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Life Cycle Assessment of an Active Safety Radar System

An environmental assessment based on ISO 14040 and 14044 in conjunction with the GHG Protocol

Master's thesis in Industrial Ecology

Alexander Almroth
Isak Rehnberg

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se
Report No. E2023:044

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Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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Abstract

The automotive industry is one large sector undergoing a transition to become more sustainable, with multiple actors in the field currently developing more ambitious climate strategies. The electrification and automation of vehicles have caused an increased production of complex information and communication technology (ICT) equipment, creating an interest among companies to further understand their products' environmental performance. This, along with the increased pressure from various stakeholders, such as regulators and customers, incentivize companies to assess their product's potential environmental impacts. This is the case for Veoneer, a company producing ICT equipment aimed towards active safety within the automotive industry. This master thesis aims to assess the environmental performance of one of Veoneer's radar products by conducting a life cycle assessment (LCA) in accordance with ISO 14040 and 14044. An additional aim is to investigate potential implications that can occur when conducting an LCA in accordance with ISO 14040 and 14044 while simultaneously producing a report that aligns with the requirements stated in the GHG Protocol Product Life Cycle Accounting and Reporting Standard.

By dividing the studied radar's life cycle into the phases extraction and material production, manufacturing, assembly, use, end-of-life, and transportation, the LCA provides a detailed overview which facilitates deeper analyses. The life cycle's inputs and outputs are modelled through ecoinvent Database and by applying the ReCiPe2016 life cycle impact method to quantify 18 potential environmental impacts, a relevant and comprehensive set of impact categories related to the radar is assessed and interpreted.

The results of the LCA indicate that the radar's environmental performance is greatly influenced by the use phase, accounting for approximately 81% of the 28kg CO2 equivalents, representing the radar's total global warming potential. The extraction and material production phase as well as the manufacturing phase are also considered impactful, while assembly, end-of-life and transportation are much less noticeable. The aspects most prominent for improvement are the radar's energy consumption, the manufacturing of integrated circuits and printed circuit board panels as well as the extraction of silver and gold.

The result of the thesis entails that one of the frameworks, GHG Protocol Product Life Cycle Accounting and Reporting Standard contra ISO 14040 and 14044, may provide more relevant results than the other depending on what is of interest to examine and present. While results based on the GHG Protocol Product Life Cycle Accounting and Reporting Standard may allow for better comparison of products, following ISO 14040 and 14044 provides a more accurate picture of a product's overall environmental performance.

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Keywords: LCA, GHG Protocol, ISO, Radar, Automotive Industry, Sustainability

Acknowledgement

We would like to express our gratitude to all those who have assisted us along the path of conducting this thesis, which is written as the conclusion of our academic studies within the programme Industrial Ecology at Chalmers University of Technology. A huge thanks to our supervisor Tomas Ekvall, adjunct professor within Environmental System Analysis at Chalmers University of Technology, whose continuous feedback and expertise within the subject of LCA have guided us to produce the best possible report. We would also like to thank Mathias Janssen, who served as our examinator for this thesis.

Gratitude is also directed towards Veoneer, who made this project possible and gave us the opportunity to challenge ourselves and gain practical experience in how to conduct an LCA on a complex electronic product. A special thanks to Madalina Popescu and Charlotta Boweden, who have helped us throughout the project to get in touch with the right people and assisting us whenever needed. Additional thanks to the employees within the various departments at Veoneer who have taken their time to help us.

Lastly, we would like to thank Katja Gradin and Jonathan Klement from Ramboll who have assisted us with feedback and guidance in the fields of methodology and life cycle modeling in the LCA software GaBi.

Gothenburg, May 2023

Alexander Almroth

Alexander Almroth
Isak Rehnberg

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List of Acronyms

Acronym	Definition
CF	Characterization Factor
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
ICT	Information and Communication Technology
IMDS	International Material Data System
IPCC	Intergovernmental Panel for Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory analysis
LCIA	Life Cycle Impact Assessment
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
PLM	Product Lifecycle Management
R&D	Research and Development
RQ	Research Question
SMT	Surface Mount Technology

1. Introduction

This chapter presents the background which describes the problem under investigation. It is followed by the aim of the thesis along with the formulated research questions, limitations, and delimitations.

1.1 Background

The last century has seen increased levels of anthropogenic greenhouse gases (GHG) being emitted worldwide, consequently generating an impact on climate change. As a matter of historic development, scientists state that carbon emissions need to be cut by approximately 85% below 2000’s level before the year 2050 in order to limit the global temperature to rise above 2 degrees Celsius above pre industrial levels (Bhatia et al., 2011). This has established various incentives and regulations within industries that aim to guide and allow corporations to develop more effective climate strategies. The GHG Protocol states that the strategy of addressing carbon emissions works as a means where risk reduction from a financial point of view can be managed, along with the potential discovery of competitive advantages (Bhatia et al., 2011).

The automotive industry is one large sector undergoing a transition to become more sustainable, with multiple actors in the field currently working on the development of a more ambitious climate strategy. Increased pressure from various stakeholders, regulators as well as customers to name a few, generates the incentive for manufacturers to get an overview of their entire value chain and produce less environmentally harmful products to meet the demands. The growing interest in analyzing products’ environmental impacts is however not limited to larger corporations with end-customers, but also involves original equipment manufacturers (OEM’s) and suppliers. This is the case for Veoneer, a company that produces equipment for Information and communication technologies (ICTs), such as cameras and radars, aimed towards active safety within mobility.

The trends of electrification and automation of vehicles and mobility have generated a significant increase in the utilization of radars and sensors worldwide. Armstrong et al. (2020) highlights that the increased usage of sensors is expected to result in 11 billion sensors to be integrated in vehicles by the year 2024. The combination of the automotive industry’s vision to become more sustainable along with the increased volumes of radars and sensors being integrated in vehicles generates an incentive and interest to further understand ICT equipment’s potential environmental impact.

Veoneer are currently in the process of identifying various angles from which they can reduce their impact on the climate. The business’ environmental roadmap and goals related to reducing their carbon emissions are stated in their sustainability report of 2021 and highlights an end goal of reaching carbon neutrality on a corporate level by 2040 (Veoneer, 2022).

The GHG Protocol states that for an efficient climate strategy to be developed and its targets to be reached, an in-depth understanding of the corporations’ GHG emissions is necessary (Bhatia et al., 2011). Therefore, Veoneer has found that one particular matter of interest in order to succeed with their climate actions is to trace the environmental performance of their products’ life cycle in order to get a greater understanding of its potential impacts. The company has begun this process by assessing the environmental performance of one of their cameras using the tool Life Cycle Assessment (LCA). Consequently, Veoneer are now looking to carry out an LCA on one of their radars.

While LCA is a prominent tool to assess the potential environmental impacts of a product during its entire life cycle, it is often subject to thorough requirements set by the International Organization for Standardization (ISO). This, along with the fact that Veoneer are encouraged to follow the reporting requirements stated in the GHG Protocol, creates a cluster of frameworks needed to be addressed in order to produce an LCA of sufficient standards.

1.2 Aim

The aim of this thesis is to investigate the potential environmental impacts associated with one of Veoneer's radar products, hereafter referred to as the Radar, during its entire life cycle by performing an LCA. Furthermore, the LCA is intended to identify which of the Radar's life cycle phases that have the greatest contribution towards environmental burdens. The main goal is thus to assess the Radar's environmental performance, identify areas of improvement and provide results applicable for communication.

An additional aim is to investigate potential implications that can occur when conducting an LCA in accordance with ISO 14040 and 14044 while simultaneously producing a report that aligns with the requirements stated in the GHG Protocol Product Life Cycle Accounting and Reporting Standard. The goal in this context is to identify how the two frameworks differ and how this affects the results.

1.3 Research questions

To successfully meet the aim of the thesis, three research questions (RQ) are formulated and addressed:

RQ1: What is the potential environmental impact of the Radar throughout its entire life cycle?

RQ2: Which phases of the Radar's life cycle are most prominent for improvement to reduce its potential environmental impact?

RQ3: What similarities and differences can be identified when assessing a product's potential environmental impact in accordance with ISO 14040 and ISO 14044, contra the GHG Protocol Product Life Cycle Accounting and Reporting Standard?

1.4 Limitations and delimitations

The thesis is subjected to a time limitation of approximately 5 months, since the study is conducted during the period between January 2023 and mid-June 2023. This influences the data collection where the use of primary data for activities further up the Radar's value chain may be limited. Secondary data is thus relied upon whenever the collection of primary data is considered to be too time consuming.

Additionally, the results and research questions assessed in this study are entirely related to the case of Veoneer’s Radar. For instance, the findings related to the research questions, such as the methodological framework used, may deviate depending on what type of system or product that is assessed. Hence, the findings and observations compiled in this study may not replicate other assessments, and thereby limits the conclusions and findings to the relative case of the Radar.

As RQ3 only pertains to the actual assessment of a product’s potential environmental impact, the framework’s requirements of how to follow up the results and track the improvement progress over time are not investigated.

2. Theoretical framework

This chapter presents theory on LCA and the GHG Protocol which provides background information to support the rest of the thesis and facilitates understanding.

2.1 Life cycle assessment

In the mid-20th century, researchers started to expand their perspective when analyzing inputs and outputs related to energy technologies' life cycles in order deal with their growing complexity and provide more accurate analyses (Horne et al., 2009). These analyses extended even further and started to incorporate more parameters as they were applied in a variety of areas such as housing and automobiles. The term 'life cycle assessment' was proposed in 1990 and became a body of approaches to assessing environmental impacts (Horne et al., 2009). Since then, LCA has developed into an important tool in the challenge of identifying and implementing progressive measures to direct the consumer society in a more sustainable direction (Baumann & Tillman, 2004).

As climate change and other environmental hazards have gained increased attention during the last couple of decades, various tools have been developed to assess and enable benchmarking of environmental impacts. LCA is in this context a comprehensive assessment tool used to estimate potential environmental impacts from a life cycle perspective. This enables the examination of various potential environmental impacts, such as climate change, toxicity, and resource scarcity. These occur throughout the entire life cycle phases of the product or system of interest, from raw material extraction to waste management (Finnveden et al., 2009).

Baumann & Tillmann (2004) highlight that LCA's unique scope of focusing on the entire life cycle makes it a useful tool in multiple fields. The authors further remark that the strength of LCA lies in its approach of examining potential environmental impacts in relation to the product's function. This creates the foundation for comparison between alternative products with similar functionality. As a result of this, LCA can provide supporting inputs for decision-making, which can be utilized from a corporate perspective in actions such as product or process design as well as sourcing. Furthermore, the comparative property of the methodology can contribute with decision support on a regulatory level, for instance policy instruments implementation. Baumann and Tillman (2004) emphasize additional applications of LCA in the context of learning and communication. By identifying potential environmental impacts and their significance through an LCA, a company will learn more about its production system. This information can be used to characterize the product system and help determine appropriate improvement possibilities. In the case of communication, LCA results can be used for benchmarking purposes along with labeling and certification of ecofriendly products or systems (Baumann & Tillman, 2004).

For an LCA to be applicable in the mentioned areas, decision-making, learning, and communication, a common ground needs to be established in how these assessments should be constructed. One such guideline, SETAC Code of Practice, was developed in 1993 and was followed by the development of various regional-based guidelines (Baumann and Tillman, 2004). However, industries started to raise concerns regarding the absence of a globally standardized methodology since LCA results of identical products or systems provided varying results depending on the methodological choices selected (Hauschild et al., 2018). This would ultimately delegitimize its application for product development or communication. Thus, the implementation of a global standard was issued and implemented by ISO in 1997. This standard has since been updated and expanded and is now a common practice in the LCA world.

2.2 Greenhouse Gas Protocol

The GHG Protocol is a multistakeholder initiative founded in 1998 as a joint collaboration between businesses, non-governmental organizations (NGOs), governments and other worldwide organizations. The protocol was developed as a response to the absence of an internationally accepted GHG management methodology that companies could utilize to overview and identify the corporations' greenhouse emissions from their provided goods and services (Bhatia et al., 2011). The Protocol works as a guidance framework that promotes and creates an incentive of establishing a low emission economy. In 2009, the protocol launched its first draft standard for product accounting, as a complement to the already existing GHG Protocol guidelines for corporate and project accounting.

The Product Life Cycle Accounting and Reporting Standard in the GHG Protocol is developed with the intention to be adoptable by any corporation, regardless of size or geographical location, that wishes for greater understanding and knowledge of emissions caused by their services. The primary aim of the protocol is to, through the usage of the general framework, support and enable companies to make informed choices to reduce their emissions of greenhouse gases. The GHG Protocol Product Life Cycle Accounting and Reporting Standard is in the context of requirements and guidelines based on the ISO 14044 (2006b) LCA standard. However, one significant difference between the two methodologies is the scope of impact categories studied, where the GHG Protocol solely requires an assessment of global warming potential (GWP). This while an LCA conducted in accordance with the ISO standards justifies a much larger portfolio of impacts to be studied and presented. Worth mentioning is that ISO released a framework in 2018, namely ISO 14067. This standard includes guidelines and requirements in how to assess and report the carbon footprint of a product, solely focusing on the impact of climate change (ISO, 2018). It does, however, in other aspects differ from the GHG Protocol Product Life Cycle Accounting and Reporting Standard in terms of methodological choices. Bhatia et al. (2011) elaborate that GHG accounting results in a simplified analysis which is found beneficial for communication purposes to stakeholders. The author does however state that the GHG accounting methodology is not intended to be used for examining or determining the overall environmental performance of the studied system or product, as this requires non-GHG related impact categories to be included in the assessment.

3. Methodology

The methodology described in this chapter builds the foundation needed to answer the thesis' research questions. The general methodology begins with a literature review and a description of the LCA methodology in accordance with ISO 14040 and 14044 in conjunction with a description of the requirements stated in the GHG Protocol Product Life Cycle Accounting and Reporting Standard, hereafter referred to as the GHG Product Standard. An explanation of the data collection processes is also included which describes the approach taken to retrieve sufficient information to accurately answer the research questions.

As the thesis is mainly an LCA with the purpose to answer RQ1 and RQ2, much of the methodology related to this is described in certain chapters pertaining to the LCA conducted in this study, namely Chapter 4 and Chapter 5. RQ3 is a broader research question as it considers aspects not only related to the LCA. In this context, the conducted LCA is seen and treated as a part of a case study in which the results are presented in a way that facilitates answering of RQ3.

3.1 Literature review

A literature review is a systematic method for identifying necessary information, evaluating its strengths and weaknesses, and summarizing what it means to the study and its target reader (Booth et al., 2021). A literature review can assist with learning more about what has previously been investigated regarding the subject and to determine knowledge gaps that would have otherwise lowered the quality of the study. According to Blomkvist & Hallin (2015), one needs to adopt a critical approach when performing a literature review. By examining the methods used and assumptions made while questioning their plausibility, it is possible to refine one's own methods to achieve more accurate results.

For this thesis, theory on LCA and its development is retrieved to broaden the knowledge and find the most suitable approach for the conducted assessment. To further facilitate this, LCA reports that have analyzed similar products are explored. Firstly, LCAs done on radar products are researched and if insufficient information is found, the literature review moves onto LCAs done on comparable electronic products or ICTs in the automotive industry. By reviewing these previous LCAs, aspects and limitations that are important when performing an LCA on a complex product can be identified and, if relevant, utilized in this LCA. Furthermore, inadequate reports will also provide an insight into which important factors must not be overlooked to provide a thorough LCA.

3.2 Life cycle assessment methodology

ISO has developed a standard for the principles and framework of LCAs, known as ISO 14040. This framework consists of four stages which are illustrated in Figure 1. ISO has also developed a standard for the requirements and guidelines of an LCA, known as ISO 14044. Finkbeiner et al. (2006) credits the international standards for their contribution to the acceptance of LCA by stakeholders and recommends that these standards are to be used as core reference for practitioners of LCA. The LCA conducted in this study is in accordance with these ISO standards.

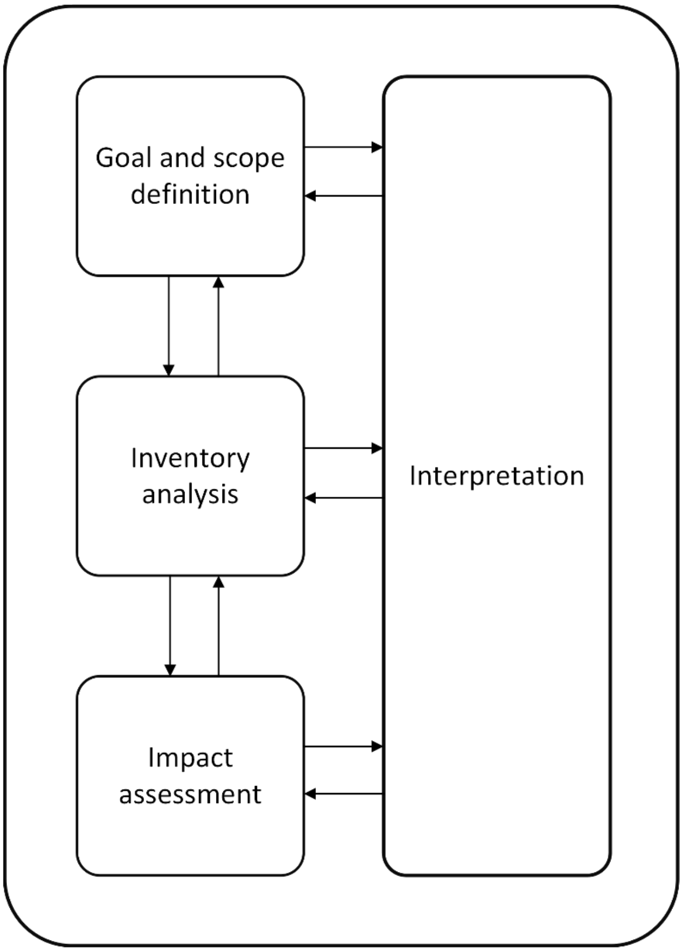


Figure 1: *The four stages of an LCA according to the ISO framework, based on ISO 14040 (ISO, 2006a)*

The fundamentals of the methodology stated in the GHG Product Standard is based on the frameworks and requirements presented in ISO 14040 and 14044 (Bhatia et al., 2011). However, some additional requirements need to be met in order to fully conduct a result in accordance with the GHG Product Standard. Below, these differences are elaborated on in conjunction with a more in-depth description of each stage of an LCA according to ISO 14040 and 14044.

3.2.1 Goal and scope definition

The goal and scope definition shall include the intended application, the reasons for carrying out the study, the intended audience, and state whether the results are to be used in comparative assertions intended for public disclosure (ISO, 2006a). Curran (2017) stresses the importance of this stage since it is meant to determine the exact approach to be followed. However, as additional information is revealed during the study, the goal and scope can be modified. According to ISO (2006b), if unforeseen limitations or constraints arise that require the goal and scope to be revised, the modifications made should be documented and justified. Furthermore, the scope of the LCA shall clearly describe the following items:

- The product system to be studied
- The functions of the product system, or in the case of comparative studies, the systems
- The functional unit
- The system boundary
- Allocation procedures
- Impact categories selected and methodology of impact assessment, and subsequent interpretation to be used
- Data requirements
- Assumptions
- Limitations
- Initial data quality requirements
- Type of critical review, if any
- Type and format of the report required for the study

The goal and scope definition illustrated by ISO is characterized by four steps in the GHG Product Standard. These are: *business goals*, *principles*, *fundamentals of product life cycle accounting* and *defining the scope*. While these steps are closely related to the goal and scope definition in ISO 14044, the major difference that sets the two frameworks apart in this stage is the selection of impact categories. While there is no requirement from ISO to choose a specific methodology of impact assessment, the GHG Product Standard requires the practitioner to examine a 100-year GWP and specifies companies to use the method of Intergovernmental Panel for Climate Change (IPCC) for calculating the inventory results (Bhatia et al., 2011).

3.2.2 Life cycle inventory analysis

The purpose of the life cycle inventory analysis (LCI) is to quantify relevant inputs and outputs of a product system (ISO, 2006a). It is common to acquire more knowledge of the system during the analysis, which may affect the other phases in the LCA (Arvidsson & Ciroth, 2021). LCI is an iterative process that involves two major steps, data collection and data calculation. Data collection includes inputs and outputs related to products, co-products, energy and raw material as well emissions to air, water and soil along with other environmental aspects (ISO, 2006a). According to Arvidsson & Ciroth (2021), collecting data is often said to be the most time-consuming part of an LCA. Data calculation includes validating the collected data and relating it to unit processes and the reference flow of the functional unit. When dealing with systems involving multiple products, allocation procedures should be considered and if conducted, they are to be clearly documented and explained (ISO, 2006b). Furthermore, ISO 14044 states that a sensitivity analysis shall be conducted if several allocation procedures seem applicable.

The GHG Product Standard divides the inventory analysis into three different steps. These are *boundary setting*, *data collection and quality assessment* together with *allocation*. The boundary setting presented in the GHG Product Standard defines the considerations and requirements that companies should consider when allocating the inventory. The identification and categorization of attributable processes must be reported and visualized in the form of a process map, where service, material and energy flows are included (Bhatia et al., 2011; Weidema, 2022).

The data collection and quality assessment in the GHG Product Standard highlights how one should structure and proceed with the acquisition of data. One significant difference, compared to the data collection step according to ISO, is that for all processes under ownership or control of the company, primary data must be collected (Bhatia et al., 2011). When considering electricity, the GHG Product Standard emphasizes that one should adopt supplier specific emission factors, and if that is not applicable, regional based electricity data should be used. Bhateia et al. (2011) also describe that documentation of efforts taken to improve data quality for significant processes is seen as a requirement according to the GHG Product Standard. As for allocation, the GHG Product Standard states that if allocation is unavoidable, the first allocation procedure that should be applied is allocation based on physical relationship. No sensitivity analysis between various allocation methods is required, only a justification of the allocation method selected. Furthermore, companies are also required to report displaced emissions and removals separately from the product's end-of-life inventory when using closed loop approximation (Bhatia et al., 2011).

Most importantly, the GHG Product Standard requires the practitioner to quantify six different GHG emissions related to the product's inventory. These are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs) (Bhatia et al., 2011).

3.2.3 Life cycle impact assessment

The life cycle impact assessment (LCIA) uses the results from the LCI to evaluate the significance of potential environmental impacts (ISO, 2006a). This stage consists of three mandatory elements. First, specific environmental impact categories and category indicators are selected. This is often done outside the study where a set of already existing impact categories can be adopted (Finnveden et al., 2009). Second, the LCI results are associated with the selected impact categories, a step referred to as classification. Lastly, the category indicator results are calculated, creating a so-called LCIA profile where the impact of each emission is expressed as a common unit, a step referred to as characterization. These steps are performed to make the results more comprehensible and improve the readability (Baumann & Tillman, 2004). Depending on the LCIA methodology chosen, different characterization factors are applied to the LCI results, meaning that the LCIA results are dependent on this choice. According to ISO 14044 (ISO, 2006b, p.17), "The selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration".

Another criterion of the LCIA is that the information presented should be graspable by its intended audience (Meijer, 2021). There are two fundamental pathways to illustrate the environmental impacts in terms of characterizations factors, which convert the inventory results into impacts. One is through illustrating midpoint effects, which have a greater relation to the environmental flow and less uncertainty. These midpoint categories can also be translated into endpoint indicators, which are higher aggregation levels that declare areas of protection. These endpoint indicators are a simplification of the LCIA result and can provide information more related to the relevance of the environmental flows, but with a higher degree of uncertainty (Dutch National Institute for Public Health and the Environment [RIVM], 2018; Huijbregts et al., 2016). By adopting endpoint modeling, often referred to as "damage modelling", the entire impact pathway of the studied product or system is considered and characterized into the three protection areas of human health, natural environment, and natural resources (Hauschild & Huijbregts, 2015).

Besides the mandatory elements, there are four optional elements that may be used if they are consistent with the goal and scope: normalization, grouping, weighting, and data quality analysis (ISO, 2006b). Normalization is used to better understand the relative magnitude for each indicator result and is helpful in checking for inconsistencies and facilitates communication regarding the significance of the results. Grouping and weighting are methods that allow the impact categories to be compared and ranked to one another. Weighting may be necessary if trade-off situations occur, but since it is based on preferences and value-choices, the weighting step cannot be done objectively and there is no “correct” set of weighting factors (Finnveden et al., 2009).

As mentioned, a requirement within the calculation of inventory results stated in the GHG Product Standard is that companies must apply a 100-year GWP factor to GHG emissions. In addition to this, the inventory calculation should visualize and highlight the percentage of each life cycle phase’s contribution (Bhatia et al., 2011). The report also states that, if possible, biogenic and non-biogenic emissions and removals should be reported separately. This also applies to the impact of land-use change.

The results from cradle-to-gate and gate-to-gate inventories should also be presented separately, if no clear issue of confidentiality limits this information to be public. The GHG Product Standard also states that, if possible, carbon contained in a product or component that is not released during end-of-life treatment shall be reported. Lastly, weighting factors should not be included for delayed emissions when calculating the climate footprint. The same applies for offsets, which also should not be included in this calculation (Bhatia et al., 2011).

3.2.4 Interpretation

In the interpretation step, the results from the LCI and LCIA are considered and evaluated together (ISO, 2006a). This includes identifying significant issues based on the results from the two previous stages and making an evaluation that considers sensitivity, completeness, and consistency checks (ISO, 2006b). The sensitivity check aims to analyze uncertainties to determine the reliability of the final results. The completeness check is done to ensure that all relevant data and information necessary for the interpretation is available and complete. The consistency check looks back at the assumptions, methods and data used to determine whether they are consistent with the goal and scope. The final interpretations made should evaluate the methodology used through the LCA, help reach conclusions and present recommendations, all in consistency with the defined goal and scope.

The two methodologies of ISO 14044 and GHG Product Standard do share similar requirements when it comes to how uncertainty should be managed and accounted for in the context of interpretation. However, the GHG Product Standards puts great emphasis on how performance tracking should be executed based on the results from the interpretation. Due to the study’s limitations, these steps are not investigated or assessed in conjunction with the ISO standards.

3.3 Data collection

A thorough LCA requires an extensive amount of data. Chapter 4 and Chapter 5 includes in more detail what specific data is needed to conduct the LCA and how it is collected. This section describes the more general approach to the data collection and which methods are applied to obtain data. The study aims to achieve a high degree of transparency but is also limited due to confidentiality towards Veoneer.

3.3.1 Primary data

Before conducting the LCA, an initial screening of the internal knowledge within the company was performed. To get more familiar with the product and the company's operations, unstructured interviews were conducted. Rowley (2012) states that unstructured interviews are performed with a limited number of questions or topics, with much of the emphasis being put towards letting the interviewee freely elaborate on the topic. This allows an interview to be conducted with little pre-knowledge of the subject. Furthermore, Rowley (2012) explains that this kind of interview allows the interviewer to freely adapt its follow-up questions which could enhance one's understanding of the matter. As an LCA covers a wide variety of aspects, many of these types of interviews were conducted, providing an initial overview of the Radar's life cycle and where detailed data can be obtained.

For acquisition of more in-depth knowledge from personnel or experts, semi constructed interviews are carried out. Rowley (2012) elaborates that semi-structured interviews can vary in number of questions and degree of adaptation regarding follow up questions. Thus, the interviews are formatted to consist of approximately eight to ten questions, structuring the interview around a limited number of aspects but still providing the opportunity to follow up specific questions if needed. For this study, the conducted interviews are carried out through physical meetings or digital meetings, as many of the interviewees are located at different continents.

Besides interviews, the internal database systems Product Lifecycle Management (PLM) and the International Material Data System (IMDS) are used to obtain primary data. PLM provides an overview of certain processes involved in the production of products and what specific components that the products consist of. IMDS is a collaboration between OEMs in the automobile industry and provides an in-depth material composition of a product and its components.

Additionally, when other methods were found to be inadequate, personal observations were performed as a means for collecting qualitative primary data. Measurements were thereby performed to gain additional data or to compare with primary data obtained from other methods in order to ensure the data is accurate. This is explained in greater detail in the sections where this is executed.

3.3.2 Secondary data

Due to the fact that the LCA requires an extensive amount of data, it is heavily reliant on secondary data sources. Blomkvist & Hallin (2015) states that a source's reliability and validity is mainly dependent on its ability to answer the question of interest, rather than being of primary or secondary origin. However, much of the LCI data obtained from secondary sources is generally considered confidential and thus concealed to the reader (Kuczenski et al., 2016). Stodden (2014) further describes this issue, confidentiality versus transparency, stating that disclosing reliable scientific knowledge is often hindered by regulatory structure. Consequently, the lack of transparency in regard to LCI data limits the opportunity to generate reproducible research.

A portion of the secondary data used comes from academic reports and official documents, which are used to avoid assumptions to its greatest length and sometimes used as a base for calculations when no primary data has been obtained. However, to accurately model a product's life cycle, the amount of information needed to calculate the inventory is immense. Thus, literature alone is not a suitable source to derive the necessary data. Instead, a larger aggregated LCI database is opted for. For this purpose, the LCA conducted in this study uses the ecoinvent 3.9.1 Database. The ecoinvent Database contains thousands of inventory datasets, each with an attributed geographic location as well as characterization factors for different LCIA methods (ecoinvent, 2022). Its aim is to provide a better understanding of environmental impacts related to one's products and is used in environmental assessments worldwide. Comprehensive documentation for all datasets are provided, which describe their aspects in detail, such as the time of measuring and what activities are included. In this study, the ecoinvent Database is used in conjunction with GaBi, an LCA Software, to model the Radar's life cycle and trace its potential environmental impact. Hereafter, the ecoinvent Database is referred to as ecoinvent.

3.4 Case study

To answer RQ3, the LCA is viewed as a part of a case study, where its execution and results are used as a base for discussion. By the definition highlighted in Flyvbjerg's publication, a case study is an "intensive analysis of an individual unit" which is functioning- and boundary specific (Flyvbjerg, 2011). The author proceeds to highlight common misconceptions of case studies, which all systematically undermine its application by questioning its credibility. For the sake of example, the knowledge generated from case studies is often credited less valuable than theoretical ones and that individual cases cannot provide generalized information. The author emphasizes that while it is true that quantitative studies could provide broader information, case studies should not be discredited nor overlooked regarding this matter. Furthermore, the publication highlights that some of the strengths of conducting case studies are its depth, the creation of understanding between cause and outcomes together with fostering new hypotheses. This consequently enables the findings related to RQ3 to be introduced and interpreted.

4. Goal and scope definition

This chapter marks the start of the LCA conducted in this thesis. The chapter presents the goal of the LCA and the defined scope. It is structured to appeal to all the requirements stated in ISO 14044.

4.1 Goal

The goal of the LCA is to identify and investigate the environmental performance of an active safety radar system and pinpoint which processes and procedures throughout its life cycle that contribute most to potential environmental impacts. The producer of the Radar and commissioner of the LCA, Veoneer, are together with certain customers interested in the result of this assessment and are thereby the intended audience. Veoneer must comply with stakeholder demands and intends to use the LCA for marketing purposes and to identify hotspots to improve the environmental performance of the product. As the study is envisioned to assist both Veoneer and its customers with external communication and marketing, the LCA is conducted in accordance with ISO 14040 and ISO 14044. An additional goal of the study is to simultaneously assess the Radar in alignment with the GHG Protocol Product Life Cycle Accounting and Reporting Standard. This is done in order to comply with standards adopted by the industry and its stakeholders. As the GHG Product Standard states that life cycle accounting for products shall follow the attributional approach, this LCA is conducted using the attributional methodology. Furthermore, the LCA is not intended to be used in comparative assertions and will thus not be tailored to make this applicable.

4.2 The product system

To understand how the scope is constructed to achieve the goal of the LCA, the product system must be defined. In this section, the product in question, the Radar, is described in more detail along with its life cycle phases.

4.2.1 The Radar

The product being assessed is a radar incorporated in vehicles with the purpose to detect surrounding objects, react to dangerous situations and prevent accidents. It is a high-resolution radar, enabling features such as active blind spot, adaptive cruise control and autonomous emergency braking. It is classified as an ICT device that consists of a wide range of components. It consists of six bulk components and two printed circuit boards (PCB), both of which contain numerous PCB components. Many of the PCB components are required in multiple quantities and come in slight variations. For example, the Radar consists of over ten different types of capacitors, where the quantity of each type differs. This results in the Radar consisting of a large number of components, all of which being accounted for in this assessment. Figure 2 presents a visualization of the Radar’s composition where the different types of PCB components have been grouped to facilitate reading.

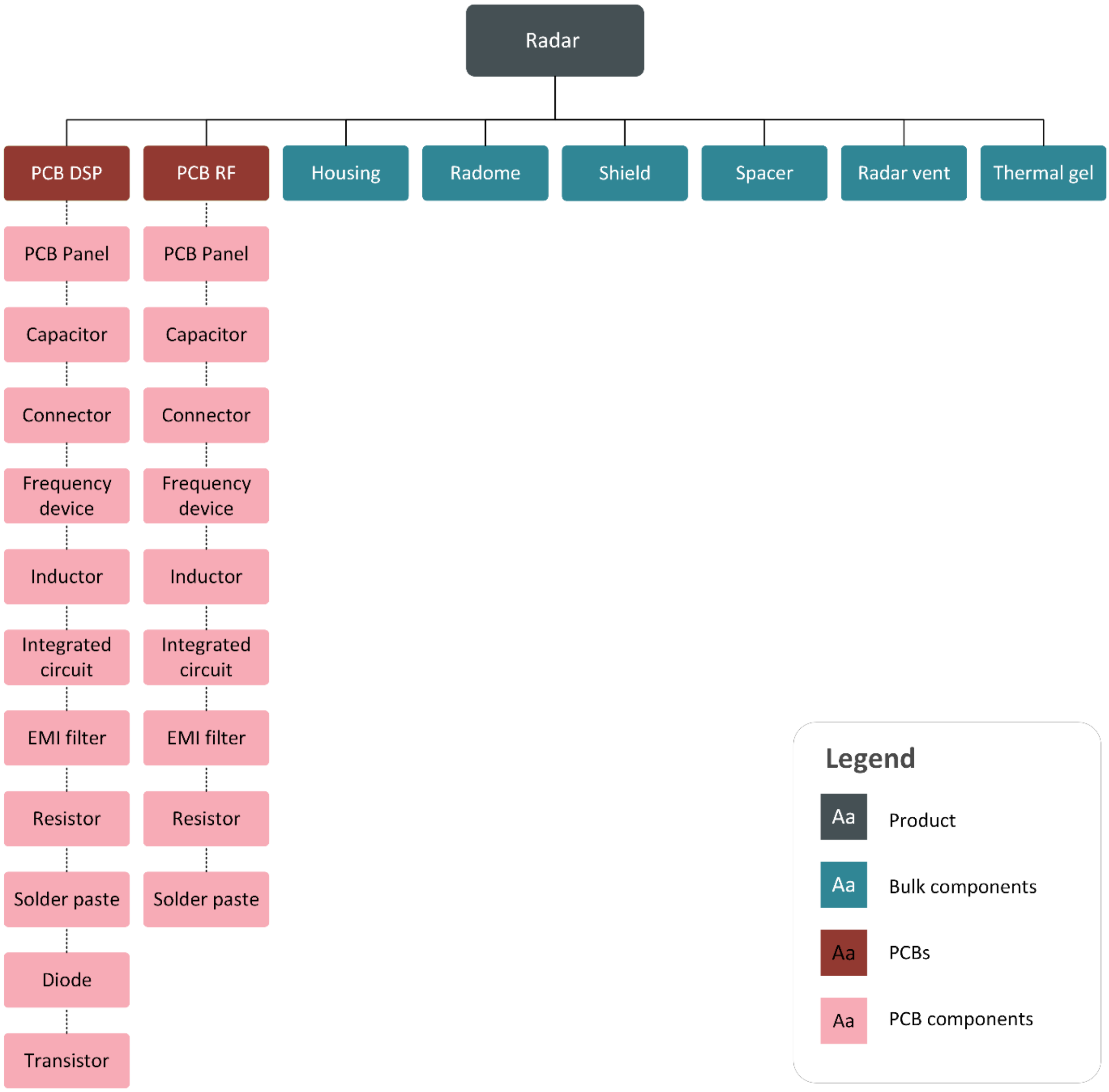


Figure 2: *Composition of the Radar*

4.2.2 System definition

The conducted assessment is a cradle-to-grave LCA, with the product system being defined by the phases extraction and material production, manufacturing, assembly, use, end-of-life along with transportation. These phases are inspired by the general life cycle stages stated in the GHG Product Standard but altered to better assess upstream and downstream processes from Veoneer's standpoint. By dividing the product system into different phases, the LCIA results can be reported for each phase, facilitating a contribution analysis. The different phases and their correlation between one another, in terms of inflows and outflows, are visualized below in Figure 3.

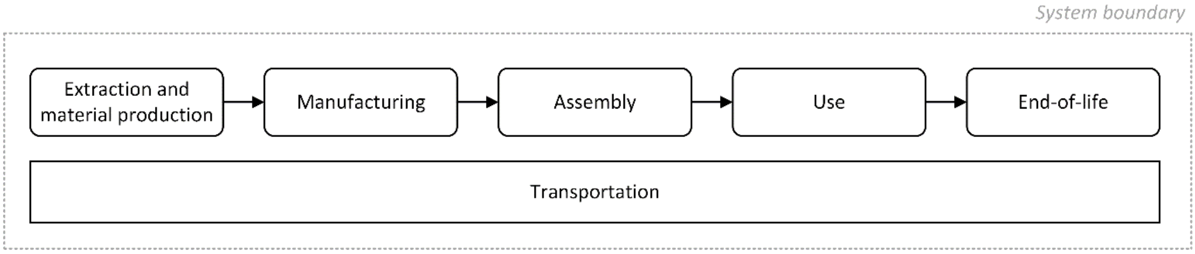


Figure 3: *Phases of the product system*

Extraction and material production: Extraction and material production is the first step of the Radar's life cycle. This phase is defined as the activities of extracting and refining all the specific raw materials and substances that the Radar consists of.

Manufacturing: The following phase in the life cycle is manufacturing, which is defined as the various activities performed by suppliers to Veoneer. These activities transform the refined raw materials into the components that the Radar consists of, as well as the packaging used for the Radar's different components.

Assembly: In the assembly phase, which is defined as the processes that are under ownership of Veoneer, the PCB components are put together in a designated assembly line. Once finished, they are moved to a second assembly line where they are assembled with the bulk components to form the Radar.

Use: The Radar's use phase is defined as the utilization of the product, where it assists a vehicle with active safety measures.

End-of-life: The last phase of the Radar's life cycle is the end-of-life which is defined as the process of treating the Radar once it is no longer being used.

Transportation: Transportation is a recurring activity where different vehicles transport the substances, materials, components, and the final product between the different phases. Transportation occurs between each phase but is presented as a separate phase.

4.3 Function and functional unit

In order to make the functional unit consistent with the goal and scope and easy to measure, one unit of Radar is defined as the functional unit. Since the Radar is an intermediate product that will end up in a vehicle and only operate as long as the vehicle is in motion, the distance traveled during the lifespan of a car is defined as the reference flow. For this study, a distance of 200,000 km is used which, according to Cox et al. (2020), is a likely vehicle lifespan corresponding to 17 years.

4.4 System boundary

Figure 4 presents the system boundary of the LCA, including all inputs and outputs for each and every process throughout the life cycle of the Radar that is assessed. The flow diagram of the system boundary is constructed to more clearly define where processes begin and end, and its receipt of materials and components in addition to what elementary flow that is related to each process. Below, what the system boundary entails for each phase is described in more detail.

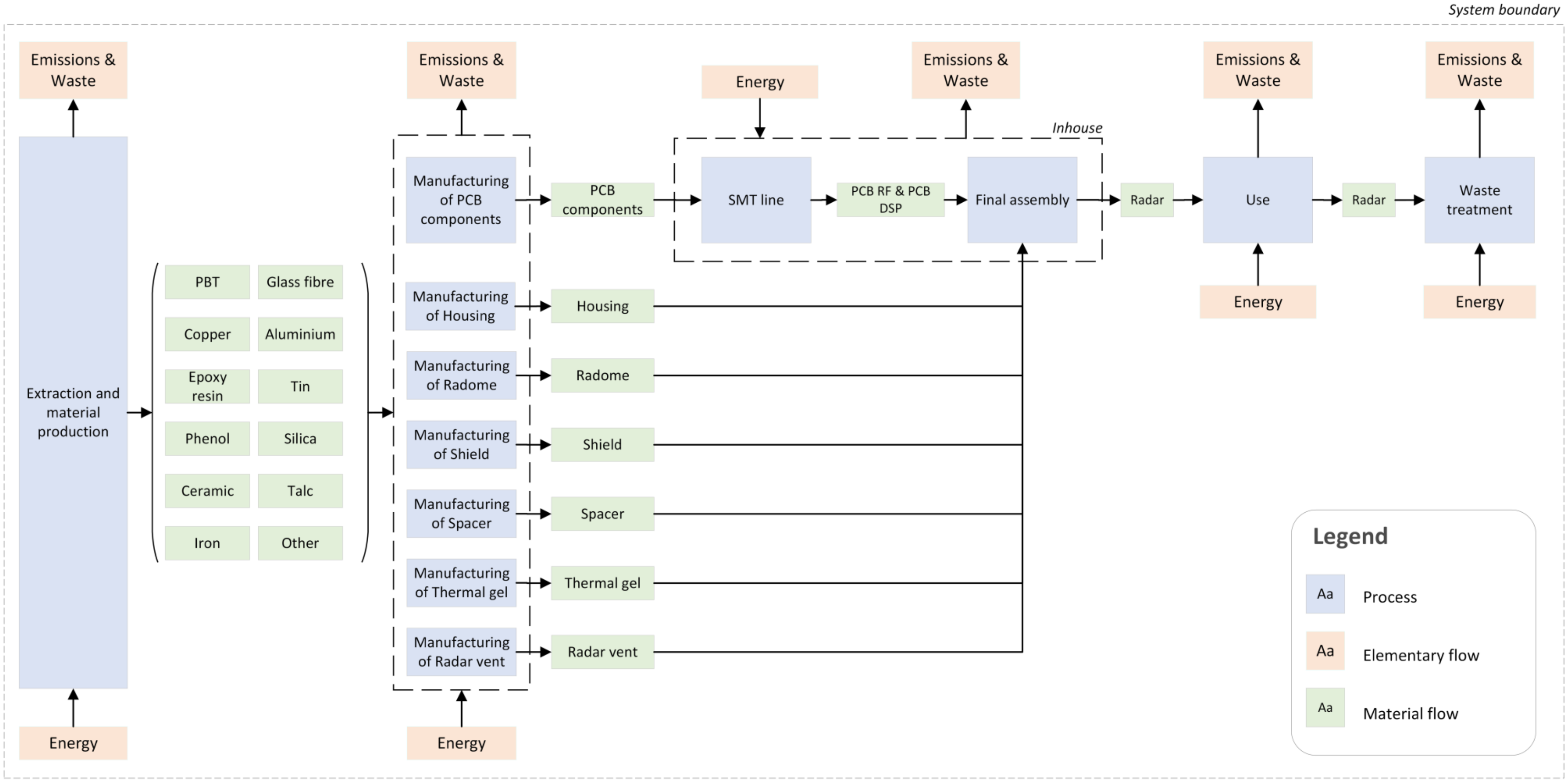


Figure 4*:* System boundary

4.4.1 Extraction and material production

The various inputs and outputs related to the extraction and material production phase such as material and energy input and outputs of emissions, losses, and waste are part of the system boundary and accounted for in an aggregated fashion. The geographical representation for this life cycle phase is global since the raw materials' origin differs from one another, and the limited timeframe of the study results in that these cannot be more accurately represented. The extraction of the materials used to manufacture the packaging is outside the system boundary.

4.4.2 Manufacturing

The various manufacturing activities related to the Radar's components are all included in the system boundary. Their inputs of material and energy along with their outputs in the form of emissions, losses and waste are accounted for. Additionally, the manufacturing of the dissipative packaging used for the components is included in the system boundary and considered as a part of this life cycle phase. All packaging are subject to allocation since the components related to the functional unit share packaging with other components not being assessed. The geographical representation of this phase is determined as global with adjusted uncertainty, since this phase includes various activities that are performed by multiple different actors.

4.4.3 Assembly

As can be seen from Figure 4, the assembly phase occurs solely in-house in Veoneer's facility in Vårgårda, Sweden, and is divided into two different assembly lines. To better understand what is included in the system boundary for this phase and the data requirements related to it, a more in-depth look of the two assembly lines is provided.

The first assembly line is called the surface mount technology line (SMT) and assembles the PCB components into finalized circuit boards. Figure 5 presents a more in-depth look at the SMT line, depicting the various stations that are assessed and all the PCB components that are incorporated. It is important to note that the two circuit boards go through the same processes but consist of different sets of components and the time to assemble them differs.

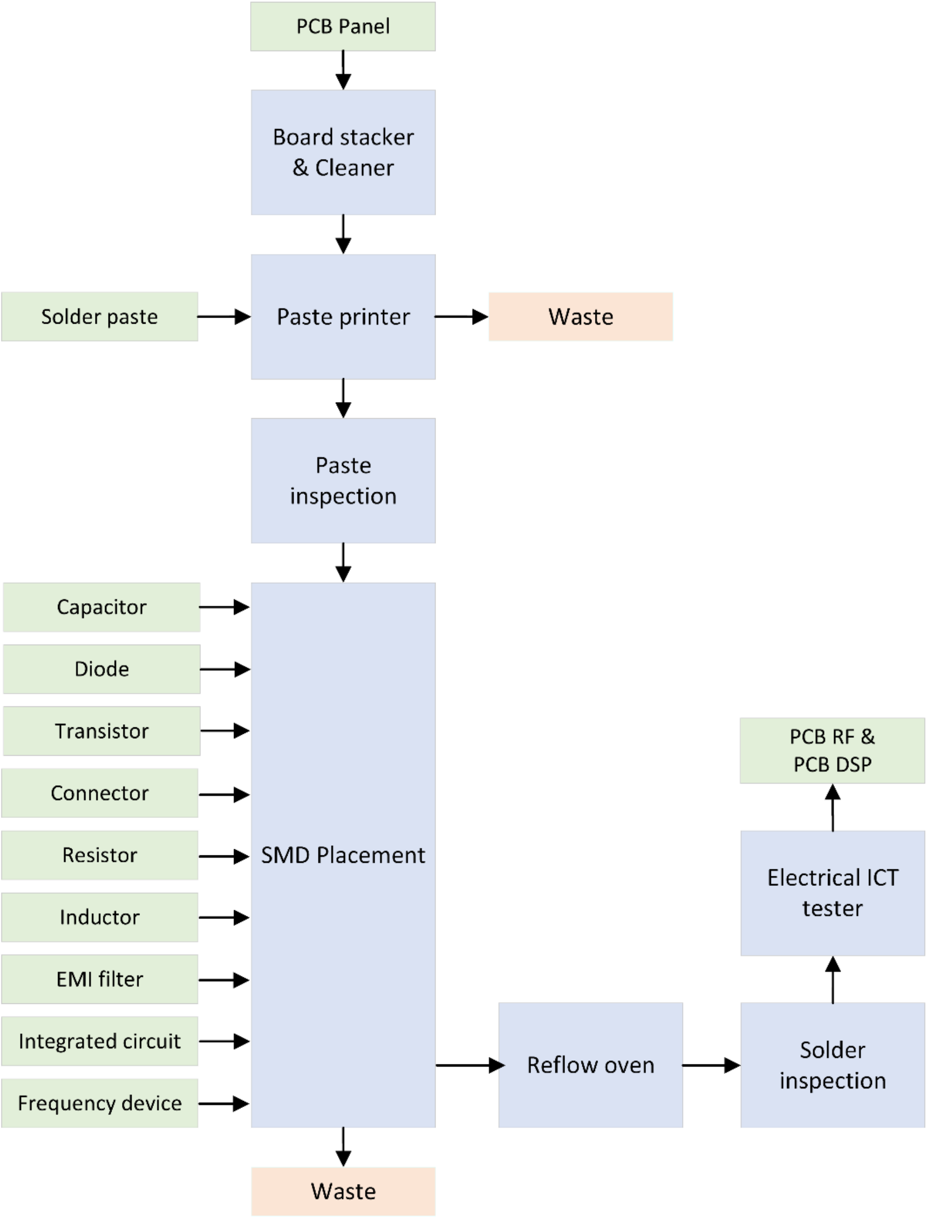


Figure 5: *Flowchart of the SMT Line*

Once the two circuit boards are assembled, they are moved to the second assembly line, Final assembly, where they are incorporated with the bulk components to form the Radar. Figure 6 presents a more in-depth look at the Final assembly.

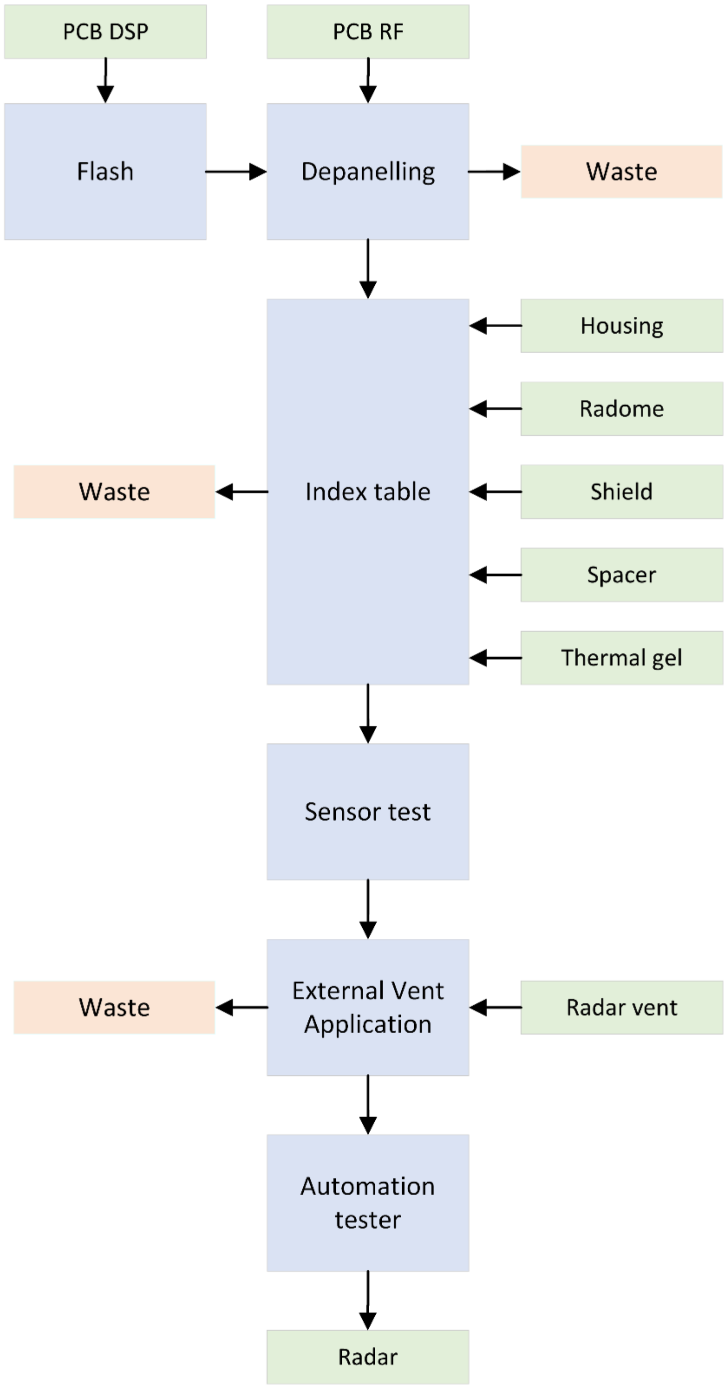


Figure 6: *Flowchart of the Final assembly*

Both assembly lines consist of numerous stations powered by electricity. Another input supporting various processes is compressed air, that is created by the stations themselves with support of its required electricity demand. Thereby, the compressed air as an input is not separately analyzed. The packaging in which the components arrive are part of the waste outputs seen in Figure 5 and Figure 6. Although the treatment of this waste does not occur at Veoneer's facility in Vårgårda, it is considered a part of the assembly phase. Since the GHG Product Standard requires primary data when it comes to processes under ownership or control of Veoneer, the energy consumption related to the assembly lines is gathered directly from their associated stations at the facility in Vårgårda.

The flowcharts of the two assembly lines in Figure 5 and Figure 6 are simplified representations of the assembly lines at Vårgårda. In reality, the assembly lines consist of more stations as well as handling processes such as conveyor belts and gates. While the handling processes are accounted for and treated as a separated station in the inventory analysis, other stations, and activities such as maintenance and ventilation that are deemed less impactful or have insufficient data are not included in the system boundary.

4.4.4 Use

During use, the radar consumes electricity while also contributing to the vehicle’s emissions due to the added weight. The emissions, waste and energy use related to these factors are accounted for in the system boundary. It is important to note that these inputs and outputs vary depending on the vehicle type and the geographical representation. For this assessment, the use phase portrays the Radar incorporated in a medium sized diesel vehicle situated in Germany, as this is a point of interest for certain customers. While the process of producing the required diesel and converting it to electricity in the vehicle is accounted for, the extraction of crude oil is outside the system boundary.

4.4.5 End-of-life

The treatment of the Radar once it reaches its end-of-life occurs in the same nation chosen for the use phase, Germany. The Radar is not collected for reuse in another vehicle, nor are the components returned to previous phases. Thus, the end-of-life simply consists of disposing of the Radar and the emissions, waste and energy use related to this process.

4.4.6 Transportation

In Figure 4, transportations are not presented. However, the resource consumption and emissions caused by the transportation between each phase is included in the assessment. As transportation occurs between multiple nations all over the world, the geographical representation of the transportation phase is global. All transportations are subject to allocation since there are multiple inputs in these processes that are not related to the Radar. Any transportations that are not directly linked to the product, its components or the materials and substances are not part of the system boundary. Examples of such transportations are transports of empty pallets, empty packaging, or empty return transports from Vårgårda.

4.5 Allocation procedures

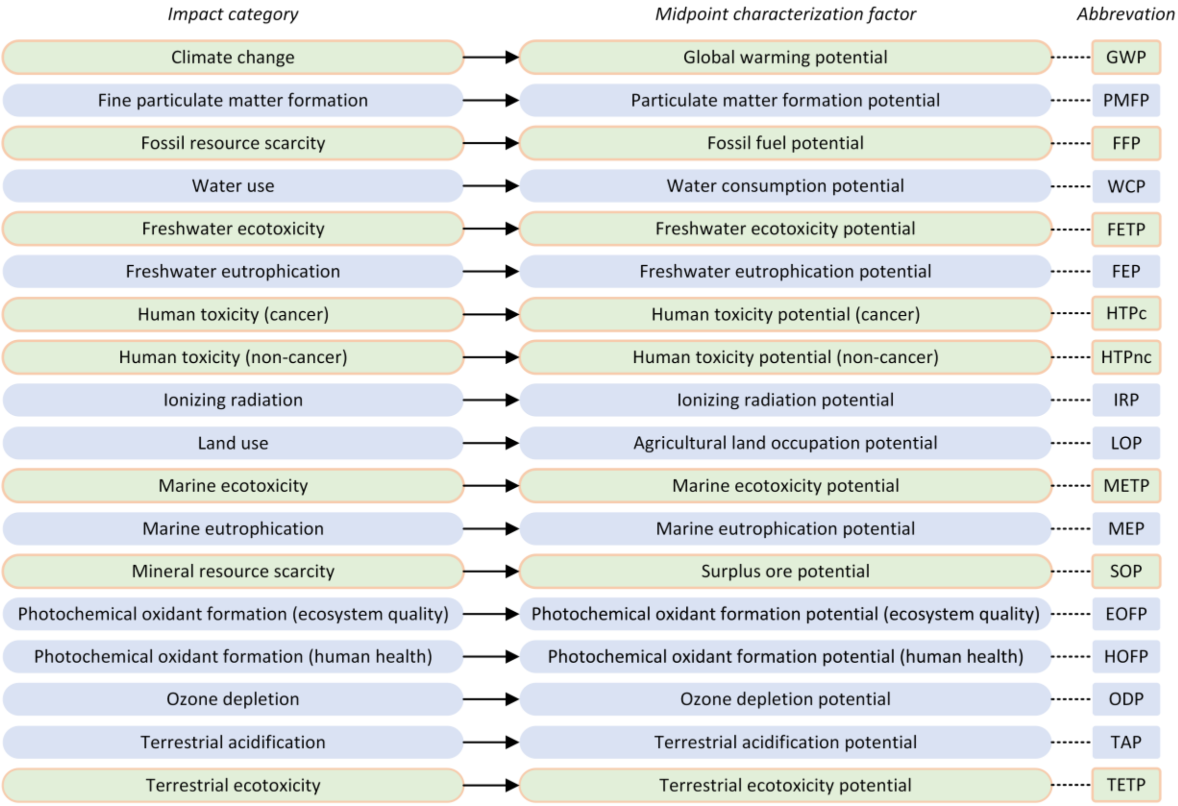
To appeal to the GHG Product Standard and the ISO standards, allocation is avoided through process subdivision, where processes are divided to only include the Radar and its components, or by system expansion. Where this is not applicable, physical allocation based on existing physical relationship between the Radar and co-products is applied to determine the Radar's emission contribution. Moreover, the physical relationship used is mass, resulting in allocation based on mass physical factors. The GHG Product Standard emphasizes that allocation based on physical relationships should be explored as the first means of method if allocation is unavoidable (Bhatia et al., 2011). Thereby, no other allocation procedure is utilized or examined in this assessment, as they are deemed less applicable by the GHG Product Standard. Thus, no sensitivity analysis is conducted to analyze the consequences of selecting different allocation methods. How allocation is performed is explained in greater detail in the inventory analysis whenever allocation occurs.

4.6 Selection of impact categories and LCIA methodology

The selection of impact categories is based on communication with Veoneer along with findings from literature reviews as to which impact categories are most relevant to the automotive industry. A paper by Mikosch et al. (2022) assessed impact categories from an automotive industry perspective by analyzing their relevance from both the sector's point of view and its stakeholders. The results from the paper show that climate change is deemed the most important impact category by both parties. Human toxicity, ecotoxicity and resource use were also determined to be highly significant. The study also investigates the impact categories' relevance to the production phase contra use phase where the previously mentioned impact categories were all deemed high or very high in relation to the production phase. Thus, making them relevant from Veoneer's standpoint. Mikosch et al. (2022) furthermore examines the recommended LCIA methods that are sufficient to utilize for the different impact categories, based on its environmental relevance and applicability. In the summary, the authors recommend ReCiPe 2016 as a suitable LCIA method for the impact categories of climate change, human toxicity and ecotoxicity.

By selecting ReCiPe 2016 as the LCIA methodology and its corresponding 18 impact categories for this study, the LCIA result provides a comprehensive and relevant set of potential environmental impacts related to the Radar. Initially, all impact categories are presented for the Radar's life cycle, but further analyses only cover the impact categories deemed most relevant. Furthermore, this study only assesses midpoint impact categories. Thus, no endpoint areas of protection are identified and neither normalization nor ranking is applied. These steps are considered unnecessary for this type of LCA as the product is highly complex and its many potential impacts should not be reduced to endpoints. Ranking is also highly subjective and because of the LCA's intended use, the authors' values should not be reflected in the results.

Figure 7 presents the 18 ReCiPe 2016 impact categories with their corresponding midpoint characterization factors. The most relevant categories for this study are highlighted and will from now on be referred to as the major categories.



Impact category	Midpoint characterization factor	Abbrevation
Climate change	Global warming potential	GWP
Fine particulate matter formation	Particulate matter formation potential	PMFP
Fossil resource scarcity	Fossil fuel potential	FFP
Water use	Water consumption potential	WCP
Freshwater ecotoxicity	Freshwater ecotoxicity potential	FETP
Freshwater eutrophication	Freshwater eutrophication potential	FEP
Human toxicity (cancer)	Human toxicity potential (cancer)	HTPc
Human toxicity (non-cancer)	Human toxicity potential (non-cancer)	HTPnc
Ionizing radiation	Ionizing radiation potential	IRP
Land use	Agricultural land occupation potential	LOP
Marine ecotoxicity	Marine ecotoxicity potential	METP
Marine eutrophication	Marine eutrophication potential	MEP
Mineral resource scarcity	Surplus ore potential	SOP
Photochemical oxidant formation (ecosystem quality)	Photochemical oxidant formation potential (ecosystem quality)	EOFP
Photochemical oxidant formation (human health)	Photochemical oxidant formation potential (human health)	HOFP
Ozone depletion	Ozone depletion potential	ODP
Terrestrial acidification	Terrestrial acidification potential	TAP
Terrestrial ecotoxicity	Terrestrial ecotoxicity potential	TETP

Figure 7: *Selection of impact categories with corresponding midpoint characterization factors, based on ReCiPe 2016 (Huijbregts et al., 2016). The most relevant impact categories for this study are highlighted in green.*

Depending on one's value choices in regards to environmental decision-making, ReCiPe 2016 provides three different perspectives, each containing its own set of characterization factors. In this study, the hierarchist perspective is adopted since it has a time horizon of 100 years and is considered neither optimistic nor pessimistic. Instead, it acts as a baseline perspective based on scientific consensus (Huijbregts et al., 2016). This provides non-subjective LCIA results that also align with the GHG Product Standard's time horizon requirement.

The result and the interpretation from the LCIA are illustrated through diagrams in Chapter 6, where the different life cycle phases' contribution to the potential environmental impacts are highlighted.

4.7 Data requirements

All of the materials and substances that the Radar is composed of are identified and quantified to accurately assess potential environmental impacts related to extraction and production. Additionally, data on how each of the substances, materials, components, and the Radar is handled in their respective phase is required. All inputs concerning resource use and energy consumption linked to these various processes in each life cycle phase are collected and quantified to assess their potential environmental impacts. The waste management of the Radar and its different components is also needed to assess the processes involved in the end-of-life phase. For the transportation, data regarding the transportation mode, distances traveled, and the weight of the freight is required. Information regarding coproducts, such as the quantity contained in shared packaging and transportations, is needed to successfully allocate according to the allocation procedures.

4.8 Data quality requirements

The quality of the data used for this study is set to align with the five parameters stated in the GHG Product Standard: relevance, completeness, consistency, transparency, and accuracy. To appeal to the GHG Product Standard, only primary data are used for processes and operations that are performed by Veoneer or processes and operations that are under ownership of Veoneer. This data is collected through internal data systems, communication with employees and by performing measurements.

To assess upstream Scope 3 emissions from extraction and material production and manufacturing performed by suppliers, secondary data are acquired through the database ecoinvent 3.9.1 and modelled in GaBi. For downstream Scope 3 emissions, where the use phase and end-of-life is analyzed, primary data are used if it is available and possible to acquire within the timeframe of the study. In cases where data are not available or not possible to acquire within the timeframe, secondary data through literature and ecoinvent are used. The requirement for the geographical representation is set to be as accurate as possible for each process throughout the life cycle. As the secondary data used for this assessment is much dependent on the data portfolio obtained through ecoinvent, the time sensitivity is adjusted according to the available data.

The Interpretation chapter discusses how the data quality requirements and any deviation made from the requirements during the study has affected the result.

4.9 Assumptions and value choices

Throughout the report, assumptions are avoided if possible. However, if no data is available or if the data is not possible to acquire within the timeframe and deemed to have less of an impact on the results, assumptions are made. Whenever assumptions are made, they are clearly stated and explained. In the case where an assumption is necessary and deemed to have a significant impact on the result of the assessment, a sensitivity analysis is conducted to assess the chosen variables.

In cases where value choices are necessary, a more conservative and pessimistic approach is adopted to not underestimate the Radar's potential environmental impacts. If a value choice is deemed to be important for the outcome of the assessment, it is made in consultation with Veoneer to stay consistent with the goal and scope.

A reoccurring value choice is the selection of which datasets in ecoinvent that are used to model the various activities in each of the life cycle phases. The choice of ecoinvent datasets is done by finding and comparing general datasets in ecoinvent and selecting the ones that are deemed to represent the reality most accurately. How these choices are made for each phase are described in more detail in the inventory analysis. However, for the sake of transparency, each dataset obtained from ecoinvent is ranked based on how accurately they are deemed to portray the reality. In Appendix A, every ecoinvent dataset used for modelling is presented and ranked either ‘good’, ‘decent’ or ‘poor’. Note that the ranking itself is subjective and can be viewed as the authors’ suggestions on which processes should be analyzed with more caution.

4.10 Limitations

The goal and scope of the study sets certain limitations which are important to acknowledge to avoid the risk of misinterpretation. The limitations and how they affect the results are discussed in the Interpretation chapter.

The study is limited to the selection of impact categories and LCIA methodology stated above, other impact categories are not quantified and interpreted. Thus, the study’s scope only entails the emissions related to the chosen impact categories. Furthermore, all characterization factors are independent of geographical location and do not take into consideration that emissions’ potential impacts vary depending on where they are emitted. Additionally, the study’s perspective is limited to the Radar’s potential environmental impacts. Other perspectives, such as social or economic, are not part of this assessment.

The system boundary is also limited to the Radar and any process directly linked to its production, use and treatment at end-of-life. The assessment does not include background systems such as resource use and energy consumption linked to establishing these processes like manufacturing of vehicles, machinery and infrastructure used throughout the product’s life cycle.

The availability and quality of the data is limited due to the product’s complexity and the many suppliers involved along with the assessment’s timeframe, which is approximately a five-month period. Since the Radar and other similar products are rather new on the market, there are also limited data in regards to specific life cycle phases such as end-of-life.

4.11 Type of critical review

Due to its intended use for external communication and the requirements placed on this LCA, a critical review is deemed necessary by the commissioner to evaluate its credibility and quality. The type of critical review used is an external third-party critical review conducted by an LCA expert to assess that the report is in accordance with ISO 14044. By opting for an external critical review, any conflict of interest is also avoided, assuring a more credible evaluation.

4.12 Type and format of the report

The format of the report is constructed to follow the requirements of ISO 14044 and complies with the GHG Product Standard. Furthermore, the report is designed in consideration to Veoneer’s and their customers’ needs. It is presented as a full comprehensive document that provides all relevant information to the reader. The methodology and results are transparent and documented in detail with tables and graphs to facilitate external use.

5. Inventory analysis

This chapter explains in detail how the inventory data are gathered and presents the LCI results for each of the Radar's life cycle phases.

5.1 Extraction and material production

The composition of substances included in the Radar is retrieved from IMDS. Since IMDS only provides the composition of each individual component in the Radar, every component is separately analyzed to derive the Radar's total composition. The result is presented in Table 1 which displays all substances and materials included in the Radar. Through ecoinvent, a dataset related to the extraction and material production for each substance is identified. This provides the necessary data to address the potential impacts from this phase.

Table 11 in Appendix A presents which datasets in ecoinvent that are used to model the extraction and material production for each substance. For some substances, ecoinvent does not contain a dataset that is directly linked to the extraction or production of a certain substance. In these cases, a dataset concerning a substance that shares similar characteristics is chosen. In the case where no dataset is deemed to be accurate enough, the substance is neglected, and its dataset is displayed as 'N/A' in the table. These substances have a cumulative weight that is less than 0.004 % of the Radar's weight and are assumed to have a low potential environmental impact based on their characteristics. Some substances such as miscellaneous and further additives are not meant to be declared according to IMDS. Therefore, no dataset is chosen for these substances as they lack data. However, the weight of every substance in Table 1 are still accounted for in their respective transportation.

Table 1: *Substances extracted and produced for the Radar*

Substance	Weight [g]	Substance	Weight [g]	Substance	Weight [g]	Substance	Weight [g]
PBT	29.8806	Silicon	0.0997	Dibismuth-trioxide	0.0023	Chromate	0.0001
Glass fibre	20.6069	Bismuth	0.0900	Phenolic Resin	0.0017	Dicyclohexyl-phthalate	0.0001
Copper	14.0866	Flame Retardant	0.0541	Lead	0.0017	Aluminium hydroxide	0.0001
Aluminium (metal)	12.1150	Graphite	0.0532	Barium-titanium-trioxide	0.0016	Nitrogen	0.0001
Aluminium oxide	4.9837	Silicon dioxide	0.0512	Indium	0.0015	Decamethylcyclopentasiloxane	4.84E-05
Epoxy resin	3.8983	EP	0.0483	Magnesium-oxide	0.0015	Titanium-dioxide	4.08E-05
Tin	2.9551	Zinc (metal)	0.0483	Antimonytrioxide	0.0014	Cadmium	3.00E-05
Phenol	2.8352	Antimony	0.0450	Oxygen	0.0013	Triazine	2.78E-05
Further additives	2.1850	Diiron-trioxide	0.0442	Strontium	0.0011	Sulphur	2.25E-05
Silica	1.7834	VMQ	0.0431	Zirconium	0.0009	Titanium	1.68E-05
Ceramic	0.5289	Zinc oxide	0.0359	Polyurethane	0.0007	Chromium oxide	1.51E-05
Talc	0.4595	Chromium	0.0231	Ruthenium(IV)oxide	0.0007	Magnesium (metal)	7.08E-06
PVMQ	0.4320	Boron	0.0168	Carbon	0.0006	Borosilicate	4.75E-06
Iron	0.3501	Polyethylene terephthalate	0.0162	Molybdenum	0.0006	FMACP	3.31E-06
LCP	0.3460	PTFE	0.0147	Phosphorus	0.0005	Ethanol	3.12E-06
Miscellaneous	0.3038	Metal oxide	0.0143	Copper chromite black spinel	0.0005	Manganese dioxide	1.62E-06
Barium sulphate	0.2939	Silicon chrome	0.0138	Arsenic	0.0005	Bismaleimide resin	1.55E-06
PAK	0.2511	Acrylic resin	0.0122	Formaldehyde	0.0004	Dodecylbenzenesulphonic-acid	1.19E-06
Nickel	0.2425	Nickel-monoxide	0.0090	Cellulose	0.0004	Isopropyl	3.70E-07
Barium	0.1785	Siloxanes and Silicones	0.0069	Inorganic Ingredient	0.0003	Chlorine	1.72E-07
Butadiene resin	0.1614	Calcium-zirconium-trioxide	0.0066	Cobalt	0.0003	Methacrylate	1.55E-07
PPE	0.1614	Gold	0.0057	Calcium	0.0003	Tungesten	5.85E-08
Silicate	0.1614	Polytetrafloroethylene	0.0038	Tricobalt-tetraoxide	0.0003	Potassium	4.39E-08
Manganese	0.1561	Oxirane	0.0031	PAI	0.0002	Gallium	2.87E-08
Carbon black	0.1547	Pigment portion	0.0031	Palladium	0.0002	Vanadium	2.87E-08
Silver	0.1496	Copper oxide	0.0028	PMMA	0.0002	Hydrogen	2.93E-09
Mineral powder	0.1383	Beeswax	0.0026	Organic Ingredient	0.0001	Selenium	1.07E-11
Iron nickel zinc oxide	0.1174	Benzenamine	0.0023	Silicone resin	0.0001	Tellurium	7.13E-12

5.2 Manufacturing

The inventory data related to the manufacturing phase is primarily obtained from ecoinvent. The database is used to identify datasets that accurately resemble the activities performed by the various suppliers. A dataset related to the manufacturing of each bulk component and each PCB component is identified in ecoinvent and the weight of the specific component is allocated towards the dataset. The choice of datasets is done by finding and comparing general datasets in the ecoinvent database and selecting the ones that are deemed the most accurate for each component. Table 12 in Appendix A presents which ecoinvent datasets are selected for which components. For some components, where no general dataset is identified, PLM is thoroughly explored to find what type of manufacturing methods the component goes through and find a suitable corresponding dataset in ecoinvent.

In accordance with the goal and scope, the manufacturing of the packaging for the components is also accounted for in this phase. The type of packaging used, its weight, and the number of units contained in the packaging is retrieved through PLM and by performing measurements at the facility in Vårgårda. Any packaging type that is reusable, such as returnable box or pallet, is not taken into consideration when it comes to manufacturing since their potential environmental impacts after allocation are considered insignificant. Therefore, only the manufacturing of dissipative packaging is accounted for.

Due to their small sizes, many components are delivered on thin tape wrapped around a plastic reel. These reels vary in size and carry between 1000 to 50,000 units. One type of component may also be delivered on different types of reels. To address this, an average reel is used for all PCB components that arrive on reels. Through communication with employees and by weighing different reels, the characteristics of this average reel are estimated. Since the reels are delivered in different types of cardboard boxes, an average box is also estimated similarly.

Table 18 in Appendix B presents the packaging type used for every component, along with their characteristics. This data is used together with the required quantity of a component to calculate the weight per functional unit for each packaging (see Equation 1).

$$\frac{Packaging\ weight\ [g]}{Units\ per\ packaging} \times Required\ component\ quantity = Weight\ per\ functional\ unit\ [g]$$

Equation 1: *Calculation of weight per functional unit for packaging*

Table 2 presents the accumulated weight per functional unit for each packaging type. When modelling, each packaging type is treated as a component and the method of selecting a relevant manufacturing dataset from ecoinvent is the same as described above. The dataset selection is presented in Table 13 in Appendix A. This inventory data only pertains to the packaging used beyond the manufacturing phase. Thus, the packaging used to contain the substances and the raw materials transported from the extraction phase is not included in this assessment as their potential impact in relation to the functional unit is considered insignificant.

Table 2: *The weight per FU for each type of packaging*

Packaging type	Weight per FU [g]
Cardboard box	18.94
Tray	9.94
Reel	7.86
PCB frame	4.22
Antistatic foil	1.11
Pail	0.39
Tube	0.18

5.3 Assembly

The electricity consumption from the SMT line is estimated using internal data provided through communication with employees and PLM. From this, the operating hours of the SMT line along with the number of specific circuit boards produced for the Radar during this period are acquired. This data provides the information of how many hours that each station on the assembly line was operating to produce a given number of circuit boards. Consequently, the effect of each station in the SMT line is multiplied by the operating hours which results in the energy consumption. By dividing the energy consumption with the number of circuit boards produced over the operating period, the allocated energy consumption per circuit board is determined. As mentioned, the two circuit boards go through the same stations in the SMT line, but the time to assemble them differs. Thus, the method of calculating the energy consumption was done separately for each circuit board. The sum of their respective energy consumption represents the energy consumption per functional unit in connection to this part of the assembly phase. The energy consumption of the SMT line is presented in Table 3.

Table 3: *Energy consumption for processes in the SMT line*

Process	Energy consumption per FU [kWh]
Board stacker & cleaner	0.0077
Paste Printer	0.0108
Paste Inspection	0.0015
SMD Placement	0.0379
Reflow Oven	0.0613
Solder Inspection	0.0015
Electrical ICT Tester	0.0108
Handling processes	0.0383

The electricity consumption for the final assembly line is done using the same method described above but instead allocating the energy consumption to one Radar. The energy consumption of the final assembly line is presented in Table 4.

Table 4: *Energy consumption for processes in the final assembly line*

Process	Energy consumption per FU [kWh]
Flash	0.0038
Depanelling	0.0057
Index Table	0.0952
Sensor Test	0.0052
External Vent Application	0.0076
Automation tester	0.0174
Handling processes	0.0056

Due to limited data, the effect of certain stations is based on their max effect and does not represent their average electricity consumption. For some stations, such as the oven, where max effect and average effect differ significantly, Veoneer have measured the energy consumption and these results are incorporated in the assessment. The stations whose max effect is used are deemed to have less of an impact, as these stations generally have a much lower electricity requirement to operate and therefore does not have a large effect on the results.

As all dissipative packaging is disposed of in the assembly phase, the waste treatment of the packaging is included in this phase. Through communication with employees, the method used to dispose of each packaging type is identified. From this, four different waste categories are established where each packaging type is placed in one of these categories based on how they are disposed of. A waste treatment dataset is then selected from ecoinvent and assigned the cumulative weight from the corresponding waste category. Table 5 presents the established waste categories and their weight per functional unit. Table 14 in Appendix A presents which waste treatment dataset from ecoinvent that are used for each waste category.

Table 5: *Waste categories for packages disposed in the assembly phase*

Packaging type	Waste category	Weight per FU [g]
Cardboard box	Paperboard waste	18.94
Tray, Reel, Antistatic foil	Plastic waste	18.91
PCB frame	Electronic waste	4.22
Pail, Tube	Toxic waste	0.57

5.4 Use

The inventory data connected to the use phase is partly obtained through internal communication with employees within the research and development (R&D) department. In order to examine the Radar's environmental performance during the use phase, its energy consumption during the utilization within a vehicle is examined. The Radar's effect is determined through calculating an average effect based on test results connected to the Radar's energy demand in varying conditions, provided by the R&D department.

In addition to the effect, the Radar's total operating time is needed to derive the total energy consumption during the entire use phase. As mentioned in the Goal and scope, the distance traveled by a vehicle during its lifespan is determined as 200,000km. Since the Radar is operating whenever the vehicle is, an average vehicle speed is needed to determine the total amount of total operating time. To estimate this factor, studies compiling the average speed of travel for personal cars in urban areas were examined, all of which highlight the complexity of this estimation. However, besides the complexity, the studies present a similar result to one another with an average speed of approximately 30km/h (Liao et al., 2020; Bebkiewicz et al., 2017). This approximation is used for the calculation of the total operating time by dividing the total distance traveled by the vehicle (km) with the vehicle's average speed (km/h). This results in an operating time of approximately 6,667 hours.

From these findings, the Radar's energy consumption (kWh) during its use phase is determined by multiplying the effect (kW) of the product with the estimated operating time (h). The result is presented in Table 6 below. It is important to note that there are energy losses during electricity conversion depending on the vehicle type. As stated in the Goal and scope, a medium sized diesel car in Germany is used for the base scenario of this assessment. In this type of car, energy loss occurs when chemical energy is converted into electrical energy, powering the Radar. The chosen dataset in ecoinvent accounts for the conversion done by the engine and its losses, which occurs when converting chemical energy to mechanical energy. However, it does not consider the losses generated by the alternator that occur when converting mechanical energy into electrical energy. Thus, the required fossil diesel used to supply the Radar with sufficient electricity is calculated by examining the energy content of fossil diesel and the efficiency of an alternator. The typical efficiency of an alternator in automobiles is 70% (Doffe & Kadiri 2010; Örn, 2014), while the energy content of fossil diesel is 45.3 MJ/kg (Rodrigue, 2020). With these factors, Equation 2 describes how the total amount of required fossil diesel is calculated. By using this result to model the conversion process in the vehicle through the chosen dataset in ecoinvent (See Table 15 in Appendix A), the emissions caused by the Radar's energy consumption is allocated.

$$\frac{Radar's\ energy\ consumption\ [MJ]}{Alternator\ efficiency\ *Energy\ content\ fossil\ diesel\ [MJ/kg]} = Required\ fossil\ diesel\ [kg]$$

Equation 2: *Calculation of required fossil diesel*

Apart from the energy consumption, the added weight from the Radar to the vehicle is also a contributing factor. Thus, part of the vehicle's emissions is allocated to the Radar based on their weight relationship. A paper by Liu et al. (2021) includes a comparison of various sized diesel cars and estimates that the average weight of a medium sized diesel car is 1326kg. This estimation is used for the following calculations. By dividing the weight of the Radar with the weight of the vehicle containing the Radar, the Radar's share of the total weight is derived. This share is then used to allocate part of the emissions caused by the vehicle during its lifetime, to the Radar. The result is presented in Table 6.

Table 6: Inventory data for the use phase, pre intensity reduction modification

Process	Energy consumption [MJ]	Required diesel [kg]	Share of vehicle emission [%]
Radar operation	115.392	3.639	0.007

When the results from Table 6 are incorporated into the chosen ecoinvent dataset, an additional factor that is taken into consideration is the replacement of fossil diesel with biodiesel, which emits significantly less GHG emissions. By 2020, Germany reported 6.1% GHG intensity reduction through their use of biodiesel as fuel (European Commission, 2022). As ecoinvent does not contain any datasets linked to the production and burning of biodiesel, this factor is used to remove 6.1% of emissions from the vehicle. These intensity reductions do solely state the diesel mixture's impact on GWP reduction, hence not how the substitution of fossil diesel with biodiesel affects other impact categories assessed in this study. However, for the case of simplicity and due to the time constraints of this study, this intensity reduction is modeled to have a proportional effect across all impact categories.

The methods used to gather and compile the inventory data in this phase contains various uncertainties. The value choices made such as which vehicle the Radar operates in and at what geographical location along with the estimation of an average speed has a significant effect on the results. Therefore, a sensitivity analysis, presented in Section 6.1.2, is deemed necessary to explore how the use phase is affected by altering the uncertain parameters.

5.5 End-of-life

Once the vehicle reaches end-of-life, so does the Radar as it is not collected for reuse in another vehicle. There is no specific documentation related to how the Radar is treated nor any demands from customers or regulators regarding this specific product. Hence, a general procedure for similar products is used to represent the disposal of the Radar in this phase. However, as smaller electronic components such as radars or cameras are fairly new additions to vehicles, there is limited information on how they are treated once the vehicle reaches end-of-life. For automotive products in general, the EU recycled and reused 90.5% of parts and materials in 2020 (Eurostat, 2023). However, no suggestions indicate that the products such as the Radar are included in this recycling scheme. Furthermore, Arushanyan (2014) states that the environmental impacts of ICT products are often underestimated when it comes to waste management. Hence, the Radar is considered as a mixture of plastic and industrial electronics and treated through incineration followed by landfilling. This choice aligns with the approach stated in the Goal and scope to not underestimate the potential environmental impacts of the product. A dataset representing the waste treatment is chosen in ecoinvent (see Table 16 in Appendix A) and the Radar's total weight is allocated towards this activity.

5.6 Transportation

The vast majority of transportation occurs between the manufacturing phase and the assembly phase. Thus, primary data is gathered to assess these transportations. Before reaching Vårgårda, each component travels between multiple locations which are difficult to pinpoint and varies depending on demand and other circumstances. To facilitate, this study investigates transports from manufacturing to distribution and distribution to the assembly at Vårgårda.

Many of the components are required in large quantities, some of which being multiple sourced, meaning that several different suppliers are used to acquire the same component. In order to accurately cover all these transportations, a compressed list of supplier- and distributor locations along with the transportation modes is constructed in conjunction with material planners at Vårgårda. By initially investigating the suppliers that deliver the greatest number of different components, and gradually adding suppliers to the list until all components are included, the necessary data covering transportation is obtained. The transportation of the finalized Radar to the customer is also accounted for. As the Radar is distributed to multiple locations globally, a specific location to which large shipments are sent is chosen.

As for the transportation between extraction and manufacturing, little information is available. Thus, an assumption is made that each raw material is transported 100km by truck. A similar assumption has been made to include the transportation between manufacturing locations and airports for components that are delivered by flight, where 50km of truck transportation is applied. Additionally, for flight transportation directly to Sweden the same approximation of an additional 50km truck transportation is added in order to account for the distance between the airport and Vårgårda. For every distance covered by flight, the airport closest to the manufacturer is chosen as the departing location. Table 19 in Appendix B presents all distances with the corresponding transportation mode used for the different components.

To account for the additional weight added by the packaging, the weight of each type of packaging and pallet used for the corresponding component is divided by the number of components they carry. This provides the packaging and pallet weight per functional unit which combined with the component weight and distance travelled, results in the freight transport (tkm) per functional unit. The packaging and pallet weight is only included for the transportation of components and the final product, not for the raw materials since their allocated packaging and pallet weight is deemed insignificant. Similarly, the sole transportation of the packaging and pallet material to either manufacturer or Veoneer is ignored as it is deemed to have a neglectable impact on the final result. Since the allocation of tkm is used in this phase, an assumption is made that the transport vehicles are fully loaded. The sum of the freight transportation for each transportation mode in the life cycle is presented in Table 7. This data is used as input for the chosen ecoinvent datasets representing the transportation modes (see Table 17 in Appendix A). Note that the only component transported with a reefer is the solder paste.

Table 7: Freight weight for each transportation mode

Transportation mode	Freight Transport per FU [tkm]
Train	0.847
Flight	0.658
Truck	0.192
Ship	0.003

5.7 LCI results

All sections in the Inventory Analysis chapter are used to derive the Radar's total inventory. Table 20 in Appendix B presents the LCI results which are calculated through GaBi. The Radar's total inventory is extremely extensive and much of its content is insignificant to the studied impacts. Thus, only a proportion of the total inventory, which represents the largest contributors to the eight major impact categories, is presented in the LCI results. However, the entire inventory is considered when calculating the LCIA results.

6. Impact assessment

The impact assessment presents the potential environmental impacts in relation to the Radar and thus addresses RQ1. In accordance with the goal and scope, the LCIA results are calculated using the LCIA method ReCiPe 2016 and the category indicator result for each of the 18 impact categories are presented. The life cycle phases which contribute most to the different impact categories are then further analyzed in the form of a contribution analysis. A sensitivity analysis is also presented, followed by the results required by the GHG Product Standard, which are presented separately.

6.1 LCIA results

To derive the LCIA results, the Radar's total inventory is first associated with the 18 impact categories selected. Using characterization factors provided by ReCiPe 2016, the category indicator results are then calculated. These two steps are automatically performed by GaBi through Equation 3. It is important to note that each inventory parameter has a different impact on different impact categories, thus being associated with numerous characterization factors. Consequently, thousands of characterization factors are used to calculate the LCIA results, which is why they are not included in this report as they are provided by GaBi.

$$Category\ indicator\ result_i = \sum(inventory_x \times characterization\ factor_{x,i,TH})$$

Equation 3: *Calculation of the category indicator result, where i is the specific impact category, x is related to a specific substance from the inventory and TH is the time horizon considered for the characterization factor.*

To get an overview of the entire life cycle's potential environmental impact, Table 8 below presents the absolute values of the category indicator results for each impact category in ReCiPe 2016.

Table 8: *Quantified result for each impact category*

CF_m	Impact category	Quantity	Equivalent
GWP	Climate change	28.2	kg CO_2
PMFP	Fine particulate matter formation	0.04	kg PM2.5
FFP	Fossil resource scarcity	12.2	kg oil
WCP	Water use	0.1	m^3 water
FETP	Freshwater ecotoxicity	2.8	kg 1,4 DB
FEP	Freshwater eutrophication	0.01	kg P
HTPc	Human toxicity (cancer)	2.3	kg 1,4-DB
HTPnc	Human toxicity (non-cancer)	55.6	kg 1,4-DB
IRP	Ionizing radiation	0.8	kBq Co-60
LOP	Land use	0.7	m^2 annual crop
METP	Marine ecotoxicity	3.6	kg 1,4-DB
MEP	Marine eutrophication	0.001	kg N
SOP	Mineral resource scarcity	0.5	kg Cu
EOFP	Photochemical oxidant formation (ecosystem quality)	0.1	kg NO_x
HOFP	Photochemical oxidant formation (human health)	0.1	kg NO_x
ODP	Ozone depletion	0.00001	kg CFC-11
TAP	Terrestrial acidification	0.1	kg SO_2
TETP	Terrestrial ecotoxicity	233.9	kg 1,4-DB

Note: CF_m = Midpoint characterization factor

To identify which life cycle phases contribute most to the different impact categories, the contribution of each phase is presented in Figure 8 below. Table 21 in Appendix C presents the contribution of each phase in absolute values.

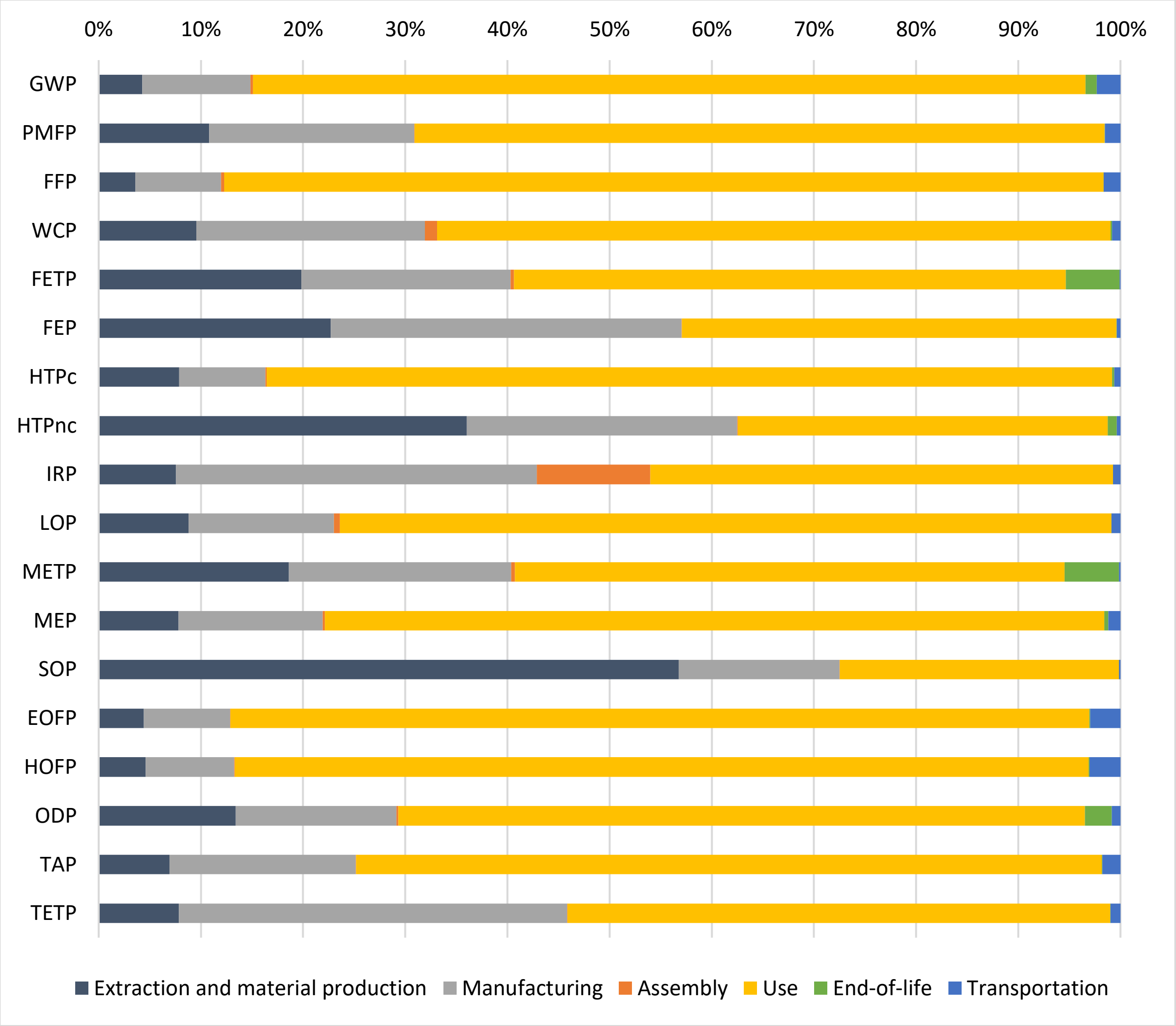


Figure 8: *Contribution to the studied impact categories for each life cycle phase*

From Figure 8 the observation can be made that the use phase is the dominant contributor for the majority of the studied impact categories. Assembly, end-of-life, and transportation contribute less than 10% to every impact category, with the exception of ionizing radiation. When assessing the eight most relevant impact categories stated in the goal and scope, extraction and material production, manufacturing, and use, are all major contributors. Most notably, the impact categories global warming potential and fossil resource scarcity are dominated by the use phase while extraction and material production accounts for approximately 57% of mineral resource scarcity. As for human toxicity and ecotoxicity, the use phase is most dominant but extraction and material production and manufacturing are also contributing a large share.

6.1.1 Contribution analysis

This section consists of a more in-depth assessment of the phases that are found to have the most influence on the LCIA results. Thereby, a visualization of which activities contribute the most to each individual life cycle phase is presented for the extraction and material production phase, the manufacturing phase, and the use phase. This provides supporting material for decision-making and optimization of activities along the Radar's life cycle. For this section, only the eight most important impact categories, which are stated in the Goal and scope, are studied.

For the extraction and production phase, seven materials contribute to over 80% of LCIA results in all the major categories (see Figure 9). Out of these, the extraction of silver, gold, and aluminium stand for over 60%.

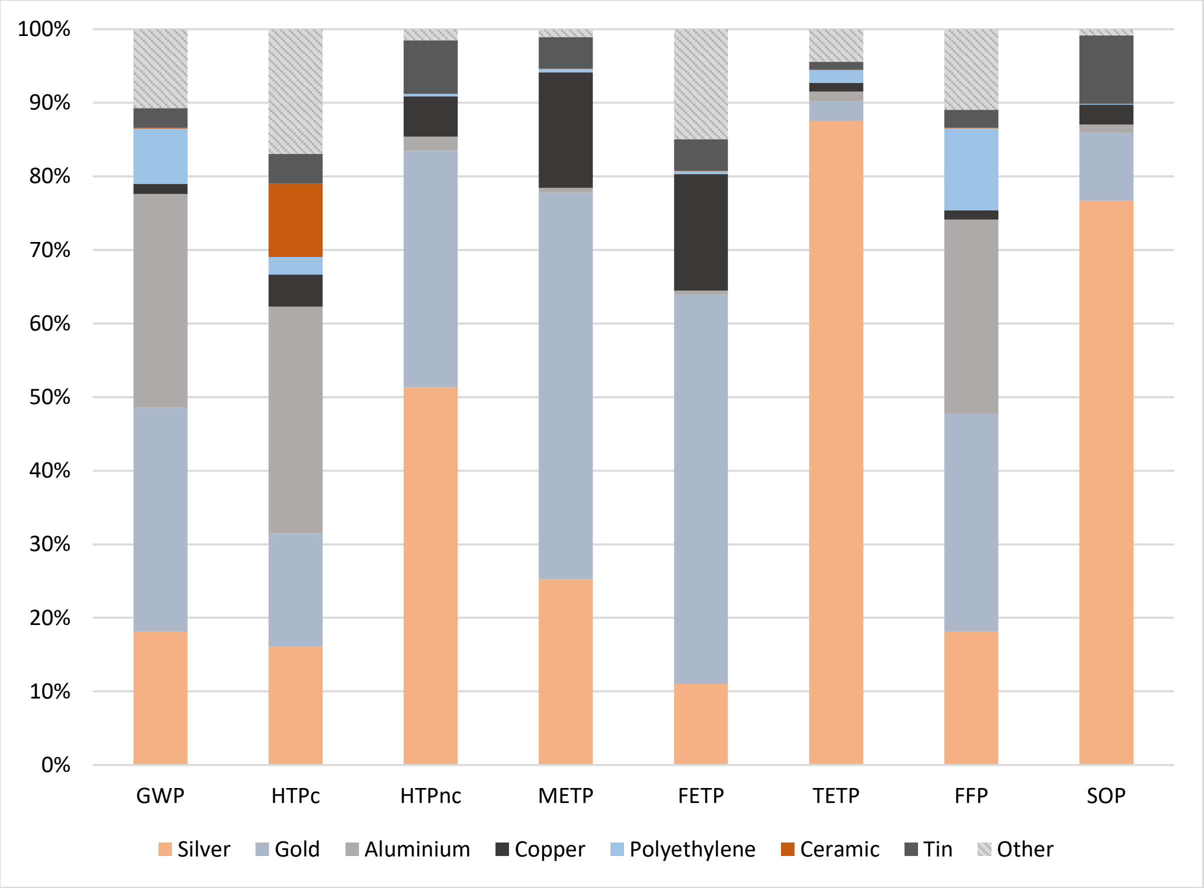


Figure 9: *Contribution analysis of the extraction and material production phase*

As for the manufacturing phase, four components are identified as the main contributors (see Figure 10). It is important to note that in this analysis, the manufacturing of the PCB panel also includes the process of manufacturing the PCB frame, which is not part of the Radar but manufactured in conjunction with the PCB panel. While the PCB panel is the prime contributor in most impact categories, the manufacturing of the integrated circuit stands for approximately 55% of the GWP in this phase.

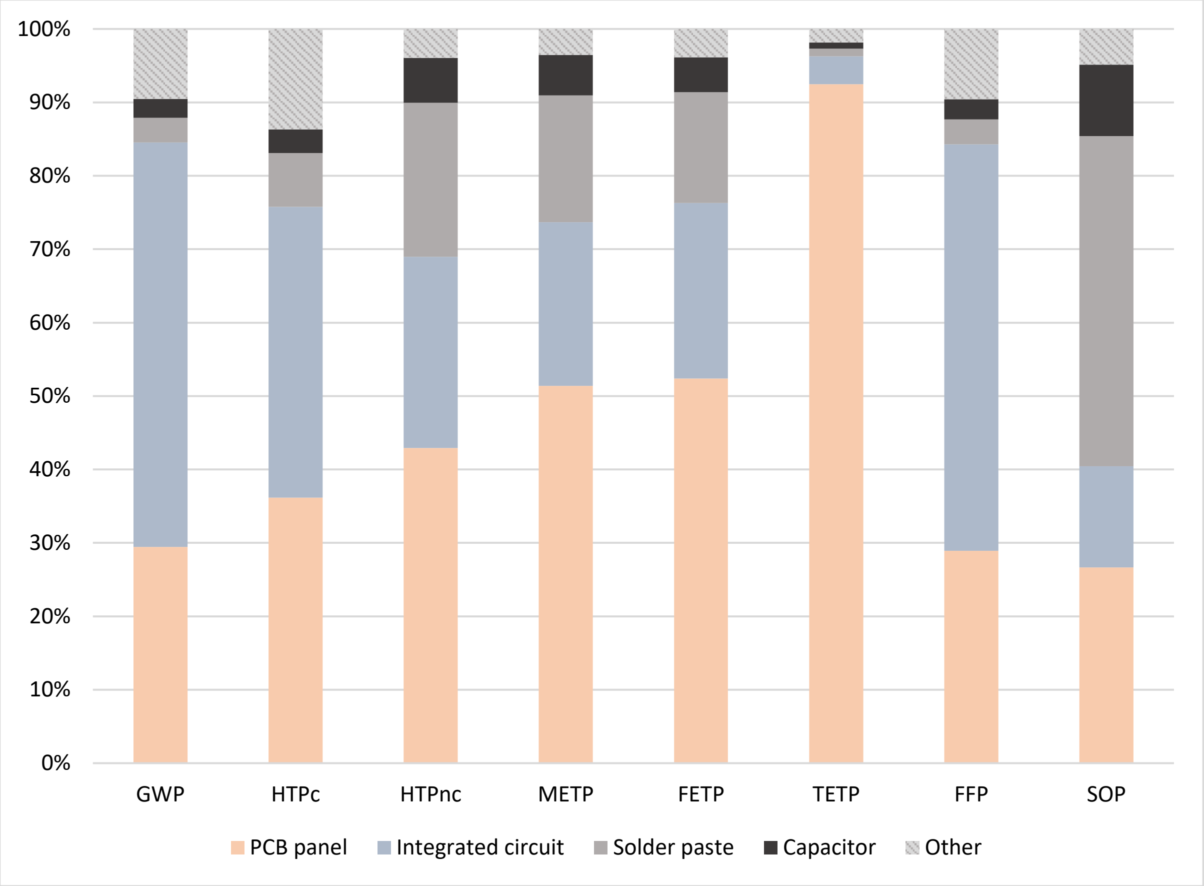


Figure 10: *Contribution analysis of the manufacturing phase*

The use phase only consists of two parameters, energy consumption, and weight contribution. Figure 11 presents their share of the LCIA results for this phase, where the energy consumption of the Radar is identified as the dominant contributor to all impacts investigated. This parameter consists of the diesel production process along with the conversion of diesel to electricity. The weight of the Radar is found to be less impactful when compared to its energy demand, but simultaneously not an insignificant factor.

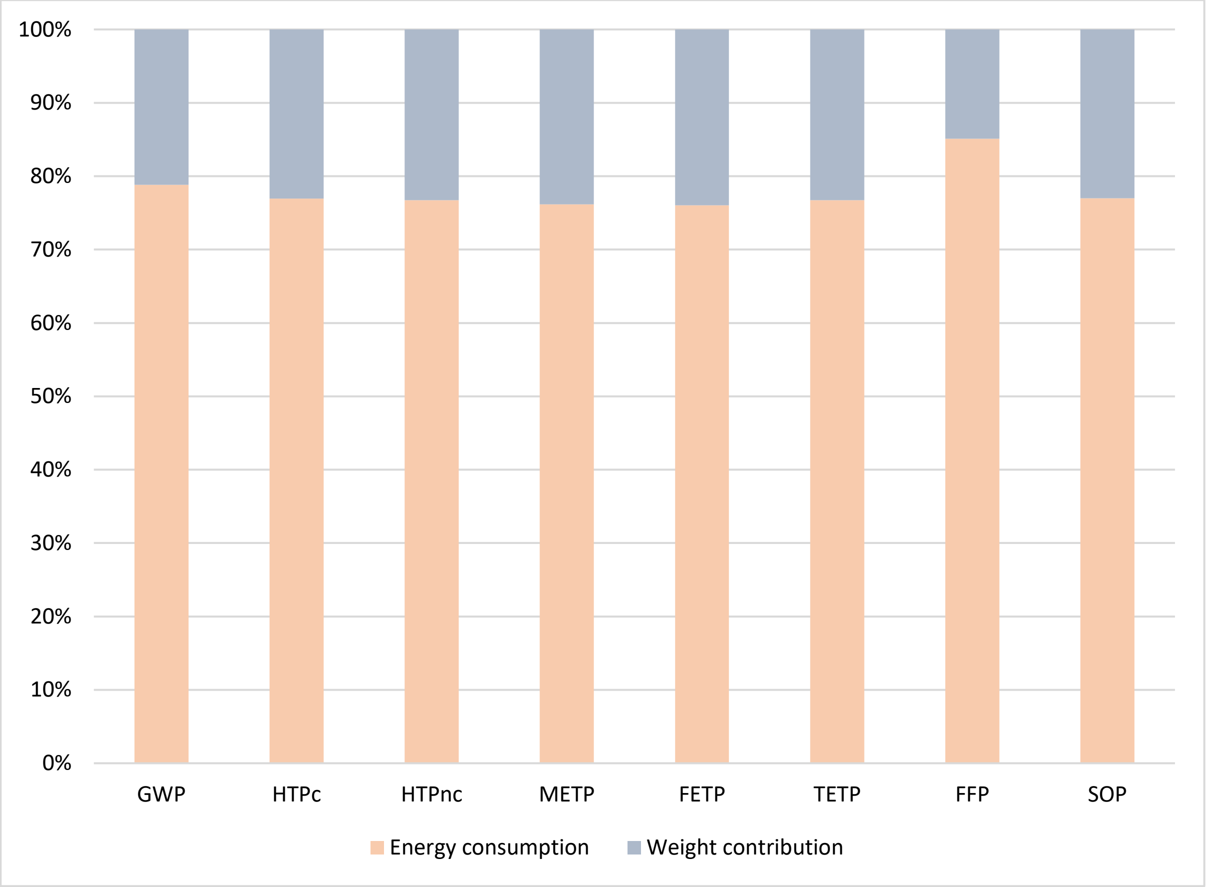


Figure 11: *Contribution analysis of the use phase*

6.1.2 Sensitivity analysis

As described in Section 4.4, the use phase contains various uncertainties which heavily influences the results. In addition to this, the LCIA result indicates that the use phase is a major contributor to the impact categories. Therefore, the uncertainties are analyzed by assessing the choice of parameters through a sensitivity analysis. For this analysis, three different parameters are investigated. These are:

1. Vehicle type

The choice of vehicle type affects the amount of emissions from the Radar's added weight as well as the emissions from generating electricity. For this analysis, one diesel car and one electric car is investigated. The diesel car has the same characteristics described in Section 5.4. As for the electric car, the paper by Liu et al. (2021) also investigates the average weight of medium sized electric vehicles, estimating it to be 1558kg. This weight is used when allocating the Radar's potential environmental impact.

2. Geographical location

The choice of geographical location affects what type of diesel mix is used and how the electricity mix is produced, for a diesel car and an electric car. For this analysis Germany, Sweden, and China are chosen. These nations are points of interest for the intended audience and they also have differentiating policies regarding the use of biodiesel as well as different electricity production methods, providing an interesting perspective.

To assess how the Radar's use phase is impacted by the different diesel mixtures, reduction obligation policies stated by the three nations have been applied. A report by the European Commission has been used to portray the GHG emissions reductions by the nation's different diesel mixtures. As stated in Section 5.4, Germany has reported a GHG intensity reduction of 6.1% in their diesel mixture while Sweden reported a reduction of 19.1% (European Commission, 2020). As for China, sources state that 0.2% of GHG intensity reduction is a target (Zhang & Bai, 2021) but this reduction is seen as neglectable for this analysis.

3. Operating time

The Radar's operating time affects how much energy it consumes during its lifetime. In Section 5.4, the operating time is calculated using the estimated distance and average vehicle speed. For this analysis, the operating time is altered by applying a variation of 20% on the average vehicle speed.

Figure 12 and Figure 13 present how the three parameters affect the GWP from the use phase, highlighting the base scenario for a sense of comparison. The whiskers showcase the change in operating time where the top represents an increase in operating time and the bottom represents a decrease in operating time.

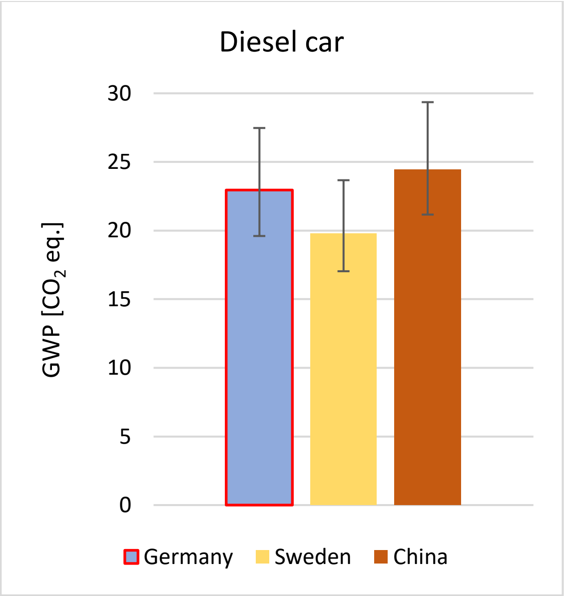


Figure 12: *Change in GWP contribution from use phase based on a diesel car*

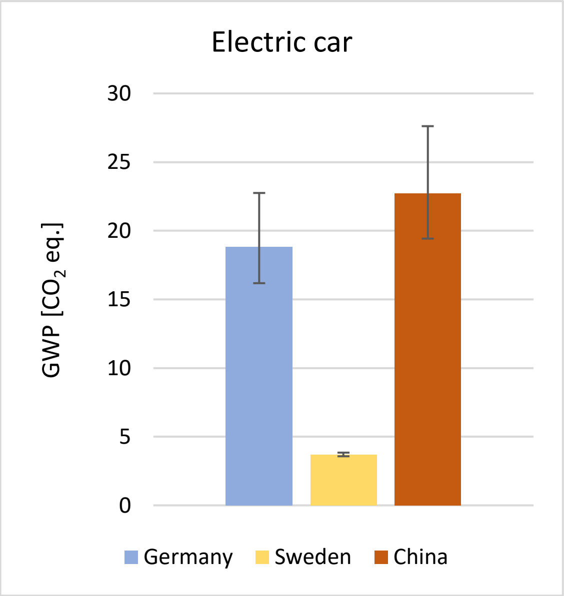


Figure 13: *Change in GWP contribution from use phase based on an electric car*

The result from the sensitivity analysis indicates that if the Radar is utilized in electric vehicles, rather than diesel vehicles, its GWP contribution reduces. This is most notable for Sweden, and less so for China, meaning that the choice of geographical location also has a large impact on the use phase contribution, if an electric vehicle is used. While the operating time is shown to be less of an important factor, it still deviates the base scenario with an approximate average of 17%.

The sensitivity analysis shows that the set of parameters selected to create a scenario for the use phase has a major impact on the LCIA result. The most optimal scenario for the Radar attributes approximately 4kg CO_2 equivalents to its GWP while the worst-case scenario attributes approximately 29kg CO_2 equivalents. The presented result connected to the electric vehicle scenarios is highly impacted by what electricity market that is considered. How this affects the sensitivity analysis is further discussed in Chapter 7.

6.2 GHG accounting

This section presents the result according to the GHG Product Standard. The six different emissions stated to be declared in its guidelines are thereby presented in Table 9 with their corresponding CO_2 equivalents. This result, together with all other data presented in this section, is based on the base scenario. The characterization factors used to translate the inventory result is in this segment based on the IPCC AR5 LCIA methodology and is used to estimate the Radar's life cycle's GWP100 contribution including biogenic sources.

Table 9: *Quantified GHG emissions, including biogenic and non-biogenic sources*

GHG	Quantity [kg]	GWP100 [kg CO_2 eq.]
CO_2	24.1	24.1
CH_4	0.1	3.1
N_2O	0.001	0.2
SF_6	1.5E-06	0.03
PFCs	7.7E-06	0.07
HFCs	8.2E-07	0.006

To further assess and demonstrate which life cycle phases that are predominantly responsible for the different greenhouse gasses presented above, a visualization of the respective life cycle phases' contribution is presented below in Figure 14.

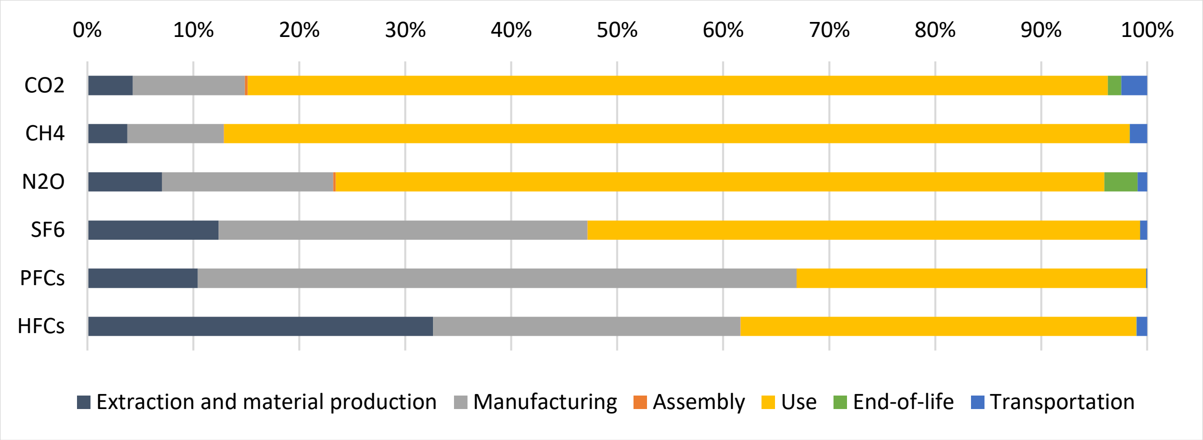


Figure 14: *Life cycle phase contribution to the different greenhouse gases*

What can be observed is that the use phase is the dominant contributor to the emissions of CO_2, CH_4 and N_2O. However, for the cases of SF_6, PFCs and HFCs, the phase extraction and material production along with manufacturing is shown to have a much greater contribution. This while none of the remaining phases of assembly, end-of-life or transportation is found to have a significant contribution to any of the presented GHG emissions.

By examining the different life cycle phases' impact to the overall GWP100, the use phase is found to be the leading contributor (see Figure 15). Responsible for more than 80% of the Radar's CO_2 equivalent emissions, it is followed by the manufacturing and extraction and material production as the second and third most impactful phases of the life cycle. Assembly and end-of-life is found to be the least contributing activities when assessing GWP100. The cradle-to-gate, which consists of the first three phases, consists of approximately 15% of the total GWP100, where manufacturing in this context is the biggest contributor. The gate-to-gate boundary only consists of assembly. Table 22 in Appendix D presents the GHG contribution for every phase separately.

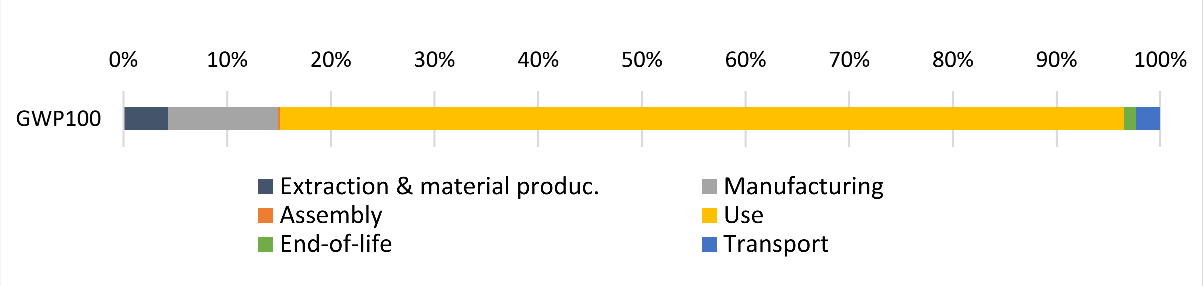


Figure 15: *Each life cycle phase' contribution to GWP100*

A different LCIA methodology, namely IPCC AR6, is used to demonstrate the total GHG inventory result, which can be viewed in Table 10 below. The table presents the emissions and removals of biogenic carbon separately along with emissions from land use change. The change of LCIA methodology was issued due to the absence of individually reported results in the case of biogenic and non-biogenic emissions in GaBi.

Table 10: *GWP100 with biogenic emissions and removals*

Emission sources	**GWP100 [kg CO_2 eq.]**
Biogenic emissions	0.36
Biogenic removal	-0.36
Emissions from land use change	0.02
Fossil GHG emissions	27.47

7. Interpretation

This chapter presents the interpretation of the LCA. This includes an interpretation of the LCIA result, evaluation of the result's robustness and limitations as well as conclusions and finally recommendations. Thus, addressing RQ2.

7.1 LCIA result

This section highlights the interpretations made from the LCIA result related to the phases of extraction and material production, manufacturing, and use. Additionally, the environmental improvement potential is assessed and elaborated upon.

7.1.1 Extraction and material production & manufacturing

When examining the extraction and material production phase in conjunction with the manufacturing phase, some similarities can be observed. For the first mentioned phase, only a few selective substances of the Radar are shown to have a significant impact, despite the large number of substances included in the Radar. While a relationship between the weight of the substance and its contribution to potential environmental impacts can be observed, some materials such as gold and silver, whose weight represent an extremely small portion of the Radar, is shown to have a significant contribution. Similar observations can be drawn from the manufacturing phase, where a small number of processes, namely the manufacturing of the PCB Panel and the integrated circuits, are found to be the major contributors. The integrated circuits stand for approximately 1% of the Radar's total weight but have a significant share of the contributions related to the manufacturing phase. This shows that the manufacturing of some specific electric components in the Radar are potentially much more energy and resource demanding and thus contribute unproportionally to their weight. This indicates the importance to not embrace a cut-off criterion solely based on weight for electronic products like the Radar, as certain materials and processes whose material input could be determined as low, can have characteristics that cause great impacts on the environment. Generally, metals in the Radar are found to have a significant contribution in comparison to the product's remaining materials.

7.1.2 Use phase & sensitivity analysis

As demonstrated by the LCIA result, the Radar's use phase is the most impactful when assessing the potential environmental impacts caused by the product. The emissions caused during this phase is primarily influenced by the two parameters of the Radar's energy consumption along with the vehicles efficiency in supplying the Radar with its required electricity demand. Consequently, an identified area of potential improvement is to reduce the electricity demand of the Radar and thereby its energy consumption. How much reduction this sole action can accomplish is however somewhat limited by the vehicle's properties and efficiency of converting fuel to electricity that powers the Radar.

In the context of the use phase, the sensitivity analysis presents additional parameters that impact the Radar's environmental performance, such as geographical representation and type of vehicle. As can be seen in the sensitivity analysis, the diesel mixture and electricity production which varies depending on what geographical region is considered plays a decisive role. When the diesel mixture used to support the Radar's energy demand is to a larger proportion consisting of non-fossil sources, the GWP is reduced with a certain amount. This while the greatest reduction of the Radar's GWP contribution is accomplished through being used in an electric vehicle. However, this parameter shows a greater dependency on what electricity mix is considered. For the case of Sweden, the Radar's GWP contribution in an electric vehicle reduces drastically compared with the diesel scenario, while in China no significant reduction can be seen. This is due to the fact that Sweden relies more on renewable sources for its electricity production, while much more CO_2 intensive sources such as coal are still widely used in other nations such as China.

These observations are however highly impacted by what electricity market is considered for the different geographical locations. The GHG Product Standard highlights that to account for the environmental contributions caused from electricity production and consumption, regional-based emissions factors should be used if no supplier specific data is available. In the sensitivity analysis, national based data regarding electricity production is used to model the electricity consumption in the different scenarios. This, as no applicable regional dataset exists in GaBi. Furthermore, due to the complexity of the electricity market, national electricity production data does not necessarily portray the electricity that is consumed within the same nation. For example, it cannot be absolutely determined that the approximations presented in the sensitivity analysis correspond with certain regions such as south Sweden or northern Germany, as they are partly included in the same electricity market. Hence, the sensitivity analysis does to a certain degree exaggerate the influence of in what geographical location the electric vehicle is utilized in. This should be taken into account when observing the approximations stated in the sensitivity analysis.

To summarize, the Radar contributes significantly less to GWP when utilized in an electric vehicle, but it is heavily dependent on how the electricity supporting the Radar is produced. The use phase and the scenarios presented should however be viewed with some skepticism. This as much of the results connected to this phase is heavily dependent on properties which could be considered outside the control of the Radar. This includes aspects such as diesel mixture and the electricity mix used in different regions. As these parameters change depending on geographical location, while the properties of the Radar do not, it could be considered rather conservative to directly allocate these emissions to the Radar. However, in this study, the assessment of how the environmental performance varies depending on the circumstances is found to be of interest and a relevant observation to consider, getting a more complete overview of the product.

7.1.3 Improvement potential

The contribution analysis showcases what to potentially prioritize when optimizing the environmental performance of the Radar. As previously mentioned, much of the impacts caused during the use phase is primarily assigned to the characteristics of the vehicle in which it is utilized. Still, the Radar's environmental performance during use can be improved by investing in R&D to decrease the Radar's energy demand as well as substituting materials to lower its weight. As the two phases of extraction and material production and manufacturing are within the cradle-to-gate boundary, these are more adaptable in the sense that Veoneer are in control and can set certain requirements to streamline these operations. This could for instance be done through material substitution of environmentally harmful materials or overlooking processes from suppliers which are found to have more of an environmental impact than desirable. It is important to note that suppliers have not been assessed on an individual level. Some products are, as stated in the Goal and scope, multiple sourced, but this LCA only looks at general manufacturing processes. Thus, deeper analyses are required in order to allocate the impacts of the manufacturing phase to specific suppliers.

7.2 Evaluation

This section evaluates the methodology used throughout the LCA and how it affects the reliability of the results by interpreting factors such as the data quality requirements, the system boundary, assumptions, and limitations.

7.2.1 ecoinvent as data source

As the Radar's life cycle involves many different processes linked to upstream Scope 3 emissions, ecoinvent is heavily relied upon in order to meet the time frame. Thus, the choice of datasets selected in ecoinvent has a large impact on the final results. While the database does provide relevant datasets linked to the life cycle of an ICT device such as the Radar, it is in some cases, less relevant in terms of geographical representation and time sensitivity.

Many of the selected ecoinvent datasets in this LCA have a global geographical representation which is often applicable, but some processes are in reality more sensitive to the choice of nation. An example of this is the waste treatment processes which are performed very differently depending on location. ecoinvent does not include the "correct" locations in the case of the Radar when it comes to these types of processes, meaning that their inventory data cannot be determined as fully accurate for this LCA. It is also difficult to determine if this type of data deviation contributes to an overestimation or underestimation of the Radar's potential environmental impact.

As for the time sensitivity, a few datasets selected in ecoinvent are 20 years old, meaning their inventory results may not be up to date. While some operations might not have seen much change during this time, others might have experienced improvements in regards to resource use as well as reductions of losses and emissions. This would ultimately allocate less potential environmental impact to the Radar. While the time period of the data is taken into consideration when assessing the data quality, no analyses have been performed to determine which data is considered outdated and how it may affect the final results.

Besides geographical representation and time sensitivity, the final results are also affected by the fact that the ecoinvent datasets selected may in some cases have overlapping inventory data, resulting in an overestimation of the Radar's total resource use or emissions. As an example, a manufacturing dataset can for some instances consider the mineral resources required to produce a component, while the chosen dataset in the extraction and material production phase already accounts for this, as well as the related emissions. Some overlaps are avoided by thoroughly examining the documentation of these datasets, provided by ecoinvent, to pinpoint exactly where activities start and end. However, as every dataset in ecoinvent contains numerous activities, some overlapping may occur.

For the purpose of this LCA, and to produce a report that is in accordance with the goal and scope, ecoinvent is considered a suitable database source. However, as stated, many parameters come with uncertainties, and it is important to acknowledge the issues with relying on ecoinvent to this extent. It also demonstrates the importance of transparency when it comes to the selection of datasets in ecoinvent, which is the reason why all datasets used in this LCA are stated in the report.

7.2.2 Primary data

The methodology used to model the assembly phase in this study requires the use of primary data and a higher level of accuracy. This is due to the fact that the phase is under the ownership of the company issuing the life cycle assessment, consequently primary data along with the inclusion of all activities under ownership should be applied. As mentioned in the Goal and scope of this assessment, some data and measurements have not been possible to obtain during the time frame of this study. Allocation of some supporting energy demanded activities such as maintenance along with ventilation has due to this not been applied. Additionally, average measurements of various activities have not been accessible and consequently lead to that max effect being considered to estimate energy consumption. While the neglected processes mentioned and average energy consumption should in theory be included to facilitate a more accurate representation of the assembly phase's environmental contribution, it is deemed to not delegitimize the overall assessment.

7.2.3 Limitations

The limitations stated in Section 4.10 affects the outcome of the LCA and steers the analyses away from certain aspects. Based on the results, some of these aspects are considered to be of more interest than others. Thus, the respective limitations are evaluated to provide a wider perspective.

As mentioned, only potential environmental impacts are assessed in this LCA, while social and economic impacts are not included. While the goal is to assess the Radar's environmental performance, it is important to note that the Radar's life cycle contributes to more than just potential environmental impacts. As the Radar's life cycle is spread across the globe with a considerable number of different activities related to it, many people are somehow involved in its life cycle. It is therefore reasonable to consider that the Radar's life cycle is associated with potential social impacts that should not be overseen.

An additional limitation in the context of this study has been the time constraint. Consequently, some simplified measures have been adopted and some areas have not been assessed to their greatest detail. For the sake of example, with more time, more primary data related to suppliers would have been possible to obtain. This would reduce the reliance of secondary data for the 1st tier suppliers, and thus provide a more accurate manufacturing phase which would to a greater degree resemble the reality.

7.3 Conclusion of LCA

The primary goal of this assessment is to provide results regarding the Radar's environmental performance throughout its life cycle. Additionally, the LCA is performed to identify what activities and life cycle phases that are deemed most significant to pin-point areas which have the greatest improvement potential from an environmental point of view.

When summarizing the result of this assessment, the environmental performance of the Radar's life cycle is greatly influenced by the use phase. As this study is structured around identifying the contributing activities to the impact categories linked to climate change, human- and ecotoxicity along with resource use, the use phase is determined as the most contributing phase of the Radar's life cycle. While the energy requirement of the Radar is deemed as an important factor within this assessment, external parameters such as vehicle type, diesel mixture and electricity production source play a big part in this contribution.

Other phases with findings of interest are the extraction and material production together with manufacturing. A few selective materials and processes within these phases, namely the extraction of silver and gold along with the manufacturing of PCB panels and integrated circuits, is identified as the primary contributors. These phases were found to have a greater outcome for the impacts linked to human- and ecotoxicity and resource use than other phases along the Radar's life cycle. Despite the multiple transports across continents and the need for large amounts of packaging, transportation and manufacturing of packaging contributes very little to the Radar's potential environmental impact. Additionally, the assembly phase and end-of-life phase showcase very little environmental impact, even though the Radar is treated through incineration and landfilling once disposed of.

Because of the Radar's complexity and the many actors involved, assumptions have been adopted which consequently contributes with some uncertainty regarding the results presented. Measures have been taken to reduce these, but the absence of accurate data and data gaps makes it important to be cautious when acting on the results. However, these obstacles are deemed to neither discredit or delegitimize the results and observations presented. Rather, they are portraying the importance of transparency when conducting an LCA on such a complex product.

7.4 Recommendations

The final result of the LCA along with the interpretation and conclusion, allows for certain recommendations to be communicated towards Veoneer. These recommendations are the author's suggestions of what actions can be taken to reduce the potential environmental impact of the Radar. The recommendations are not presented in any specific order.

1. Veoneer should oversee the Radar’s energy consumption and identify any potential opportunity to develop a more energy efficient product.

2. Veoneer should oversee the material composition of the Radar to reduce the need for environmentally harmful materials while potentially decreasing the Radar’s weight.

3. For components with large environmental burdens that are multiple sourced, Veoneer should assess the different suppliers to learn how their manufacturing methods differ and identify which supplier contributes less to potential environmental impacts.

4. For future assessments, Veoneer should perform continuous and structured measurements of their in-house processes to obtain all relevant inventory data, creating an accurate representation of reality and facilitating reporting of all necessary information in accordance with the GHG Protocol Product Life Cycle Accounting and Reporting Standard.

8. Discussion of RQ3

The following chapter is constructed around answering RQ3. Hence the similarities and differences of the respective accounting methodologies, ISO 14040 and 14044 and the GHG Product Standard, are highlighted and their influence on the assessment is addressed.

The two are in several ways compatible with one another, while at times they do differ. Much of the methodology presented in the GHG Product Standard is based upon the ISO standards. For instance, its scope on assessing impacts related to the life cycle of a functional unit, and its similar characteristics when it comes to allocation procedures and how inventory is translated into impacts. However, their diverse intention of use highly influences how one could and should interpret and utilize the results generated by two methodologies.

The ISO 14040 and 14044 guidelines are developed to facilitate an evaluation of a product's or system's environmental performance in a standardized fashion. The GHG Product Standard is on the other hand constructed to support businesses to make more informed choices in how they can reduce their emissions of greenhouse gases related to their products. This consequently causes major differences in what inventories and impacts that are of relevance. The ISO standards declare that the selection of impact categories should be based on its relevance to the product or system being studied, thereby considering the most significant environmental issues caused by it. This while the GHG Product Standard limits itself by only investigating the contribution towards climate change from a hierarchist perspective based on a specific LCIA method, namely IPCC. Thus, an ISO compliant LCA provides a more complete assessment in the context of evaluating a product's overall environmental performance.

In terms of data requirements, ISO 14044 has various measures and segments that should be considered to ensure accuracy in this context. The GHG Product Standard has additional requirements in terms of data and how inventory should be presented. Primary data should be applied for all processes and activities under ownership and be reported in the form of a process map. It could therefore be interpreted that the GHG Product Standard requests greater understanding of attributable processes, which could result in a more time-consuming data collection. This became clear when assessing the assembly phase, where aggregated general data was not an option. Instead, primary data had to be obtained.

The GHG Product Standard also requires quantification and presentation of specific inventory related to certain greenhouse gases, along with a separate reporting of biogenic and non-biogenic emissions and removals and land use change. These requirements create a need for more in-depth knowledge of certain processes to properly appeal to the GHG Product Standard. This became evident when considering the various nations' GHG reduction intensity policies connected to diesel mixtures. As no dataset of biofuel production or combustion can be obtained from the database used in this assessment, the results presented of biogenic emissions and removals together with land use change impacts are not represented with the highest degree of accuracy. Hence, more knowledge of these specific processes is needed to meet these requirements more accurately.

As the GHG Product Standard has more specific requirements when it comes to data quality and what data should be quantified and separately reported, the results can be debated as more applicable for making comparisons between specific products. This, as an ISO compliant study lacks niche company specific requirements where its guidelines provide more room for interpretation. It should be mentioned that ISO 14044 implements more strict obligations when an assessment is to be used for comparative assertions. Still, the collection of primary data is not an obligation as other measures are taken to ensure an accurate representation. It must also be mentioned that the GHG Product Standard is not invulnerable to precariousness, as a certain degree of freedom and interpretation still exists within the framework.

To summarize, the respective methodological approaches share many similarities. However, depending on the product and what is of interest to examine and present, one framework may provide more relevant results than the other. The result generated by an assessment aligned with the GHG Product Standard declares more specific elements that should be reported and presented. Hence, it could be portrayed that it is more suitable for comparison. Its limited scope on solely assessing the potential impact of climate change does however make it invalid for examining a product's overall environmental performance. ISO 14044 encourages impact categories and an impact assessment methodology to be selected depending on the characteristics of the product, making it more appropriate for this task. This is especially relevant for complex product systems, such as the Radar, where a larger variety of impact categories are of relevance to the product's life cycle.

9. Conclusion

The Radar's life cycle consists of an extensive number of activities spanning across different continents, emphasizing the need to track its emissions. By conducting an LCA, potential environmental impacts associated with the Radar are identified and interesting findings regarding its environmental performance are highlighted. Impacts linked to climate change, toxicity and resource scarcity are deemed as the most important for the Radar's life cycle, where approximately 28kg CO_2 equivalents are attributed to the impact category GWP. Considering all the 18 impact categories addressed, the use phase is the biggest contributor, accounting for approximately 81% of the impact category GWP. The extraction and material production phase as well as the manufacturing phase are also considered impactful, while assembly, end-of-life and transportation are much less noticeable.

In order to reduce the Radar's potential environmental impact, certain activities within the most contributing phases can be addressed. The extraction and beneficiation of gold, silver, and copper as well as the manufacturing of the integrated circuits and PCB panels are the main concerns in the Radar's first two life cycle phases. As for the use phase, the Radar's energy consumption is a large contributor. However, this aspect is greatly affected by external parameters such as vehicle type, diesel mixture, and electricity production and should thus be analyzed with more caution.

As the GHG Product Standard is based on the framework stated in ISO 14040 and 14044, they share many similarities and performing an environmental assessment that satisfies both of their requirements is easily achievable. However, one framework may provide more relevant results than the other depending on what is of interest to examine and present. While results based on the GHG Product Standard may allow for better comparison of products, following ISO 14040 and 14044 provides a more accurate picture of a product's overall environmental performance.

References

Armstrong, K., Das, S., & Cresko, J. (2020). The energy footprint of automotive electronic sensors. In Sustainable Materials and Technologies (Vol. 25, p. e00195). Elsevier BV. https://doi.org/10.1016/j.susmat.2020.e00195

Arushanyan, Y., Ekener-Petersen, E., & Finnveden, G. (2014). Lessons learned – Review of LCAs for ICT products and services. In Computers in Industry (Vol. 65, Issue 2, pp. 211–234). *Elsevier BV*. https://doi.org/10.1016/j.compind.2013.10.003

Arvidsson, R., Ciroth, A. (2021). Life Cycle Inventory Analysis: Methods and Data. Series: The Complete World of Life Cycle Assessment. *Springer Cham*. https://doi.org/10.1007/978-3-030-62270-1

Baumann, H., & Tillmann, A. (2004). The Hitch Hiker's Guide to LCA: An Orientation in Life Cycle Assessment Methodology and Application. *Studentlitteratur AB*

Bebkiewicz, K., Chłopek, Z., Stosio, G., Szczepański, K., & Zimakowska-Laskowska, M. (2017). Effect of average velocity of passenger cars on national annual emission of pollutants. In Combustion Engines (Vol. 171, Issue 4, pp. 121–126). *Polish Scientific Society of Combustion Engines*. https://doi.org/10.19206/ce-2017-420

Bhatia, P., Cummis, C., Brown, A., Drauker, L., Rich, D., Lahd, H. (2011). Greenhouse Gas Protocol Product Life Cycle Accounting and Reporting Standard. Washington DC: *World Resources Institute and World Business Council for Sustainable Development*.

Blomkvist, P., Hallin, A. (2015). Metod för teknologer: Examensarbete enligt 4-fasmodellen. *Studentlitteratur.*

Booth, A., Sutton, A., Clowes, M., & James, M. M.-S. (2021). Systematic approaches to a successful literature review (3rd ed.). *London, England: SAGE Publications.*

Cox, B., Bauer, C., Mendoza Beltran, A., van Vuuren, D. P., & Mutel, C. L. (2020). Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios. In Applied Energy (Vol. 269, p. 115021). Elsevier BV. https://doi.org/10.1016/j.apenergy.2020.115021

Curran, M. A. (2017). Goal and Scope Definition in Life Cycle Assessment. Series: The Complete World of Life Cycle Assessment. *Springer Dordrecht*. https://doi.org/10.1007/978-94-024-0855-3

Doffe, L. & Kadiri, M. (2010). Alternator contribution to CO2 emission reduction policies, *The XIX International Conference on Electrical Machines - ICEM 2010*, Rome, Italy, pp. 1-5, doi: 10.1109/ICELMACH.2010.5607747.

Dutch National Institute for Public Health and the Environment. (2018). *LCIA: the ReCiPe model*. Retrieved from: https://www.rivm.nl/en/life-cycle-assessment-lca/recipe

ecoinvent. (2022). *ecoinvent Database*. Retrieved from: https://ecoinvent.org/the-ecoinvent-database

European Commission. (2020). *Quality of petrol and diesel fuel used for road transport in the European Union (Reporting year 2020)*. Brussel. Retrieved from: https://climate.ec.europa.eu/system/files/2022-10/com_2022_515_en.pdf

Eurostat. (2023). End-of-life vehicle statistics. Retrieved from: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=End-of-life_vehicle_statistics

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

Finkbeiner, M., Inaba, A., Tan, R. et al. (2006). The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. *Int J Life Cycle Assessment 11, 80–85*. https://doi.org/10.1065/lca2006.02.002

Flyvbjerg, B. (2011). Case Study. In Denzin, N. K., & Lincoln, Y. S, *The SAGE Handbook of Qualitative Research*. (p. 301-316). SAGE Publication, Inc.

Hauschild, M. Z., & Huijbregts, M. a. J. (2015). Introducing Life Cycle Impact Assessment. In LCA compendium (pp. 1–16). *Springer Nature (Netherlands)*. https://doi.org/10.1007/978-94-017-9744-3_1

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). Life Cycle Assessment. In Springer eBooks. *Springer Nature*. https://doi.org/10.1007/978-3-319-56475-3

Horne, R. E., Grant, T., & Verghese, K. (2009). Life Cycle Assessment: Principles, Practice and Prospects. *CSIRO PUBLISHING*.

Huijbregts, M. a. J., Steinmann, Z. J. N., Elshout, P. M. F., G, S., Verones, F., Vieira, M. T., Hollander, A., Mc, Z., & Van Zelm, R. (2016). ReCiPe 2016 : A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization. *National Institute for Public Health and the Environment*. Retrieved from: https://repository.ubn.ru.nl/handle/2066/165757

ISO. (2006a). Environmental management — Life cycle assessment — Principles and Framework (ISO Standard No. 14040). *International Organization for Standardization*, Geneva, Switzerland.

ISO. (2006b). Environmental Management – Life Cycle Assessment – Requirements and Guidelines (ISO Standard No. 14044). *International Organization for Standardization*, Geneva, Switzerland.

ISO. (2018). Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification (ISO Standard No. 14067). *International Organization for Standardization*, Geneva, Switzerland. Retrieved from: https://www.iso.org/standard/71206.html

Kuczenski, B., Sahin, C., & Abbadi, A. E. (2016). Privacy-preserving aggregation in life cycle assessment. *Environment Systems and Decisions*, 37(1), 13–21. https://doi.org/10.1007/s10669-016-9620-7

Liao, Y., Gil, J., Pereira, R., Yeh, S., & Verendel, V. (2020). Disparities in travel times between car and transit: Spatiotemporal patterns in cities. Scientific Reports, 10(1). https://doi.org/10.1038/s41598-020-61077-0

Liu, Y., Chen, H., Gao, J., Li, Y., Dave, K., Chen, J., Federici, M., & Perricone, G. (2021). Comparative analysis of non-exhaust airborne particles from electric and internal combustion engine vehicles. In Journal of Hazardous Materials (Vol. 420, p. 126626). *Elsevier BV*. https://doi.org/10.1016/j.jhazmat.2021.126626

Meijer, E. (2021). Making LCA results count - PRé Sustainability. Retrieved from: https://pre-sustainability.com/articles/consider-your-audience-when-doing-lca/

Mikosch, N., Dettmer, T., Plaga, B., Gernuks, M., & Finkbeiner, M. (2022). Relevance of impact categories and applicability of life cycle impact assessment methods from an automotive industry perspective. Sustainability, 14(14), 8837. https://doi.org/10.3390/su14148837

Rodrigue, J.-P. (2020). The geography of transport systems the geography of transport systems (5th ed.). London, England: Routledge.

Rowley, J. (2012). Conducting research interviews. *Management Research Review*, 35(3/4), 260–271. https://doi.org/10.1108/01409171211210154

Stodden, V. (2014). Enabling Reproducibility in Big Data Research: Balancing Confidentiality and Scientific Transparency. In Lane, J., Stodden, V., Bender, S., Nissenbaum, H. Privacy, Big Data, and the Public Good: Frameworks for Engagement (p. 112 – 135). *Cambridge University Press*.

Veoneer (2022). Sustainability Report 2021. Retrieved February 27, 2023 from: https://www.veoneer.com/en/sustainability-report

Weidema B P. (2022). Comparison of the requirements of the GHG Protocol Product Life Cycle Standard and the ISO 14040 series. Aalborg, Denmark: 2.-0 LCA consultants.

Zhang, L., & Bai, W. (2021). Sustainability of crop–based biodiesel for transportation in China: Barrier analysis and life cycle ecological footprint calculations. *Technological Forecasting and Social Change,* 164, 120526. https://doi.org/10.1016/j.techfore.2020.120526

Örn, M. (2014). Towards Better Alternator Efficiency (Dissertation). *Linköping University* Retrieved from: http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-109098

Appendix A – ecoinvent modelling

Table 11: *Choice of modelling datasets in ecoinvent for the extraction and material production phase*

Substance	ecoinvent dataset	Accuracy
Triazine	RoW: triazine-compound production, unspecified ecoinvent 3.9.1	Good
Isopropyl	RoW: isopropyl acetate production ecoinvent 3.9.1	Good
Benzenamine	RoW: aniline production ecoinvent 3.9.1	Decent
Acrylic resin	RoW: acrylic acid production ecoinvent 3.9.1	Decent
Aluminium (metal)	IAI Area, Asia, without China and GCC: aluminium production, primary, ingot ecoinvent 3.9.1	Good
Aluminium hydroxide	IAI Area, Asia, without China and GCC: aluminium hydroxide production ecoinvent 3.9.1	Good
Aluminium oxide	IAI Area, Asia, without China and GCC: aluminium oxide production ecoinvent 3.9.1	Good
Antimony	RoW: antimony production ecoinvent 3.9.1	Good
Antimonytrioxide	RoW: antimony production ecoinvent 3.9.1	Decent
Arsenic	GLO: arsine production ecoinvent 3.9.1	Good
Barium	GLO: barium carbonate production ecoinvent 3.9.1	Good
Barium sulphate	GLO: barium sulfide production ecoinvent 3.9.1	Decent
Barium-titanium-trioxide	GLO: barium carbonate production ecoinvent 3.9.1	Poor
Beeswax	N/A	-
Bismaleimide resin	RoW: market for epoxy resin, liquid ecoinvent 3.9.1	Poor
Bismuth	GLO: arsine production ecoinvent 3.9.1	Decent
Boron	GLO: boron carbide production ecoinvent 3.9.1	Good
Butadiene resin	RoW: butadiene production ecoinvent 3.9.1	Good
Cadmium	RoW: cadmium production, semiconductor-grade ecoinvent 3.9.1	Good
Calcium	RoW: calcium carbonate production, precipitated ecoinvent 3.9.1	Good
Calcium-zirconium-trioxide	RoW: calcium carbonate production, precipitated ecoinvent 3.9.1	Decent
Carbon	RoW: activated carbon production, granular from hard coal ecoinvent 3.9.1	Good
Carbon black	GLO: carbon black production ecoinvent 3.9.1	Good
Cellulose	RoW: cellulose fibre production ecoinvent 3.9.1	Good
Ceramic	GLO: ferrite production ecoinvent 3.9.1	Good
Chlorine	RoW: chlorine production, liquid ecoinvent 3.9.1	Decent
Chromate	RoW: sodium dichromate production ecoinvent 3.9.1	Decent
Chromium	RoW: chromium production ecoinvent 3.9.1	Good
Chromium oxide	RoW: chromium oxide production, flakes ecoinvent 3.9.1	Good
Cobalt	GLO: cobalt production ecoinvent 3.9.1	Good

Copper	RoW: copper mine operation and beneficiation, sulfide ore ecoinvent 3.9.1	Good
Copper chromite black spinel	RoW: copper oxide production ecoinvent 3.9.1	Poor
Copper oxide	RoW: copper oxide production ecoinvent 3.9.1	Good
Decamethylcyclopentasiloxane	RoW: silicon production, metallurgical grade ecoinvent 3.9.1	Decent
Dibismuth-trioxide	GLO: arsine production ecoinvent 3.9.1	Poor
Dicyclohexyl-phthalate	RoW: phthalic anhydride production ecoinvent 3.9.1	Decent
Diiron-trioxide	RoW: iron(III) chloride production, product in 40% solution state	Poor
Dodecylbenzenesulphonic-acid	GLO: benzaldehyde-2-sulfonic acid production	Poor
EP	RoW: market for epoxy resin, liquid ecoinvent 3.9.1	Decent
Epoxy resin	RoW: market for epoxy resin, liquid ecoinvent 3.9.1	Good
Ethanol	RoW: ethanol production from maize ecoinvent 3.9.1	Good
Flame Retardant	RoW: polyurethane production, flexible foam, TDI-based, flame retardant ecoinvent 3.9.1	Decent
FMACP	RoW: ethylene vinyl acetate copolymer production ecoinvent 3.9.1	Poor
Formaldehyde	RoW: urea formaldehyde resin production ecoinvent 3.9.1	Decent
Further additives	DND	-
Gallium	GLO: gallium production, semiconductor-grade ecoinvent 3.9.1	Good
Glass fibre	RoW: glass fibre production ecoinvent 3.9.1	Good
Gold	RoW: gold mine operation and gold production, unrefined ecoinvent 3.9.1	Good
Graphite	RoW: graphite production ecoinvent 3.9.1	Good
Hydrogen	N/A	-
Indium	RoW: indium production ecoinvent 3.9.1	Good
Inorganic Ingredient	DND	-
Iron	RoW: iron ore beneficiation ecoinvent 3.9.1	Good
Iron nickel zinc oxide	GLO: ferrite production 3.9.1	Poor
LCP	RoW: ethylene vinyl acetate copolymer production ecoinvent 3.9.1	Decent
Lead	GLO: primary lead production from concentrate ecoinvent 3.9.1	Good
Magnesium (metal)	RoW: magnesium-alloy production, AZ91 ecoinvent 3.9.1	Good
Magnesium-oxide	RoW: magnesium oxide production ecoinvent 3.9.1	Good
Manganese	RoW: manganese production ecoinvent 3.9.1	Good
Manganese dioxide	GLO: manganese dioxide production ecoinvent 3.9.1	Good
Metal oxide	RoW: aluminium hydroxide production ecoinvent 3.9.1	Decent
Methacrylate	RoW: methyl methacrylate production ecoinvent 3.9.1	Good
Mineral powder	DND	-
Miscellaneous	DND	-
Molybdenum	RoW: molybdenum production ecoinvent 3.9.1	Good

Nickel	RoW: nickel mine operation and benefication to nickel concentrate, 7% Ni ecoinvent 3.9.1	Decent
Nickel-monoxide	RoW: nickel mine operation and benefication to nickel concentrate, 7% Ni ecoinvent 3.9.1	Poor
Nitrogen	RoW: market for nitrogen, liquid	Decent
Organic Ingredient	DND	-
Oxirane	RoW: ethylene oxide production ecoinvent 3.9.1	Good
Oxygen	N/A	-
PAI	RoW: glass fibre reinforced plastic production, polyamide, injection moulded ecoinvent 3.9.1	Decent
PAK	GLO: polyacrylamide production ecoinvent 3.9.1	Poor
Palladium	RU: platinum group metal mine operation, ore with high palladium content ecoinvent 3.9.1	Good
Borosilicate	RoW: market for sodium silicate, solid ecoinvent 3.9.1	Poor
PBT	RoW: polyethylene terephthalate production, granulate, amorphous ecoinvent 3.9.1	Decent
Phenol	RoW: market for phenol ecoinvent 3.9.1	Good
Phenolic Resin	RoW: phenolic resin production ecoinvent 3.9.1	Good
Phosphorus	RoW: phosphate rock beneficiation ecoinvent 3.9.1	Decent
Pigment portion	RoW: cadmium production, primary	Poor
PMMA	RoW: methyl methacrylate production ecoinvent 3.9.1	Poor
Polyethylene terephthalate	RoW: polyethylene terephthalate production, granulate, amorphous ecoinvent 3.9.1	Good
Polytetrafluoroethylene	RoW: tetrafluoroethylene production ecoinvent 3.9.1	Decent
Polyurethane	RoW: polyurethane production, rigid foam ecoinvent 3.9.1	Good
Potassium	GLO: potassium perchlorate production ecoinvent 3.9.1	Good
PPE	GLO: polyphenylene sulfide production ecoinvent 3.9.1	Decent
PTFE	RoW: tetrafluoroethylene production ecoinvent 3.9.1	Poor
PVMQ	RoW: silicone product production ecoinvent 3.9.1	Good
Ruthenium(IV)oxide	ZA: market for platinum group metal concentrate	Poor
Selenium	RoW: selenium production ecoinvent 3.9.1	Good
Silica	RoW: silica sand production ecoinvent 3.9.1	Good
Silicate	RoW: market for sodium silicate, solid ecoinvent 3.9.1	Decent
Silicon	RoW: silicon production, metallurgical grade ecoinvent 3.9.1	Good
Silicon chrome	RoW: silicon production, metallurgical grade ecoinvent 3.9.1	Decent
Silicon dioxide	RoW: silicon production, metallurgical grade ecoinvent 3.9.1	Decent
Silicone resin	RoW: silicone product production ecoinvent 3.9.1	Decent
Siloxanes and Silicones	RoW: silicone product production ecoinvent 3.9.1	Decent
Silver	PE: silver mine operation with extraction ecoinvent 3.9.1	Good
Strontium	CN: strontium mine operation and beneficiation ecoinvent 3.9.1	Good

Sulphur	GLO: market for sulfur ecoinvent 3.9.1	Good
Talc	RoW: magnesium-alloy production, AZ91 ecoinvent 3.9.1	Poor
Tellurium	RoW: tellurium production, semiconductor-grade ecoinvent 3.9.1	Good
Tin	RoW: tin production ecoinvent 3.9.1	Good
Titanium	GLO: titanium production ecoinvent 3.9.1	Good
Titanium-dioxide	RoW: titanium dioxide production, sulfate process ecoinvent 3.9.1	Good
Tricobalt-tetraoxide	GLO: market for cobalt oxide	Poor
Tungsten	RoW: tungsten mine operation and beneficiation ecoinvent 3.9.1	Good
Vanadium	CN: vanadium-titanomagnetite mine operation and beneficiation ecoinvent 3.9.1	Poor
VMQ	RoW: silicone product production ecoinvent 3.9.1	Good
Zinc (metal)	RoW: primary zinc production from concentrate ecoinvent 3.9.1	Good
Zinc oxide	RoW: zinc oxide production ecoinvent 3.9.1	Good
Zirconium	RoW: zirconium oxide production ecoinvent 3.9.1	Poor

Table 12: *Choice of modelling datasets in ecoinvent for the manufacturing of components*

Component	ecoinvent dataset	Accuracy
Housing	RoW: injection moulding ecoinvent 3.9.1	Good
Radome	RoW: injection moulding ecoinvent 3.9.1	Good
Shield	RoW: injection moulding ecoinvent 3.9.1	Good
Spacer	RoW: impact extrusion of steel, cold, deformation stroke	Decent
Thermal gel	RER: metallization paste production, back side, aluminium	Decent
Radar vent	RoW: thermoforming of plastic sheets ecoinvent 3.9.1	Poor
PCB Panel	GLO: printed wiring board production, for surface mounting, Pb free surface ecoinvent 3.9.1	Good
Capacitor	GLO: capacitor production, for surface-mounting ecoinvent 3.9.1	Good
Connector	GLO: electric connector production, peripheral type buss ecoinvent 3.9.1	Good
Frequency device	GLO: inductor production, low value multilayer chip ecoinvent 3.9.1	Good
Inductor	GLO: inductor production, low value multilayer chip ecoinvent 3.9.1	Good
Integrated circuit	GLO: integrated circuit production, memory type ecoinvent 3.9.1	Good
EMI filter	GLO: inductor production, ring core choke type ecoinvent 3.9.1	Decent
Transistor	GLO: transistor production, surface-mounted ecoinvent 3.9.1	Good
Resistor	GLO: resistor production, surface-mounted ecoinvent 3.9.1	Good
Diode	GLO: diode production, auxilliaries and energy use ecoinvent 3.9.1	Good
Solder paste	GLO: solder production, paste, Sn95.5Ag3.9Cu0.6, for electronics industry ecoinvent 3.9.1	Good

Table 13: *Choice of modelling datasets in ecoinvent for the manufacturing of packaging*

Package type	ecoinvent dataset	Accuracy
Cardboard box	RoW: folding boxboard carton production ecoinvent 3.9.1	Good
Tray	RoW: thermoforming of plastic sheets ecoinvent 3.9.1	Good
Reel	RoW: thermoforming of plastic sheets ecoinvent 3.9.1	Good
Antistatic foil	RoW: ethylvinylacetate production, foil	Good
PCB Frame	GLO: printed wiring board production, for surface mounting, Pb free surface ecoinvent 3.9.1	Good
Pail	RoW: thermoforming of plastic sheets ecoinvent 3.9.1	Decent

Table 14: *Choice of modelling datasets for waste management in the assembly phase*

Waste management	ecoinvent dataset	Accuracy
Cardboard box	CH: treatment of waste paperboard, municipal incineration ecoinvent 3.9.1	Good
Electronic waste	CH: treatment of waste plastic, industrial electronics, municipal incineration ecoinvent 3.9.1	Decent
Plastic waste	CH: treatment of waste plastic, mixture, municipal incineration ecoinvent 3.9.1	Good
Toxic waste	CH: treatment of hazardous waste, hazardous waste incineration ecoinvent 3.9.1	Good

Table 15: *Choice of modelling datasets in ecoinvent for the use phase and sensitivity analysis*

Process	ecoinvent dataset	Accuracy
Diesel car operating *	RoW: transport, passenger car, medium size, diesel, EURO 5 ecoinvent 3.9.1	Good
Electric car operating	GLO: transport, passenger car, electric ecoinvent 3.9.1	Good
Electricity production, Sweden	SE: electricity, high voltage, production mix ecoinvent 3.9.1	Decent
Electricity production, Germany	DE: electricity, high voltage, production mix ecoinvent 3.9.1	Decent
Electricity production, China	CN-CSG: electricity, high voltage, production mix ecoinvent 3.9.1	Decent
Diesel production *	RoW: diesel production, petroleum refinery operation ecoinvent 3.9.1	Good

** Processes used for the base scenario*

Table 16: *Choice of modelling datasets in ecoinvent for the end-of-life phase*

Process	ecoinvent dataset	Accuracy
Waste treatment	CH: treatment of waste plastic, industrial electronics, municipal incineration with fly ash extraction ecoinvent 3.9.1	Decent

Table 17: *Choice of modelling datasets in ecoinvent for transportation*

Transportation mode	ecoinvent dataset	Accuracy
Truck	RER: transport, freight, lorry 16-32 metric ton, EURO5 ecoinvent 3.9.1	Good
Truck with reefer	GLO: transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO5, R134a refrigerant, freezing ecoinvent 3.9.1	Good
Flight	GLO: transport, freight, aircraft, all distances to generic market for transport, freight, aircraft, unsp ecoinvent 3.9.1	Good
Flight with reefer	GLO: transport, freight, aircraft with reefer, cooling ecoinvent 3.9.1	Good
Train	RoW: transport, freight train, electricity ecoinvent 3.9.1	Good
Ship	GLO: transport, freight, sea, container ship ecoinvent 3.9.1	Good

Appendix B – Life Cycle Inventory

Table 18: *Packaging data*

Component	P1	Weight [g]	U/P1	P2	Weight [g]	U/P2
Housing	Tray	200	45	Cardboard box	841	135
Radome	Tray	400	100	Cardboard box	452	200
Shield	Tray	150	100	Cardboard box	585	1302
Spacer	Returnable box	1568	400	N/A	-	-
Thermal gel	Pail	1792	25 000	N/A	-	-
Radar vent	Reel	180	7000	Cardboard box	1069	105 000
PCB Panel	Antistatic foil	100	90	Cardboard box	915	450
	PCB frame	19	9			
Capacitor	Reel	100	3000	Cardboard box	500	15 000
Connector	Reel	100	3000	Cardboard box	500	15 000
Frequency device	Reel	100	3000	Cardboard box	500	15 000
Inductor	Reel	100	3000	Cardboard box	500	15 000
Integrated circuit	Reel	100	3000	Cardboard box	500	15 000
EMI filter	Reel	100	3000	Cardboard box	500	15 000
Transistor	Reel	100	3000	Cardboard box	500	15 000
Resistor	Reel	100	3000	Cardboard box	500	15 000
Diode	Reel	100	3000	Cardboard box	500	15 000
Solder paste	Tube	72	1200	Cardboard box	500	12 000
Final product	Returnable box	1000	32	N/A	-	-

Note: P1 = Primary packacking type, P2 = Secondary packaging type, U = units. N/A entails that the component does not have a secondary packaging.

Table 19: *Transportation data*

Component	Transportation mode$_d$	Distance [km]	Transportation mode$_m$	Distance [km]
Housing	Truck	1324	Rail	9800
Radome	Truck	1324	Rail	9800
Shield	Truck	1324	Rail	9800
Spacer	Truck	1875	N/A	-
Thermal gel	Boat	1213	N/A	-
Radar vent	Flight	6540	N/A	-
PCB Panel	Flight	8588	N/A	-
Capacitor	Truck	1193	Flight	9101
	Truck	1185	Flight	9101
	Flight	8827	N/A	-
Connector	Truck	1324	Rail	9800
Frequency Device	Flight	765	Flight	8733
	Truck	1185	Flight	9101
Inductor	Truck	1193	Flight	9101
	Truck	1015	Flight	10564
	Flight	8720	Flight	693
Integrated circuit	Flight	1036	Flight	8778
	Truck	1193	Flight	8860
	Flight	884	Flight	9154
EMI filter	Truck	1185	Flight	9101
Resistor	Truck	803	Flight	8249
	Truck	1193	N/A	-
Diode	Truck	1193	Flight	9050
Transistor	Flight	884	Flight	8860
	Flight	694	Flight	8557
Solder paste	Flight	1231	N/A	-
Final product	Truck	820	N/A	-

Note: d = Transportation from distributor to Vårgårda, m = Transportation from manufacturer to distributor. N/A entails that the component is manufactured at the distributor location. Whenever a component has multiple transportations, it entails that multiple suppliers are required to supply the total amount of components required.

Table 20: *LCI Results*

Substance	Type	Quantity
1,1,1-Trichloroethane	[Halogenated organic emissions to air]	6,70E-09
Acrolein	[urban air close to ground]	5,25E-05
Aluminium	[Non renewable elements]	6,42E-02
Antimony	[ecoinvent long-term to fresh water]	5,01E-04
Antimony	[Heavy metals to air]	6,75E-06
Antimony	[Heavy metals to fresh water]	2,54E-04
Antimony	[Heavy metals to industrial soil]	4,13E-07
Antimony	[non-urban air or from high stacks]	1,44E-06
Antimony	[urban air close to ground]	6,27E-05
Arsenic (+V)	[Heavy metals to fresh water]	3,80E-05
Arsenic	[ecoinvent long-term to air]	7,29E-08
Arsenic	[Heavy metals to air]	3,54E-07
Arsenic	[non-urban air or from high stacks]	1,04E-05
Arsenic	[urban air close to ground]	7,22E-07
Arsenic, ion	[ecoinvent long-term to fresh water]	6,70E-05
Barium	[ecoinvent long-term to fresh water]	3,70E-03
Barium	[Inorganic emissions to air]	2,99E-05
Barium	[Inorganic emissions to fresh water]	8,51E-04
Barium	[Inorganic emissions to industrial soil]	1,83E-04
Barium	[Inorganic emissions to sea water]	3,12E-04
Barium	[Non renewable elements]	6,48E-02
Benzene	[Hydrocarbons to fresh water]	2,22E-03
Benzene	[non-urban air or from high stacks]	2,49E-04
Benzene	[urban air close to ground]	6,17E-04
Benzo(a)pyrene	[non-urban air or from high stacks]	1,67E-06
Beryllium	[ecoinvent long-term to fresh water]	2,96E-05
Beryllium	[Inorganic emissions to air]	4,39E-09
Beryllium	[non-urban air or from high stacks]	1,78E-08
Beryllium	[urban air close to ground]	5,18E-09
Cadmium	[ecoinvent long-term to air]	4,19E-08
Cadmium	[Heavy metals to agricultural soil]	4,49E-07
Cadmium	[Heavy metals to air]	3,86E-07
Cadmium	[non-urban air or from high stacks]	3,41E-06
Cadmium	[urban air close to ground]	2,99E-07
Cadmium, ion	[ecoinvent long-term to fresh water]	6,84E-05
Carbon dioxide	[Inorganic emissions to air]	2,41E+01
Carbon dioxide, fossil	[ecoinvent long-term to air]	7,51E-07
Carbon disulphide	[Inorganic emissions to air]	2,30E-04
Carbon tetrachloride (tetrachloromethane)	[Halogenated organic emissions to air]	3,17E-07
Chlorinated hydrocarbons (unspecified)	[Halogenated organic emissions to air]	5,23E-06
Chlorobenzene	[Halogenated organic emissions to fresh water]	1,98E-03
Chloroform	[non-urban air or from high stacks]	3,28E-08
Chloroform	[urban air close to ground]	1,45E-06
Chlorpyriphos	[Pesticides to agricultural soil]	1,86E-06

Chromium (+VI)	[ecoinvent long-term to fresh water]	2,33E-04
Chromium (+VI)	[Heavy metals to fresh water]	6,80E-05
Chromium	[Heavy metals to air]	4,88E-06
Chromium	[Heavy metals to industrial soil]	2,95E-06
Chromium	[Non renewable elements]	3,78E-03
Chromium	[non-urban air or from high stacks]	1,89E-05
Chromium	[urban air close to ground]	6,44E-07
Chromium VI	[ecoinvent long-term to air]	8,73E-09
Chromium VI	[non-urban air or from high stacks]	5,13E-07
Chromium VI	[urban air close to ground]	1,34E-08
Chromium, ion	[surface water]	1,87E-06
Chromium, ion	[unspecified]	1,59E-06
Clay	[Non renewable resources]	1,46E-01
Coal, brown, in ground	[Lignite (resource)]	7,13E-01
Coal, hard, unspecified, in ground	[Hard coal (resource)]	3,03E+00
Cobalt	[ecoinvent long-term to fresh water]	2,79E-04
Cobalt	[Heavy metals to air]	1,73E-06
Copper	[ecoinvent long-term to air]	2,83E-07
Copper	[ecoinvent long-term to fresh water]	1,45E-02
Copper	[Heavy metals to air]	8,83E-05
Copper	[Heavy metals to fresh water]	2,73E-05
Copper	[Heavy metals to sea water]	1,85E-05
Copper	[Non renewable elements]	2,02E-02
Copper	[non-urban air or from high stacks]	2,92E-05
Crude oil ecoinvent	[Crude oil (resource)]	8,62E+00
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene)	[Halogenated organic emissions to fresh water]	1,37E-03
Dinitrogen monoxide	[ecoinvent long-term to air]	2,76E-08
Dolomite	[Non renewable resources]	1,66E-02
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	[ecoinvent long-term to air]	1,57E-08
Ethylene oxide	[urban air close to ground]	1,62E-04
Fluoranthene	[Hydrocarbons to fresh water]	7,42E-07
Formaldehyde	[non-urban air or from high stacks]	8,63E-06
Formaldehyde	[urban air close to ground]	1,87E-04
Gallium	[Non renewable elements]	1,98E-05
Gas, mine, off-gas, process, coal mining	[Natural gas (resource)]	2,43E-02*
Gas, natural, in ground	[Natural gas (resource)]	1,57E+00*
Gold	[Non renewable elements]	1,27E-05
Hafnium	[Non renewable elements]	9,38E-06
Halon (1211)	[Halogenated organic emissions to air]	8,12E-10
Halon (1301)	[Halogenated organic emissions to air]	2,95E-08
Iron	[Non renewable elements]	7,61E-01
Lead	[ecoinvent long-term to air]	3,40E-07
Lead	[ecoinvent long-term to fresh water]	2,79E-03
Lead	[Heavy metals to air]	3,09E-04
Lead	[Non renewable elements]	1,50E-02
Magnesite	[Non renewable resources]	4,39E-03

Magnesium	[Non renewable elements]	1,26E-01
Manganese	[Non renewable elements]	1,13E-02
Mercury	[ecoinvent long-term to air]	1,35E-09
Mercury	[ecoinvent long-term to fresh water]	6,07E-06
Mercury	[Heavy metals to air]	5,49E-07
Mercury	[Heavy metals to fresh water]	2,17E-07
Methane (biotic)	[Organic emissions to air (group VOC)]	7,35E-04
Methane	[Organic emissions to air (group VOC)]	1,04E-01
Methane, dichloro-, HCC-30	[non-urban air or from high stacks]	9,69E-08
Methane, dichloro-, HCC-30	[urban air close to ground]	4,49E-08
Methane, from soil or biomass stock	[Organic emissions to air (group VOC)]	1,91E-06
Methane, monochloro-, R-40	[non-urban air or from high stacks]	1,77E-07
Methyl bromide	[Halogenated organic emissions to air]	8,28E-07
Molybdenum	[ecoinvent long-term to fresh water]	8,70E-05
Molybdenum	[Heavy metals to air]	7,03E-06
Molybdenum	[Non renewable elements]	4,28E-04
Nickel	[ecoinvent long-term to air]	3,61E-08
Nickel	[Non renewable elements]	8,74E-03
Nickel, ion	[ecoinvent long-term to fresh water]	8,66E-04
Nickel, ion	[ocean]	4,51E-06
Nitrous oxide (laughing gas)	[Inorganic emissions to air]	6,46E-04
Palladium	[Non renewable elements]	6,94E-07
Peat, in ground, ecoinvent	[Peat (resource)]	3,93E-03
Pentachlorophenol (PCP)	[Halogenated organic emissions to air]	7,34E-07
Phenol (hydroxy benzene)	[Hydrocarbons to fresh water]	1,09E-04
Platinum	[Non renewable elements]	9,09E-07
Polycyclic aromatic hydrocarbons (PAH)	[Group PAH to air]	1,19E-05
Polycyclic aromatic hydrocarbons (PAH, unspec.)	[Hydrocarbons to fresh water]	7,45E-06
Pyrene	[Hydrocarbons to fresh water]	4,08E-07
R 11 (trichlorofluoromethane)	[Halogenated organic emissions to air]	7,82E-10
R 113 (trichlorotrifluoroethane)	[Halogenated organic emissions to air]	5,92E-08
R 116 (hexafluoroethane)	[Halogenated organic emissions to air]	3,79E-06
R 12 (dichlorodifluoromethane)	[Halogenated organic emissions to air]	5,87E-08
R 124 (chlorotetrafluoroethane)	[Halogenated organic emissions to air]	8,23E-09
R 134a (tetrafluoroethane)	[Halogenated organic emissions to air]	1,63E-07
R 152a (difluoroethane)	[Halogenated organic emissions to air]	2,86E-07
R 22 (chlorodifluoromethane)	[Halogenated organic emissions to air]	9,77E-07
R 23 (trifluoromethane)	[Halogenated organic emissions to air]	3,66E-07
Rhodium	[Non renewable elements]	1,18E-07
Selenium	[ecoinvent long-term to fresh water]	1,65E-05
Selenium	[Heavy metals to air]	2,46E-06
Selenium	[Heavy metals to fresh water]	2,59E-06
Selenium	[Non renewable elements]	3,96E-05
Silicon	[Non renewable elements]	1,99E-03
Silver	[ecoinvent long-term to air]	2,04E-09
Silver	[Heavy metals to air]	2,87E-09

Silver	[Non renewable elements]	7,40E-04
Silver, ion	[ground-, long-term]	1,71E-04
Silver, ion	[ocean]	7,26E-08
Silver, ion	[surface water]	1,99E-07
Sulfuric acid	[surface water]	2,53E-05
Sulphur	[Non renewable elements]	6,45E-03
Sulphur hexafluoride	[Inorganic emissions to air]	1,46E-06
Sulphuric acid	[Inorganic emissions to air]	1,06E-06
Tantalum	[Non renewable elements]	4,13E-05
Tetrafluoromethane	[Halogenated organic emissions to air]	3,90E-06
Thallium	[ecoinvent long-term to fresh water]	5,98E-05
Thallium	[Heavy metals to air]	1,04E-07
Tin	[Heavy metals to air]	7,96E-06
Tin	[Non renewable elements]	9,93E-03
Titanium	[Non renewable elements]	4,04E-03
Uranium, in ground	[Uranium (resource)]	2,81E-05
Vanadium	[ecoinvent long-term to air]	2,25E-07
Vanadium	[Heavy metals to air]	3,72E-05
Vanadium	[Heavy metals to industrial soil]	8,79E-06
Vanadium, ion	[ecoinvent long-term to fresh water]	4,12E-04
Vanadium, ion	[ground-]	2,21E-07
Vanadium, ion	[surface water]	1,44E-06
Zinc	[ecoinvent long-term to air]	4,05E-07
Zinc	[Heavy metals to agricultural soil]	1,18E-06
Zinc	[Heavy metals to air]	5,17E-05
Zinc	[Heavy metals to industrial soil]	5,26E-05
Zinc	[Non renewable elements]	2,97E-02
Zinc, ion	[ecoinvent long-term to fresh water]	3,63E-03
Zinc, ion	[ground-]	5,87E-05
Zinc, ion	[ocean]	1,41E-04
Zinc, ion	[surface water]	1,01E-04
Zinc, ion	[unspecified]	2,42E-06

Note: This is not the Radar's total inventory. The quantities presented are the largest contributors to the eight major impact categories that are examined with greater precision due to their relevance to the automotive industry.

** All quantities are stated in kg except for gases, which are stated in Nm^3.*

Appendix C – LCIA Results

Table 21: *LCIA results for each life cycle phase*

Impact category	EaMP	Manufacturing	Assembly	Use	End-of-life	Transportation
GWP	1.203	2.979	0.066	22.950	0.306	0.655
PMFP	0.004	0.008	1.41E-05	0.026	1.24E-05	0.001
FFP	0.435	1.021	0.038	10.459	0.001	0.199
WCP	0.010	0.023	0.001	0.067	1.60E-04	0.001
FETP	0.563	0.580	0.010	1.531	0.149	0.003
FEP	0.002	0.002	2.29E-06	0.003	1.67E-06	2.63E-05
HTPc	0.184	0.198	0.003	1.934	0.005	0.014
HTPnc	20.009	14.701	0.046	20.107	0.487	0.203
IRP	0.062	0.290	0.091	0.371	0.000	0.006
LOP	0.057	0.093	0.004	0.494	0.000	0.006
METP	0.676	0.790	0.013	1.955	0.194	0.005
MEP	9.48E-05	0.0002	2.64E-06	0.001	4.74E-06	1.44E-05
SOP	0.266	0.074	5.70E-05	0.128	2.86E-05	0.001
EOFP	0.004	0.008	5.08E-05	0.085	9.45E-05	0.003
HOFP	0.004	0.008	4.95E-05	0.079	9.41E-05	0.003
ODP	1.15E-06	1.35E-06	1.70E-08	5.77E-06	2.24E-07	7.36E-08
TAP	0.006	0.016	3.55E-05	0.064	3.83E-05	0.002
TETP	18.357	88.885	0.068	124.277	0.061	2.278

Note: All values are stated in equivalents for the respective impact category

Appendix D – GHG Accounting

Table 22: *Quantified GHG emissions for each life cycle phase*

GHG	EaMP	Manufacturing	Assembly	Use	End-of-life	Transportation
CO2	1.032	2.547	0.065	19.544	0.300	0.591
CH4	0.119	0.285	0.001	2.681	3.90E-04	0.051
N2O	0.012	0.028	3.92E-04	0.124	0.005	0.002
SF6	0.004	0.012	7.74E-06	0.018	1.80E-06	2.28E-04
PFCs	0.007	0.038	1.45E-06	0.022	3.22E-07	4.69E-05
HFCs	0.002	0.002	2.35E-06	0.002	1.69E-06	5.63E-05

Note: All values are stated in kg CO_2 equivalents

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

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