have direct influence over all machine element suppliers, they can request this material choice from the specific supplier to whom they directly commission a significant portion of the machine elements, constituting 32% of the total mass. Implementing such a change could result in substantial enhancements in the overall environmental performance, as highlighted by the sensitivity analysis.

The transportation of machine elements to IWES is another process in which improvements might be achieved. In a close analysis, it was found that road transportation contributed a substantially higher share of environmental footprint than water transportation. Sensitivity analysis further revealed the potential for a new transportation strategy that could significantly reduce the environmental impacts of endurance test projects and the whole organization. This strategy involves minimizing the distance traveled by machine elements on the road and, instead, increase the distance traveled by water. This approach is feasible given the strategic locations of the LBL and European machine element suppliers in cities with access to ports. This situation seems promising because it improves the results for all 18 analyzed impact categories.

It is important to recall that during the year used as reporting unit (2020) operations in the LBL were affected by the Covid-19 pandemic, although precisely accounting for the repercussions in both, number of executed projects and patterns of office operations, is not possible. One process, for which it was feasible to assess the impact of the pandemic was business travel. It could be appreciated that if business trips were executed as usual, the organizational footprint would have been slightly bigger in all impact categories (a maximum increase of 4.3% was observed); but the increase seems more significant when compared to the group of processes belonging to the office operations. It is also recommended to keep track of business trips that are made by long distance train.

The system boundaries of this study did not contemplate some elements as the services that the LBL outsources (cleaning, building maintenance and security), because information for them could not be obtained and no datasets were available in the ecoinvent database. It might be interesting to evaluate the degree of contribution of these processes in a future assessment.

Finally, processes like packing, test rig assembly and disassembly, waste management, office services, office supplies, and employees commuting account for a minimal portion of the total environmental impacts. Thus, no specific short-term modifications to the business as usual scenario are proposed for these processes. However, the LCA practitioner recommends that LBL decision-makers continue their waste treatment strategies, which have proven effective in recycling waste steel and properly disposing of other waste materials, even if quantities are small.

6 Discussion

6.1 Product life cycle assessment

Results for this system clearly present that the manufacturing of the machine elements dominates the contributions to almost all impact categories in the business as usual (BAU) scenario. In a deeper analysis, it was also found that steelmaking is responsible for most of the emissions originating in these processes. It is important to remark that BAU model has been developed using the ecoinvent dataset for world market for low alloy steel, which considers that around 74.2% of the steel supplied in the global market is manufactured with Blast Furnace – Basic Oxygen Furnace (BF-BOF) technology and 25.8% with Electric Arc Furnace (EAF) technology.

It was initially expected that the process of endurance test execution at the LBL would represent a higher share of the total environmental emissions, nevertheless, the values for this process were lower than 20% for most impact categories, except for LOP and ODPinfinite, with 21.6% and 43.12% respectively. It is important to note that BAU scenario considers electricity supply at the LBL to be contracted from renewable sources.

The transportation process also shows a significant contribution to the overall environmental impacts of the analyzed system. While for a few impact categories its contribution remains below 5%, there are other impact categories where its influence is notably higher. For instance, the contributions to the TETP account for around 30% of the total emissions; GWP100 close to 14%, and both HOFP and EDFP account for around 26%. Notably, the contributions for TETP and WGP100 arise mainly from road transportation. Despite covering a distance seven times greater than road transportation, sea transportation exhibits relatively lower environmental impacts than road transportation in most of the impact categories, as an example, 11.9% of the emissions of GWP100 come from road transport while only 1.9% are emitted during sea transport.

6.2 Organizational life cycle assessment (O-LCA)

The results of this system suggest that most of the environmental contributions related to the large bearing laboratory as an organization originate from the endurance testing activities, as described in Figure 32, which was previously discussed in the product LCA. Some remarkable impact categories and the contributions arising from the endurance testing group of activities are SOP with 99% of the total emissions; WCP, LOP, and TAP with around 95%, and GWP100 with 91.3% of the total $CO_{2\text{-eq}}$ emissions. Since the processes linked to the product LCA clearly dominate the organizational emissions, the processes that are most impactful for the endurance testing might also be for the organization.

It is worth noting that, the processes analyzed in the office operation group presented a more balanced contribution to the environmental impact categories when compared to the endurance testing group of processes, which is clearly dominated by the machine elements manufacturing. The three processes that contributed the most for the office operations are office services, office supplies, and IT and data services.

6.3 Sensitivity analysis

6.3.1 Machine elements manufacturing done with EAF steel manufactured in Europe.

Results discussed in Sections 4.3.1 and 5.3.1 indicated that machine elements manufacturing is the process that most significantly contributes to the overall environmental footprint, not only of endurance testing activities, but also for the organization. Within manufacturing, steelmaking is the most impactful process to be considered in the system boundaries.

In figures Figure 28 and Figure 53 It can be noted that on both product and organizational level, there is a potential improvement in the performance of 16 out of 18 impact categories if the manufacturing process is done with EAF steel that has been produced in Europe. GWP100 exhibits a reduction of 14% and 13% for product LCA and O-LCA respectively, which represents nearly 43 ton of $CO_{2=eq}$. Other impact categories where significant reductions are achieved are SOP with nearly 26% in both scenarios, this is explained by the usage of steel scrap as main raw material in secondary steel production; FFP also decreases significantly because secondary steel production is less energy intensive as primary production. The obtained improvements become even more promising since only a share of 32% of the total steel mass is being analyzed. Nevertheless, the adoption of EAF steel as raw material also implies an increase in two impact categories, HTPc and IRP. The increase in HTPc can be explained to the slag waste and high amount of fine particulate matter present in EAF manufacturing, which contains iron, zinc, manganese, lead, chromium, nickel, cadmium, among others (Cappelletti et al., 2016). IRP increase is explained by the electricity supply required in the EAF process, which would be partly supplied by nuclear energy, while primary production relies mostly on fossil sources for energy supply.

6.3.2 Electricity supply with Germany's electricity mix

As previously discussed, Fraunhofer IWES opted for a renewable energy supply for the analyzed testing facility to minimize environmental impacts since operations started in 2018. On top of the contracted renewable electricity supply, renewable energy certificates (REC) are acquired to make sure that CO_2 emissions related to electricity supply are offset. A sensibility analysis has been conducted to assess how an electricity supply from Germany's grid would affect the results of the analyzed environmental impact categories. The results for this analysis are presented in Figure 29 and Figure 54, where a substantial increase in almost all impact categories can be appreciated under the analyzed scenario. IRP is the category exhibiting the greatest variation in comparison to the BAU scenarios; supplying the LBL with electricity from the German grid could imply an increase bigger than 500% over the BAU scenario which considers a renewable electricity supply. Such increase is explained because Germany's electricity grid still considered nuclear power plants in the analyzed year, activity that is linked to ionizing radiation. The second biggest difference can be appreciated in FEP indicator, which would increase by over 200% in both systems. This increase is explained due to the mining of lignite that is required to power Germany's electricity grid. GWP100 emissions would also increase by nearly 50% in both product LCA and O-LCA.

Although a worse performance is not appreciated in every impact category (for example LOP and TETP), the great majority of environmental categories present a more impactful performance under the scenario considering electricity supply from the grid, meaning that the measure of ensuring a renewable energy supply for the LBL in the effort of minimizing environmental impacts has very likely been effective and might have translated to less emissions over the years of operation. This measure could also apply to other organizations whose testing activities require substantial amounts of electricity to conduct their activities.

6.3.3 Transportation logistic that minimizes the distance travelled by road.

Analysis of the results presented in the Sections 4.3.1 and 5.3.1 indicated that, even if the contributions arising from the transportation process were not the biggest, they were still relevant. A deeper analysis into the results showed that between road transportation and sea transportation, the first one was responsible for the biggest share of emissions. As presented in Figure 8, there are two machine elements suppliers located in Europe, with an average distance of 2000 km to the LBL. In the BAU systems, the delivery of the machine elements from these locations to the LBL is carried out by road transportation. Therefore, a logistic which could minimize the distance covered by road and use more sea transportation is analyzed. This is feasible, because both machine elements suppliers located in Europe and the LBL have their facilities located in a city with access to a seaport.

Figure 30 Figure 56 present the results of the proposed transportation strategy, under which the performance on all environmental categories presents improvements in both product LCA and O-LCA. For the GWP100, a reduction of 11% and 10% could be expected respectively, and the category with the greatest improvement would be TEPT, with a reduction of a little 25% of the total emissions.

6.3.4 Machine elements commissioned by Fraunhofer IWES manufactured with renewable energy supply.

In the manufacturing processes, not only steel supply can be evaluated, but the machining processes also which require a significant amount of electricity can be analyzed too. In this sensibility analysis is assessed the change in total environmental impacts if it is requested to IWES's suppliers that they exclusively use electricity that originates from renewable sources for the machining processes. This sensibility analysis was conducted only for the product life cycle assessment. Results showed that improvements would be under 1% for almost all impact categories (17 out of 18). The complexity of the request would be too great for the possible benefits of this measure.

6.3.5 Business travel modelled to resemble a normal year operation.

The analyzed year for the O-LCA was highly affected by the Covid-19 pandemic. One of the aspects that showed greater variations was business travel. In the year 2020, no business trips by plane were executed. For this sensibility analysis, data for business travels of a different year was used (2022), as it is expected to better represent a normal operating year. This scenario is analyzed only for the O-LCA, and as expected, the environmental footprint increases across all environmental impact categories, nevertheless, the increase is very small in comparison to the overall footprint (under 1% for 12 out of 18 impact categories). The GWP100 would increase by 2.6%. The variations observed in this analysis are too small to lead to any conclusion.

7 Conclusions

The present master thesis made use of two case studies, a product LCA and an O-LCA following an attributional approach to identify the main hotspots for large structure testing in the wind industry as a product and for the organization in charge of conducting these research activities. Alongside, sensitivity analyses have been conducted to identify processes with potential for environmental impacts reductions and strategies that could lead to them. Findings highlight that machine elements manufacturing is the process with the highest environmental footprint, mainly due to the steelmaking process. Business as usual scenario considers global market steel supply, while sensitivity analysis underscores a significant potential for reducing emissions across most analyzed impact categories through a shift to EAF steel manufactured in Europe supply. However, it is important to note that sensitivity analysis has been conducted under the assumption of full elasticity in EAF steel supply, meaning that an increase in demand from the analyzed process results in an equal increase in the supply. Therefore, the organization should ensure that the shift to electric arc furnace steel results in an additionality of the mentioned technology, which might be difficult to achieve. On the other hand, state-of-the-art technologies for steel production with a lower environmental footprint are emerging in Europe, and opting for these technologies would not only result in reduced environmental impacts, but also facilitate a more straightforward assurance of additionality in the market.

This study remarks on the important role of electricity supply in large structure testing and in the organizations in charge of conducting such research activities. Given that large structure testing typically spans over several weeks or months, it requires a substantial amount of electricity. Sensitivity analysis hinted that implementing a renewable energy supply at the LBL has been a successful measure for curtailing the environmental footprint of the testing activities and the organization as a whole. It is worth noting that electricity supply is contractually committed to be from renewable sources, additionally, Fraunhofer IWES goes a step further by acquiring renewable energy certificates (REC) to ensure that their emissions associated with energy supply are offset, and to incentive the growth of renewables installed capacity.

The two previous measures can be applied to large structure testing in general if they require large steel machine elements to be manufactured and if the testing activities require big amounts of electricity over a prolonged period of time. These characteristics have not only been identified at the LBL but are common to other testing facilities in the wind industry.

Another process in which improvement potential has been identified is the transportation of machine elements. Sensibility analysis showed that implementing a strategy that minimizes road transportation and uses water transportation, when possible, might result in a substantial reduction in environmental impacts across all evaluated impact categories, nevertheless this measure is feasible for the analyzed process due to the availability of seaports in the cities involved. For other large structure testing organizations, their transportation logistic should be detailly analyzed.

For future research, it is recommended that a consequential life cycle assessment is conducted to validate the reduction in environmental footprint that the strategies identified in this study would have. This is necessary because the presented case studies correspond to attributional

LCA studies, whose main objective is to understand the current state of environmental impacts arising from the endurance testing activities and the LBL rather than evaluating measures to reduce them. It is also recommended to incorporate an economic perspective into the analysis, since this study has exclusively concentrated on assessing environmental impacts. Future work should also aim to estimate the environmental footprint arising from exchange of structures due to pitch bearing system failure in the wind industry and compare it with the testing activities assessed in this research, whose main goal is to prevent the forementioned failures.

5. References

ACCIONA. (2023). *ACCIONA to build pioneering wind blade recycling plant in Navarra*.

Arias, F. (2016). Assessment of Present/Future Decommissioned Assessment of Present/Future Decommissioned Wind Blade Fiber-Reinforced Composite Material in the United States. https://www.researchgate.net/publication/338430512_Assessment_of_PresentFuture_Decommissioned_Wind_Blade_Fiber-Reinforced_Composite_Material_in_the_United_States

Arzoumanidis, I., D'Eusanio, M., Raggi, A., & Petti. Luigia (Eds.) (2020). *Functional Unit Definition Criteria in Life Cycle Assessment and Social Life Cycle Assessment: A Discussion: Chapter 1*. Springer.

Asdrubali, F., Baldinelli, G., D'Alessandro, F., & Scrucca, F. (2015). Life cycle assessment of electricity production from renewable energies: Review and results harmonization. *Renewable and Sustainable Energy Reviews*, *42*, 1113–1122. https://doi.org/10.1016/j.rser.2014.10.082

Babbitt, C. W., Althaf, S., Cruz Rios, F., Bilec, M. M., & Graedel, T. E. (2021). The role of design in circular economy solutions for critical materials. *One Earth*, *4*(3), 353–362. https://doi.org/10.1016/j.oneear.2021.02.014

Bararzadeh Ledari, M., Khajehpour, H., Akbarnavasi, H., & Edalati, S. (2023). Greening steel industry by hydrogen: Lessons learned for the developing world. *International Journal of Hydrogen Energy*, *48*(94), 36623–36649. https://doi.org/10.1016/j.ijhydene.2023.06.058

BASF SE (2021). BASF Methodology for Product Carbon Footprint Calculation.

Baumann, H., & Tillman, A. M. (2004). *The Hitch Hiker's Guide to LCA: An Orientation in Life Cycle Assessment Methodology and Application*. *The Hitch Hikers's Guide to LCA: An Orientation in Life Cycle Assessment Methodology and Application*. Professional Publishing House. https://books.google.de/books?id=3QdsQgAACAAJ

Bosch, J., Staffell, I., & Hawkes, A. D. (2018). Temporally explicit and spatially resolved global offshore wind energy potentials. *Energy*, *163*, 766–781. https://doi.org/10.1016/j.energy.2018.08.153

Burton, T. (2011). *Wind energy Handbook* (second). J. Wiley.

Cappelletti, R., Ceppi, M., Claudatus, J., & Gennaro, V. (2016). Health status of male steel workers at an electric arc furnace (EAF) in Trentino, Italy. *Journal of Occupational Medicine and Toxicology (London, England)*, *11*, 7. https://doi.org/10.1186/s12995-016-0095-8

Davidsson, S., Höök, M., & Wall, G. (2012). A review of life cycle assessments on wind energy systems. *The International Journal of Life Cycle Assessment*, *17*(6), 729–742. https://doi.org/10.1007/s11367-012-0397-8

DeBoer, B., Nguyen, N., Diba, F., & Hosseini, A. (2021). Additive, subtractive, and formative manufacturing of metal components: a life cycle assessment comparison. *The International Journal of Advanced Manufacturing Technology*, *115*(1-2), 413–432. https://doi.org/10.1007/s00170-021-07173-5

Dolan, S. L., & Heath, G. A. (2012). Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power. *Journal of Industrial Ecology*, *16*(s1), S136-S154. https://doi.org/10.1111/j.1530-9290.2012.00464.x

ecoinvent. *ecoinvent Database*. https://ecoinvent.org/the-ecoinvent-database/

Ekvall, T [T.], & Weidema, B. P. (2004). System boundaries and input data in consequential life cycle inventory analysis. *Int. J. LCA*, *9*, 161–171. https://doi.org/10.1007/BF02994190

Ellen Macarthur Foundation. (2015). *Towards a circular economy: Business rationale for an accelerated transition.*

European Commission (2013). Recommendations on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013H0179

European Commission (2022). Proposal for a Regulation on Ecodesign for Sustainable Products: establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC.

European Commission. (2023). *Ecodesign for Sustainable Products Regulation.* European Commission. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en#:~:text=The%20new%20regulation%20will%20improve,and%20other%20environmental%20sustainability%20aspects.&text=The%20current%20Ecodesign%20Directive%202009,businesses%2C%20consumers%20and%20the%20environment.

Finkbeiner, M., & König, P. (2013). Carbon footprint and life cycle assessment of organizations. *Journal of Environmental Accounting and Management*, *1*, 55–63. https://doi.org/10.5890/JEAM.2012.01.005

Finnveden, G., Hauschild, M. Z., Ekvall, T [Tomas], Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S [Sangwon] (2009). Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, *91*(1), 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Fraunhofer IWES. *Rolling bearings.* Fraunhofer IWES. https://www.iwes.fraunhofer.de/en/test-centers-and-measurements/drive-train-components.html#1

Fraunhofer-Gesellschaft e.V. (2021). *Fraunhofer Klimaneutral 2030.* Fraunhofer-Gesellschaft e.V. https://www.fraunhofer.de/content/dam/zv/de/institute-einrichtungen/Verbuende/energie-und-klima/Politik-Papier-Klimaneutral-2030.pdf

Ghenai, C. (Ed.). (2012). *Sustainable Development - Energy, Engineering and Technologies - Manufacturing and Environment.: Life Cycle Analysis of Wind Turbine.* https://doi.org/10.5772/29184

Greenhouse Gas Protocol. (2004). *A Corporate Accounting and Reporting Standard*. World Resources Institute.

Greenhouse Gas Protocol. (2011). *Product Life Cycle Product Life Cycle Accounting and Reporting Standard*. World Resources Institute. www.ghgprotocol.org

Guevara Opinska, L., Mahmoud, M., Bene, C., & Rademaekers, K. (2021). *Moving towards Zero-Emission Steel, Publication for the committee on Industry, Research and Energy (ITRE),* *Policy Department for Economic, Scientific and Quality of Life Policies,: Technologies Available, Prospects, Timeline and Costs.*

H2 green steel. (2022). *On course for large-scale production from 2025.* H2 green steel. https://www.sms-group.com/plants/projects/h2-green-steel

Hammond, G. P., Jones, C. I., & O'Grady, Á. (2015). Environmental Life Cycle Assessment (LCA) of Energy Systems. In J. Yan (Ed.), *Handbook of Clean Energy Systems* (pp. 1–26). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118991978.hces139

Han, J. W., Nam, J. S., Park, Y. J., Lee, G. H., & Nam, Y. Y. (2015). An experimental study on the performance and fatigue life of pitch bearing for wind turbine. *Journal of Mechanical Science and Technology*, *29*(5), 1963–1971. https://doi.org/10.1007/s12206-015-0417-2

Hau, E. (2013). *Wind Turbines*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-27151-9

Hidalgo, R., Areitioaurtena, M., Hinojosa, I., Segurajauregi, U., & Urresti, I. (2023). Novel Methodology for Induction Hardening Simulation of a Large Pitch Bearing. In G. Conte & O. Sename (Eds.), *Proceedings of 10th International Conference on Mechatronics and Control Engineering* (pp. 11–18). Springer Nature Singapore.

M.A.J. Huijbregts et al. (2016). *ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization*. RIVM Report 2016-0104.

IEA. (2021a). *Net Zero by 2050: A Roadmap for the Global Energy Sector* (4th). International Energy Agency.

IEA. (2021b). *Net Zero by 2050 Data Explorer.* IEA. https://www.iea.org/data-and-statistics/data-tools/net-zero-by-2050-data-explorer

IEA. (2022). *Wind Electricity: Tracking report - September 2022.* IEA. https://www.iea.org/reports/wind-electricity

IEA. (2023). *Steel: Overview and tracking.* IEA. https://www.iea.org/energy-system/industry/steel

IPCC (Ed.). (2022). *Climate change 2022: Mitigation of climate change*. IPCC. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf

iPoint. (2023). *Umberto.* iPoint. https://www.ifu.com/umberto/lca-software/

ISO. ISO/DIS 59004.

ISO (2006a). *ISO 14040:* Environmental management — Life cycle assessment - Principles and framework (Standard ISO 14040:2006(E)).

ISO (2006b). *ISO 14044:* Environmental management — Life cycle assessment - Requirements and guidelines (Standard ISO 14044:2006(E)).

ISO (2014). *ISO/TS 14072:* Environmental management — Life cycle assessment — Requirements and guidelines for organizational life cycle assessment (Technical Specification). ISO.

ISO (2018). *ISO 14067:* Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification (Standard ISO 14067:2018(E)). ISO.

Jensen, P. D., Purnell, P., & Velenturf, A. P. (2020). Highlighting the need to embed circular economy in low carbon infrastructure decommissioning: The case of offshore wind.

Sustainable Production and Consumption, *24*, 266–280. https://doi.org/10.1016/j.spc.2020.07.012

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G [Gerald], & Rosenbaum, R. (2003). IMPACT 2002+: A new life cycle impact assessment methodology. *The International Journal of Life Cycle Assessment*, *8*(6), 324–330. https://doi.org/10.1007/BF02978505

Jolliet, O., Saade-Sbeih, M., Shaked, S., Jolliet, A., & Crettaz, P. (2015). *Environmental Life Cycle Assessment* (1st). CRC Press.

Jordaan, S. M., Combs, C., & Guenther, E. (2021). Life cycle assessment of electricity generation: A systematic review of spatiotemporal methods. *Advances in Applied Energy*, *3*, 100058. https://doi.org/10.1016/j.adapen.2021.100058

Kamp Albæk, J., Shahbazi, S., McAloone, T. C., & Pigosso, D. C. A. (2020). Circularity Evaluation of Alternative Concepts During Early Product Design and Development. *Sustainability*, *12*(22), 9353. https://doi.org/10.3390/su12229353

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Klöpffer, W., & Grahl, B. (Eds.). (2014). *Life Cycle Assessment (LCA): A Guide to Best Practice*. John Wiley & Sons, Ltd.

Lerides, M., & Reiland, J. (2019). Wind turbine blade circularity: Technologies and practices around the value chain. https://baxcompany.com/wp-content/uploads/2019/06/wind-turbine-circularity.pdf

Liu, Z., & Zhang, L. (2019). A review of failure modes, condition monitoring and fault diagnosis methods for large-scale wind turbine bearings. *Measurement*, *149*, 107002. https://doi.org/10.1016/j.measurement.2019.107002

Liu, Z., Zhang, L., & Carrasco, J. (2020). Vibration analysis for large-scale wind turbine blade bearing fault detection with an empirical wavelet thresholding method. *Renewable Energy*, *146*, 99–110. https://doi.org/10.1016/j.renene.2019.06.094

M. A. Parvez Mahmud, Shahjadi Hisan Farjana, Candace Lang, & Nazmul Huda. (2023). Chapter Two - State-of-the-art life cycle assessment methodologies applied in renewable energy systems. In M. A. Parvez Mahmud, Shahjadi Hisan Farjana, Candace Lang, & Nazmul Huda (Eds.), *Green Energy* (pp. 7–46). Academic Press. https://doi.org/10.1016/B978-0-32-385953-0.00008-2

Martínez, E., F. Sanz, S. Pellegrini, E. Jiménez, & J. Blanco (2009). Life cycle assessment of a multi-megawatt wind turbine. *Renewable Energy*, *34*(3), 667–673. https://doi.org/10.1016/j.renene.2008.05.020

Martinez-Blanco, J., Inaba, Atsushi, & Finkbeiner, M. (2016). *Life Cycle Assessment for Organizations* (1st) [Special types of Life Cycle Assessment].

Martínez-Blanco, J., Forin, S., & Finkbeiner, M. (2018). Launch of a new report: “Road testing organizational life cycle assessment around the world: applications, experiences and lessons learned”. *The International Journal of Life Cycle Assessment*, *23*(1), 159–163. https://doi.org/10.1007/s11367-017-1409-5

Martínez-Blanco, J., Forin, S., & Finkbeiner, M. (2019). Challenges of organizational LCA: lessons learned from road testing the guidance on organizational life cycle assessment. *The*

International Journal of Life Cycle Assessment, *25*(2), 311–331. https://doi.org/10.1007/s11367-019-01699-3

Marx, H., Forin, S., & Finkbeiner, M. (2020). Organizational Life Cycle Assessment of a Service Providing SME for Renewable Energy Projects (PV and Wind) in the United Kingdom. *Sustainability*, *12*(11), 4475. https://doi.org/10.3390/su12114475

METINVEST. *S690Q-brand steel*. https://metinvestholding.com/en/products/steel-grades/s690q

Michael L. Morrison, & Karin Sinclair. (2004). Wind Energy Technology, Environmental Impacts of. In Cutler J. Cleveland (Ed.), *Encyclopedia of Energy* (pp. 435–448). Elsevier. https://doi.org/10.1016/B0-12-176480-X/00419-8

Niero, M., & Rivera, X. C. S. (2018). The Role of Life Cycle Sustainability Assessment in the Implementation of Circular Economy Principles in Organizations. *Procedia CIRP*, *69*, 793–798. https://doi.org/10.1016/j.procir.2017.11.022

Oebels, K. B., & Pacca, S. (2013). Life cycle assessment of an onshore wind farm located at the northeastern coast of Brazil. *Renewable Energy*, *53*, 60–70. https://doi.org/10.1016/j.renene.2012.10.026

OpenLCA. (2022). *OpenLCA: The world's leading, high performance, open source Life Cycle Assessment software.* OpenLCA. https://www.openlca.org/

Rebitzer, G [G.], Ekvall, T [T.], Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S [S.], Weidema, B. P., & Pennington, D. W. (2004). Life cycle assessment part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International*, *30*(5), 701–720. https://doi.org/10.1016/j.envint.2003.11.005

Riesener, M., Kuhn, M., Hellwig, F., Ays, J., & Schuh, G. (2023). Design for Circularity – Identification of Fields of Action for Ecodesign for the Circular Economy. *Procedia CIRP*, *116*, 137–142. https://doi.org/10.1016/j.procir.2023.02.024

Rimano, M., Simboli, A., Taddeo, R., & Raggi, A. (2019). Life Cycle Approaches for the Environmental Impact Assessment of Organizations: Defining the State of the Art. *Administrative Sciences*, *9*(4), 94. https://doi.org/10.3390/admsci9040094

Salzgitter AG. (2023). *Our SALCOS program: The concept for a sustainable future.* Salzgitter AG. https://salcos.salzgitter-ag.com/de/salcos.html

Schwack, F., Halmos, F., Stammler, M., Poll, G., & Glavatskih, S. (2022). Wear in wind turbine pitch bearings—A comparative design study. *Wind Energy*, *25*(4), 700–718. https://doi.org/10.1002/we.2693

SGRE. (2023). *Pioneering turbine recyclability.* Siemens Gamesa Renewable Energy. https://www.siemensgamesa.com/en-int/explore/journal/recyclable-blade

Shah, I. H., Hadjipantelis, N., Walter, L., Myers, R. J., & Gardner, L. (2023). Environmental life cycle assessment of wire arc additively manufactured steel structural components. *Journal of Cleaner Production*, *389*, 136071. https://doi.org/10.1016/j.jclepro.2023.136071

SimaPro. (2023). *About SimaPro.* SimaPro. https://simapro.com/about/

SMS group. *H2 Green Steel: The world's first carbon-neutral steel plant.* SMS group. https://www.sms-group.com/plants/projects/h2-green-steel

Sphera Solutions. (2023). *LCA for Experts (GaBi).* Sphera Solutions. https://sphera.com/life-cycle-assessment-lca-software/

Stammler, M. (2020). *Endurance Test Strategies for Pitch Bearings of Wind Turbines*. Fraunhofer Verlag.

Stammler, M., Menck, O., Guo, Y., & Keller, J. (2023). The Wind Turbine Design Guideline DG03: Yaw and Pitch Rolling Bearing Life Revisited - An Outline of Suggested Changes: Preprint.

Stammler, M., Thomas, P., Reuter, A., Schwack, F., & Poll, G. (2019). Effect of load reduction mechanisms on loads and blade bearing movements of wind turbines. *Wind Energy*, *23*(2), 274–290. https://doi.org/10.1002/we.2428

Stella, C. (2019). *Unfurling The Waste Problem Caused By Wind Energy.* NPR. https://www.npr.org/2019/09/10/759376113/unfurling-the-waste-problem-caused-by-wind-energy?t=1614410135094

Talens Peiró, L., Polverini, D., Ardente, F., & Mathieux, F. (2020). Advances towards circular economy policies in the EU: The new Ecodesign regulation of enterprise servers. *Resources, Conservation, and Recycling*, *154*, 104426. https://doi.org/10.1016/j.resconrec.2019.104426

Thomson, C., & Harrison, G. (2015). Life cycle costs and carbon emissions of wind power: Executive Summary. https://www.climatexchange.org.uk/research/projects/assessing-the-life-cycle-costs-and-carbon-emissions-of-wind-power/

Thomson, R. C. (2014). *Carbon and energy payback of variable renewable generation*. The University of Edinburgh.

Together for Sustainability. (2022). *The Product Carbon Footprint Guideline for The product Carbon Footprint Guideline for the Chemical Industry: Specification for product Carbon Footprint and Corporate Scope Specifications for product Carbon Footprint and Corporate Scope 3.1 Emission Accounting and Reporting*. https://www.tfs-initiative.com/how-we-do-it/scope-3-ghg-emissions

Uddin, M. S., & Kumar, S. (2014). Energy, emissions and environmental impact analysis of wind turbine using life cycle assessment technique. *Journal of Cleaner Production*, *69*, 153–164. https://doi.org/10.1016/j.jclepro.2014.01.073

UNEP (2011). Global guidance principles for life cycle assessment databases : a basis for greener processes and products : 'Shonan guidance principles', 156. http://digitallibrary.un.org/record/785158

UNEP. (2015). *Guidance on Organizational Life Cycle Assessment.*

UnionStahl. *Structural steel S355J2+N according to DIN EN 10025-2*. https://www.unionstahl.com/structural-steel-s355j2n/?lang=en#:~:text=S355J2%20%2B%20N%20is%20used%20in,a%20length%20of%2016%2C000%20mm.

Vestas. (2017). *Life cycle Assessment of electricity production from an onshore V105-3.45 MW wind plant.* Vestas Wind Systems A/S.

Vestas. (2023). *Vestas unveils circularity solution to end landfill of turbine blades.* Vestas. https://www.vestas.com/en/media/company-news/2023/vestas-unveils-circularity-solution-to-end-landfill-for-c3710818

Wang, L., Wang, Y., Du, H., Zuo, J., Yi Man Li, R., Zhou, Z., Bi, F., & Garvlehn, M. P. (2019). A comparative life-cycle assessment of hydro-, nuclear and wind power: A China study. *Applied Energy*, *249*, 37–45. https://doi.org/10.1016/j.apenergy.2019.04.099

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Yang, J., & Chen, B. (2015). Life Cycle Assessment of Wind Power Generation System. In J. Yan (Ed.), *Handbook of Clean Energy Systems* (pp. 1–18). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118991978.hces115

Annex A: Environmental impact categories description

Acidification: terrestrial - terrestrial acidification potential (TAP)

According to (M.A.J. Huijbregts et al., 2016), the atmospheric deposition of certain inorganic substances like sulphates, nitrates, and phosphates, have an impact in the acidity level of the soil. For almost all plants, there is an ideal pH level, and if altered, it can be very hurtful to the ecosystem. A change in acidity level may impact nutrients being washed out and increase the solubility of metals into soils. TAP is measured in kg of sulphur dioxide equivalents.

Climate change - global warming potential (GWP100)

Emissions of greenhouse gases lead to an increase in concentration in the atmosphere, which at the same time raises the radiative forcing capacity (w/m^2), resulting in an growth in the global mean temperature (°C). This environmental impact category is measured in kg of CO_2-eq (M.A.J. Huijbregts et al., 2016). When an LCA focuses on this environmental impact, it is considered a carbon footprint analysis.

Ecotoxicity: freshwater ecotoxicity potential (FETP)

This impact category refers to the impact on freshwater ecosystems, as a result of emissions of toxic substances to air, water, and soil. It is measured in kg of 1,4 dichlorobenzene equivalents (M.A.J. Huijbregts et al., 2016) (Vestas, 2017).

Ecotoxicity: marine ecotoxicity potential (METP)

This impact category refers to the impact on marine water ecosystems, as a result of emissions of toxic substances to air, water, and soil. It is measured in kg of 1,4 dichlorobenzene equivalents (M.A.J. Huijbregts et al., 2016) (Vestas, 2017).

Ecotoxicity: terrestrial ecotoxicity potential (TETP)

This impact category refers to the impact on terrestrial ecosystems, as a result of emissions of toxic substances to air, water, and soil. It is measured in kg of 1,4 dichlorobenzene equivalents (Vestas, 2017) (M.A.J. Huijbregts et al., 2016).

Energy resources: non-renewable, fossil fuel potential (FFP)

This impact category assesses the total use of energy resources that come from non-renewable sources over the complete life cycle, in other words, it measures the depletion of natural fossil fuel resources. It is measured in kg of oil equivalent (M.A.J. Huijbregts et al., 2016).

Eutrophication: freshwater eutrophication potential (FEP)

Freshwater eutrophication potential evaluates the discharge of nutrients into soil or into freshwater bodies and the subsequent rise of nutrients levels in freshwater bodies. Phosphorus and nitrogen are some of the main nutrients that promote eutrophication. This phenomenon damages the environment by increasing the nutrient uptake of some organisms such as cyanobacteria, algae, fish, and invertebrates. At the end, this leads to loss of species (Vestas, 2017) (M.A.J. Huijbregts et al., 2016).

Eutrophication: marine eutrophication potential (MEP)

Marine eutrophication potential evaluates enrichment of nutrients levels in marine water ecosystems. This phenomenon damages the environment by increasing the nutrient uptake of some organisms which leads to unbalances in the ecosystem. It is measured as kg of nitrogen equivalents (M.A.J. Huijbregts et al., 2016).

Human toxicity: carcinogenic - human toxicity potential (HTPc)

This category refers to the impact on humans as a result of emissions of toxic substances to air, water, and soil. This category focusses on the emissions that are related to carcinogenic impacts. It is measured in kg of 1,4 dichlorobenzene equivalents (Vestas, 2017) (M.A.J. Huijbregts et al., 2016).

Human toxicity: non-carcinogenic - human toxicity potential (HTPnc)

This category refers to the impact on humans as a result of emissions of toxic substances to air, water, and soil. This category focusses on the emissions that are related to non-carcinogenic impacts. It is measured in kg of 1,4 dichlorobenzene equivalents (Vestas, 2017) (M.A.J. Huijbregts et al., 2016).

Ionising radiation - ionising radiation potential (IRP)

This category evaluates the emissions of radionuclides, which are directly related to damage to human health and ecosystems. Anthropogenic emissions of radionuclides are generated in the nuclear fuel cycle (mining, processing, and waste disposal), but they are also generated in other activities such as burning of coal and some mining activities. Exposure to these radionuclides can lead to damage to DNA molecules. This impact category is measured in kBq Co-60-Eq.

Land use - agricultural land occupation (LOP)

This impact category assesses the direct and local impact of land use on terrestrial species by considering the change of land cover and the actual use of the new land. Change of the land cover directly affects the original habitat and the original species composition (M.A.J. Huijbregts et al., 2016). This impact category considers the change in soil quality as well, for example the erosion resistance and the mechanical filtration. Results are presented in m^2 annual crop equivalents.

Material resources: metals/minerals - surplus ore potential (SOP)

This impact category analyses the impact of mineral resources extraction, whose increase leads to a decrease in the overall ore grade, meaning that the concentration of said mineral/metal in the ore decreases. If the concentration is lower, then more mineral resources need to be mined to achieve the same level of production. The factor for mineral resources scarcity is the surplus ore potential (SOP), which expresses the average extra amount of ore to be mined in the future to achieve the same functional unit. It is measured in kg of cooper equivalent (M.A.J. Huijbregts et al., 2016).

Ozone depletion - ozone depletion potential (ODPinfinite)

Emissions of ozone depleting substances ultimately lead to damage to human health because of the resultant increase in UV radiation. Ozone depleting chemicals are very persistent in the atmosphere. The increase in ozone depleting potential leads to an increase in the atmospheric ozone concentration, which allows a higher amount of UV radiation to hit the earth. This impact category is measured in kg of CFC-11.

Particulate matter formation potential (PMFP)

This impact category addresses the emissions of fine particulate matter with a diameter of less than 2.5 µm and are emitted by primary and secondary aerosols. Particulate matter has been directly linked to negative effects in human health, ranging from respiratory symptoms to hospital admissions and death. Emissions are measured in kg of PM2.5 equivalents.

Photochemical oxidant formation potential: humans (HOFP)

This impact category assesses the emissions of nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOCs), which can photochemically react in the atmosphere and produce ozone. As previously described in ozone depletion potential impact category, an increase in ozone concentration has a negative impact on human health. It is measured by the kg of NO_x equivalents.

Photochemical oxidant formation potential: ecosystems (EOFP)

Like the previous impact category, this one assesses the emissions of nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOCs), which can photochemically react in the atmosphere and produce ozone. The difference is that the previous one focusses on the impacts on human health, while this one measures the impacts to ecosystems. If the concentration of ozone increases, the uptake of it by plants also increases, which then leads to the disappearance of some plant species. It is also measured by the kg of NO_x equivalents.

Water use - water consumption potential (WCP)

This impact category assesses all water consumption, which is defined as the use of water in such a way that the water is evaporated, incorporated into products, transferred to other watersheds, or disposed into the sea. Meaning that the consumed water is no longer available in the original watershed for humans or for the ecosystem. This impact category us measured in m^3 of water withdrawal from surface water bodies or the abstraction of groundwater from aquifers (M.A.J. Huijbregts et al., 2016).