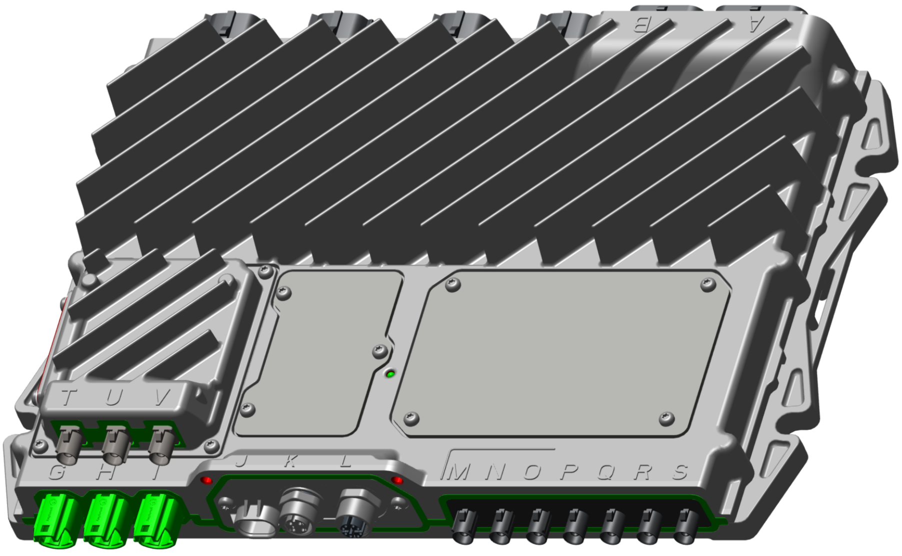

Life cycle assessment and environmental impact reduction strategies of an electronic control unit

Master's thesis in Industrial Ecology

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
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Cover:
An illustration of the Hydra, the product under study in this master thesis. Picture obtained from CPAC Systems with permission.

Gothenburg, Sweden 2024

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Summary

The electronics industry faces many challenges when it comes to sustainability. This study is therefore aimed at identifying the environmental hotspots in the cradle-to-gate life cycle of one of CPAC system's (CPAC) electronic control units (ECUs), the Hydra. The life cycle assessment (LCA) conducted on the Hydra showed that the main environmental impact of the product is related to the aluminium housing covering the assembled printed circuit board (PCBA), as well as the main PCBA itself. This is due to the energy intensive aluminium production and the amount of geochemically rare minerals, such as gold, used in the components on the PCBA. To help CPAC make informed decisions about possible emission reductions of the Hydra, a scenario analysis aiming at lowering the environmental impact of the product was conducted. Three scenarios were included in the analysis, which all focused on the aluminium housing, as it was an environmental hotspot as well as a component possible to change. First, the electricity mix for the aluminium production was changed from Chinese to Norwegian. Second, the primary aluminium ingots were entirely replaced by recycled aluminium scrap. Third, the material of the housing was changed to glass fibre reinforced plastic. All three scenarios resulted in impact reductions and provided knowledge that enabled the formulation of emission reduction strategies to minimize the overall environmental impact related to the Hydra. The following strategies can be of use for reducing the environmental impact of the Hydra: either a combination of increasing the share of renewable energy in the electricity mix for aluminium production and using recycled aluminium in the housing of the Hydra, or changing the material of the housing from aluminium to glass fibre reinforced plastic.

Keywords: Life Cycle Assessment (LCA), Electronic Control Unit (ECU), Printed circuit board (PCB), Global warming, Mineral resource scarcity

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Ellinor Kleiven and Sonja Henriksson, Gothenburg, May 2024.

Contents

List of Acronyms

Below are acronyms that have been used throughout this thesis, which are listed in alphabetical order:

Acronym	**Definition**
AOI	Automated optical inspection
BOM	Bill of materials
CF	Characterisation factor
CSI	Crustal scarcity indicator
CSPs	Crustal scarcity potentials
ECU	Electronic control unit
EMI	Electromagnetic interference
ESD	Electrostatic discharge
EQ	Equivalents
GHG	Greenhouse gas
IC	Integrated circuit
ICT	Integrated circuit testing
IMDS	International material data system
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LED	Light emitting diode
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LCI	Life cycle inventory
PCB	Printed circuit board
PCBA	Printed circuit board assembly
SMD	Surface mounted device
SMT	Surface mount technology
SPI	Solder paste inspection
SOP	Surplus ore potential
THT	Through hole technology

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1 Introduction

In today's society, environmental concerns have become increasingly pressing topics. With the publication of Intergovernmental Panel of Climate Change's (IPCC) reports on the progress of global warming, it has become apparent that it is time to take action, in order to keep global warming below 2°C (IPCC, 2023). According to IPCC (2023), the sectors contributing the most to greenhouse gas (GHG) emissions are the energy sector, the manufacturing industry, agriculture and other land use, as well as the transport sector. There is thus high pressure on these sectors to reduce their emissions, and thereby limit the effects of global warming.

The global north has historically contributed the most and is currently a major contributor of GHG emissions (IPCC, 2023). The industrialization and establishment of companies within different sectors has led to a steady increase in carbon emissions. The electronics industry is one industry that faces many challenges when it comes to sustainability. The industry accounted for 4% of global GHG emissions in 2022 (Al-Dhahir, 2022), and also faces many other problems such as the generation of hazardous waste (World Health Organization, 2023). These problems need to be tackled during the coming years to make the electronics industry more sustainable.

One company that contributes to the GHG emissions of the global north is Volvo Group. However, they have set ambitious targets to reduce their GHG emissions that are approved by the Science Based Targets Initiative, and are in line with the Paris Agreement (Volvo Group, 2022). These targets require the value chain across Volvo Group to have net-zero GHG emissions by 2050 throughout the whole life cycle, but Volvo Group is aiming to reach net zero emissions already by 2040.

CPAC Systems (onwards referred to as CPAC) is a Swedish-based company in the electronics industry that (among other things) manufactures electronic control units (ECUs) that are used in various applications, such as construction equipment, marine vessels and commercial vehicles (CPAC Systems, 2024a). CPAC is owned by Volvo Penta which is a part of Volvo Group, and hence the sustainability targets of Volvo Group also apply to CPAC. In order to improve the company's sustainability performance going forward, one important part is to have information regarding their products' current climate and other environmental impacts. This will help CPAC on their way towards net-zero emissions, by enabling efficient strategies to be formulated and pursued.

The aim of this study is to investigate the potential environmental impact associated with the Hydra, which is one of CPAC's ECUs. Furthermore, the aim is to propose strategies that can be used to reduce the environmental impact related to the Hydra. The proposed strategies are aiming to reduce the environmental impact of the Hydra by 30%, seen from raw material acquisition to storage of the finished product (cradle to gate), which is the main environmental target for CPAC.

2 Background

In this section, the company and the product under study are presented, as well as the life cycle assessment (LCA) framework.

2.1 CPAC and ECUs

The headquarters of CPAC are located in Gothenburg, Sweden, and the main production sites of their products are located in Poland and Slovakia. The company employs about 210 employees and its revenue in 2022 was about 1280 million SEK. CPAC is owned by Volvo Penta and therefore, companies of the Volvo Group are the primary clients of CPAC.

As mentioned, CPAC produce ECUs which is a control system that is used in different types of vehicles to control and regulate different functions (CPAC Systems, 2024b). An ECU is also defined in Hakak et al. (2023) as an embedded electronic system used to control different electrical systems in a vehicle, such as the system that controls the brakes of a car or the function of a combustion engine. Zalman (2017) explains the function of an ECU in greater detail, and suggests that it controls and monitors the functions of different vehicle systems. An ECU uses inputs of a predetermined set of physical variables such as temperature, voltage and rotational speed, which are collected from sensors placed in the vehicle. Control is achieved by varying the physical input values of the system that is to be controlled, which are related to certain physical properties in the vehicle. The sensors that collect input data convert the physical inputs to electrical signals, which are sent to the ECU. The ECU then processes these signals, and depending on their value, generate output signals to alter and control the current physical properties. This enables the ECU to control certain properties in systems of the vehicle, and thus maintain a desired function or specific set of properties.

2.2 The Hydra

The Hydra is the product under study. It is an ECU designed and produced by CPAC, and is developed to be more multi-functional than their previous ECUs (CPAC Systems, 2024b). The Hydra combines multiple control units in one, making it more efficient than previous ECUs developed by CPAC, functioning as a central unit and a productivity network hub simultaneously. It can for example be installed in vehicles used for agriculture, forestry, construction, material handling and mining. The Hydra was launched in 2023, together with software to improve efficiency and productivity for a wide range of machines operating with the Hydra platform.

The weight of the product is approximately 2450 g and it contains several different components and materials (CPAC Systems, 2024b). The main parts are the housing and the assembled printed circuit board (PCBA), of which the PCBA is the most complex. The unit has Wi-Fi and Bluetooth connections, a GPS and satellite communication module, and it supports up to four touch screens and cameras enabling a 360° view. The Hydra uses a three-processor solution, with one Android processor for productivity and experience applications, one embedded processor for vehicle integration and one processor for power handling. The housing is made of aluminium and is designed so that the ECU is passively ventilated. The main unit consists of a large housing containing the PCBA, but in addition to this there are also three separate modules that can be added on top of the main housing. Generally, only one of these modules is included in the unit, consisting of a modem. The modem is added separately to the unit to enable development of the separate part without demanding changes to the PCBA, such as updating from using 4G to 5G. This study will include the main PCBA and its housing, as well as the modem-module and its housing. The two other separate modules will be excluded from this study, as they are not currently in use. For an illustration of the unit and its main parts, see Figure 1.

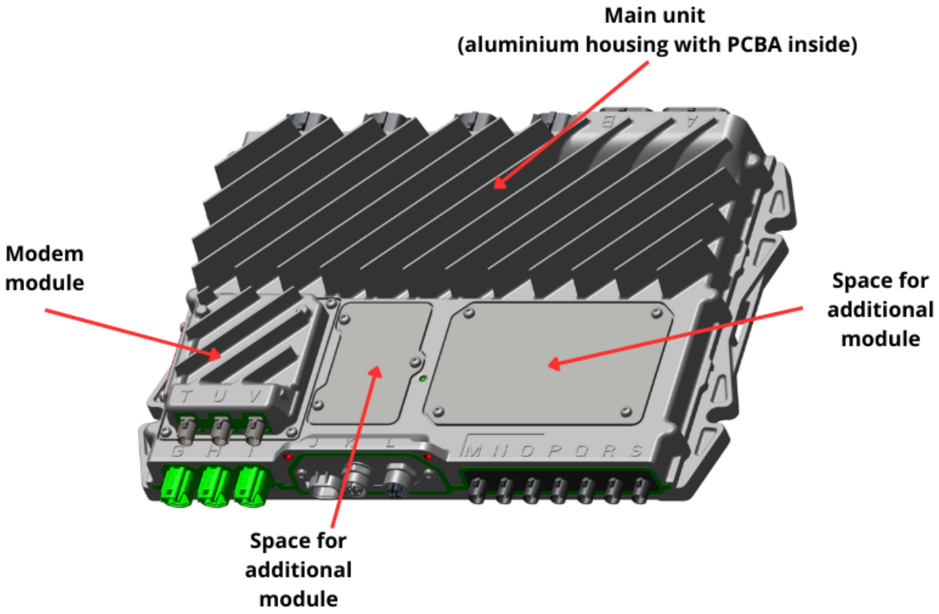

Figure 1: Illustration of the Hydra and its different parts. Each major component of the unit is labeled in the illustration with a red arrow and a description. The figure is produced by the authors, with permission from CPAC.

2.3 Life cycle assessment framework

LCA is a tool that can be used to analyze the environmental impact of products and services, from which the results can be used to address the environmental hotspots in product systems (Baumann & Tillman, 2004). The LCA framework (illustrated in Figure 2) is an iterative procedure consisting of a goal and scope definition, an inventory analysis, an impact assessment and an interpretation. The LCA methodology follows general guidelines described in the International Organization for Standardization (ISO) 14040 series (14040 - 14044) (Baumann & Tillman, 2004).

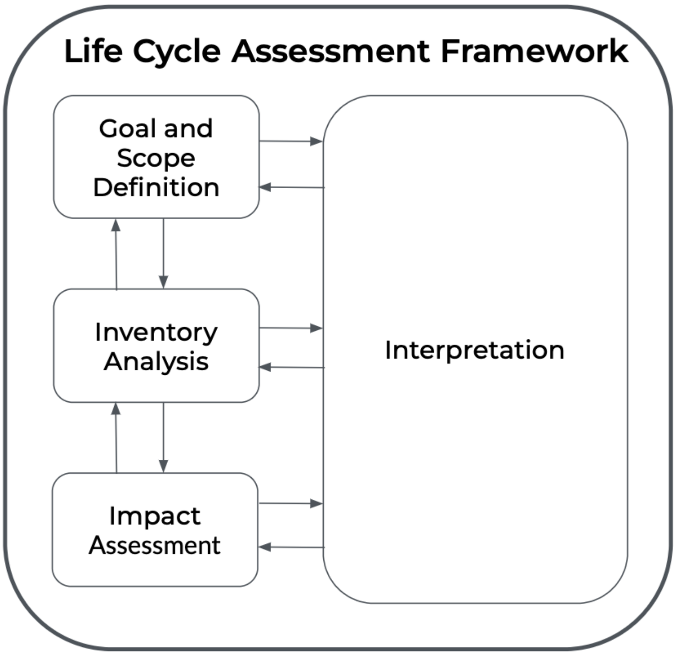

Figure 2: LCA framework, as described by Rebitzer et al. (2004) Figure produced by the authors.

2.3.1 Goal and scope definition

In the first part of the LCA the goal of the study is defined, including the intended application and audience, as well as the motivation behind why the study is carried out (Baumann & Tillman, 2004). Further methodological choices are then made based on the goal of the study. Hence, it is useful to define a rather clear and specific goal of the study. The scope should include information about the specific product or process options to be studied, and it is also helpful to create a general flowchart of the system for the intended product. One important step in the scope definition is the definition of the functional unit of the study, which should be quantitative and correspond to a reference flow. The functional unit should describe the function of the product under study. In addition, the scope definition should include other aspects, such as the system boundaries (including boundaries in relation to the natural- and technical system), geographical scope, time horizon and impact categories. This part of the LCA should also explain whether an attributional or consequential LCA is performed (Finnveden et al., 2009). An attributional LCA aims to describe all environmentally relevant physical flows to and from a life cycle, while a consequential LCA aims to describe how these flows change as a result of decisions.

2.3.2 Inventory analysis

In the life cycle inventory (LCI) analysis, all environmentally relevant flows are considered in a flow model of the technical system according to the system boundaries identified in the goal and scope definition (Baumann & Tillman, 2004). The flowchart should be more detailed than the initial general flowchart, including all modeled activities and the flows between them. The LCI also includes the most time-consuming step of the LCA - the data collection - where data of all inputs and outputs are gathered, such as energy requirements, raw materials needed and the emissions related to each process. When both the flowchart and data collection are finalized, the calculation procedure can be initiated. This is where the total resource extraction from the environment and emissions to the environment for the whole product system (referred to as elementary flows) are calculated, which can be done using LCA software when conducting a study of a larger system.

2.3.3 Impact assessment

From the elementary flows calculated in the LCI, the life cycle impact assessment (LCIA) is conducted to assess the environmental impacts associated with the flows (Baumann & Tillman, 2004). The purpose of this is to make the results easier to understand, interpret and enable a comparison. This is done by first conducting a classification, where the flows from the inventory analysis are categorized into the impact categories selected in the scope definition. The classification is followed by characterisation, where equivalency factors (called characterisation factors (CFs)) are applied to calculate the magnitude of the environmental impacts per category and per functional unit. There are also additional elements that can be applied, such as normalization, grouping and weighting.

There are ready-made LCIA methods that can be applied, which consist of pre-calculated impact pathways for midpoint and/or endpoint CFs (Huijbregts et al., 2017). One example of an established LCIA method is ReCiPe 2016, which includes 17 midpoint categories and three endpoint categories, as well as CFs for these. A midpoint impact category is located in the middle of the impact pathway (or cause-effect chain) for each of the elementary flows. An endpoint impact category is located towards the end of the pathway and is more aggregated, typically reflecting the damage to human health, ecosystem quality or resource scarcity. Using endpoint impact categories facilitates the interpretation of the results, while using midpoint impact categories implies lower uncertainty in the LCIA. All the midpoint impact category names included in the ReCiPe method are listed in Table 1 together with their CFs and units of measurement, and an overview of the ReCiPe 2016 method is shown in Figure 3.

Table 1: Midpoint impact categories included in the ReCiPe 2016 method, and their CFs and units (Huijbregts et al., 2017).

Impact category	**Characterisation factor**	**Unit of measurement**
Particulate matter	Particulate matter formation potential	*kg PM2.5-eq to air*
Trop. ozone formation (human)	Photochemical oxidant formation potential	*kg NOx-eq to air*
Ionizing radiation	Ionizing radiation potential	*kBq Co-60-eq to air*
Strat. ozone depletion	Ozone depletion potential	*kg CFC-11 eq to air*
Human toxicity (cancer)	Human toxicity potential	*kg 1,4-DCB-eq to urban air*
Human toxicity (non-cancer)	Human toxicity potential	*kg 1,4-DCB-eq to urban air*
Global warming	Global warming potential	*kg* CO_2*-eq to air*
Water use	Water consumption potential	m^3 *water-eq consumed*
Freshwater ecotoxicity	Freshwater ecotoxicity potential	*kg 1,4-DCB-eq to freshwater*
Freshwater eutrophication	Freshwater eutrophication potential	*kg P-eq to freshwater*
Trop. ozone (ecosystems)	Photochemical oxidant formation Potential	*kg NOx-eq to air*
Terrestrial ecotoxicity	Terrestrial ecotoxicity potential	*kg 1,4-DCB-eq to marine water*
Terrestrial acidification	Terrestrial acidification potential	*kg SO2-eq to air*
Land use/transformation	Agricultural land occupation potential	m^2 *x yr annual cropland-eq*
Marine ecotoxicity	Water consumption potential	*kg 1,4-DCB-eq to marine water*
Mineral resources	Surplus ore potential	*kg Cu-eq*
Fossil resources	Fossil fuel potential	*kg oil-eq*

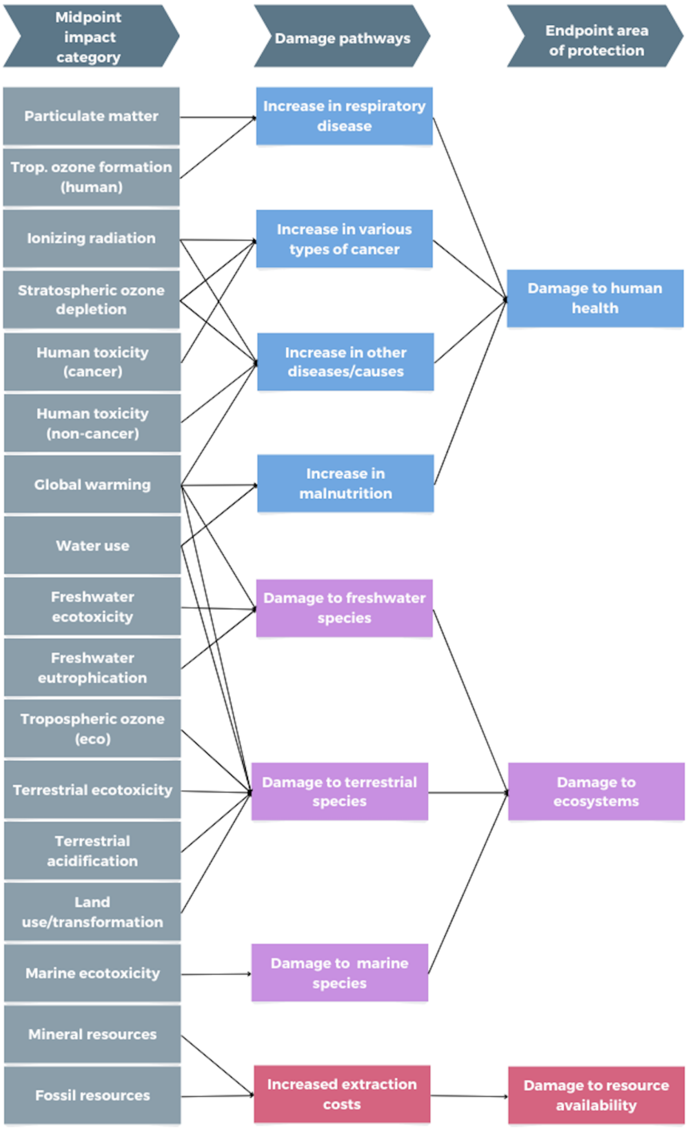

Figure 3: Overview of the ReCiPe 2016 method, as described by Huijbregts et al. (2017). Figure produced by the authors.

In addition, the crustal scarcity indicator (CSI) is another impact indicator for mineral resource scarcity, which complements the surplus ore potential (SOP), in the ReCiPe 2016 method. The CSI was developed by Arvidsson et al. (2020), and uses a different model as compared to SOP. It is a midpoint-level impact method that uses CFs called crustal scarcity potentials (CSPs), which are measured in kg silicon equivalents (eq) per kg element. These potentials are based on average crustal concentrations of different minerals and metals, which is a measurement of the geochemical rarity of different elements and thus a proxy for potential long-term global elemental scarcity. The

CF SOP, included in the ReCiPe 2016 impact assessment method, measures the additional amount of ore needed to obtain the same quantity of metal as ore grades decline due to increased extraction (Huijbregts et al., 2017). However, SOP includes time-sensitive parameters and procedures, such as economic allocation within the CFs, making it more temporally uncertain. Such parameters and procedures are avoided in the CSI, which gives this impact assessment indicator a more long-term scarcity perspective compared to the SOP (Arvidsson et al., 2020).

2.3.4 Interpretation

In the final step of the LCA, the environmental hotspots are identified and the results are analyzed in order to draw conclusions (Baumann & Tillman, 2004). In the LCA terminology, this is called interpretation. When the aim is to identify the most polluting activities in the life cycle, a dominance analysis can be performed. A similar approach is a contribution analysis, which instead can be used to identify which environmental loads contribute most to the total impact. To analyze the robustness of the results, either an uncertainty, a sensitivity or a variation analysis can be conducted (Baumann & Tillman, 2004). The uncertainty analysis is used to analyze the effect of imprecise data to give an estimation of the range in which the environmental performance lies. This can be used when the data for one parameter can vary over an interval, such as different yields of a chemical process. When dealing with uncertain data, a sensitivity analysis can be performed instead by systematically altering the input parameters. Thereby, the parameters that influence the results the most can be identified and more accurate data can be gathered for these parameters. Additionally, a variation analysis can be conducted to investigate how changes in specific parts of the life cycle model alter the results.

2.4 Previous studies

This study is a contribution to a growing field of LCAs on electronics, and specifically on ECUs. Through a literature review, previous studies, which also conducted LCAs on ECUs, were identified. A master thesis written by Suyang and Jingjing (2010) performed an LCA from cradle to grave on an ECU produced by the company Autoliv, using 1 ECU as the functional unit for the study. This study revealed that the material production phase was the primary contributor to the environmental impact of the unit under study, and that the use phase also had a significant environmental impact. Another master thesis, performed by Ashok and Kanni (2023), studied the environmental impact of 1 ECU produced at the company Scania through a cradle-to-gate LCA and a multi-criteria decision analysis. This LCA concluded that the manufacturing of the printed circuit board (PCB) and the integrated circuits (ICs) contribute the most to the impact of the ECU, due to their energy intensive production processes. However, the two products analyzed in these studies are not completely comparable to the Hydra, due to the Hydra being more complex and larger than the ECUs studied in these studies.

3 Goal and scope

In this section, the goal and scope of this study is presented. This includes the goal definition, functional unit, system boundaries, data requirements, chosen impact categories, assumptions, procedural aspects and a simplified initial flowchart of the system.

3.1 Goal definition

The goal of this study is equivalent to the two aims described in Section 1. Based on the goal of this study, two research questions were formulated:

- What are the environmental hotspots in the life cycle of the Hydra from cradle to gate?
- Which potential strategies can reduce the environmental impacts of the Hydra by 30%?

The intended audience of this study is mainly the company that produces the Hydra, since it provides improvement potential regarding its environmental performance. CPAC can consider this information when the product is re-designed or when evaluating new designs for similar products, to decrease their environmental impacts. In addition, other producers and users of ECUs may find this study useful and insightful. Furthermore, the study is a contribution to the growing scientific literature on LCAs of electronics and ECUs, and should thus be of relevance to LCA researchers and practitioners focusing on electronics (Ashok & Kanni, 2023; Suyang & Jingjing, 2010).

3.2 Scope of the study

Regarding technical boundaries, a cradle-to-gate LCA is considered. Thus, the life cycle under study starts with raw material acquisition and ends with the finished ECU placed in CPAC's storage facility, located in Gothenburg. The data availability of the use phase and end-of-life phase is low and CPAC's potential to influence the environmental impacts of these phases is limited. Therefore, as one of the first studies that this company does on the environmental impacts of its products, this study focuses on raw material extraction and the production, which are the life cycle phases that the company has a high possibility to influence. The LCA considered is also attributional, as it is performed to identify the environmental impact associated with a certain product.

In terms of multifunctionality, none of the main processes developed within this study generate co-products, so no specific choice of allocation method is made in this study. However, the upstream datasets from the Ecoinvent database might contain pre-defined allocation procedures, which are accepted as is in this study.

3.2.1 Functional unit

The functional unit of the system under study is *1 Hydra*, as the Hydra is a product that provides several different functions. Furthermore, this enables the investigation of the potential environmental impacts of all components included in the Hydra, which is an important part of the goal of this study. The chosen reference flow is shown in the system flowchart (Figure 4), which represents the flow of one stored Hydra out of the system. The functional unit and reference flow are thus effectively equivalent in this study.

3.2.2 System boundaries

The technical boundary of this system encloses all the relevant steps for the production of the Hydra and all its components, from raw material acquisition to CPAC's storage facility, as shown in the flowchart (Figure 4).

CPAC outsources the assembly of the Hydra to a factory located in Slovakia and the finished products are thereafter transported to Sweden for storage. However, the components of the Hydra are produced in countries all over the world and then transported to Slovakia. Thus, the geographical boundary for the system includes all countries of origin for the components of the Hydra, as well as Slovakia and Sweden. However, as specific information about country of origin for each component is unknown, global averages are used to enable calculation of the environmental impacts. Thus, in the component approximations presented in Appendix A1, unless a specific country is stated, global average data has been used. The time horizon is approximately the present, as the LCA represents the current production and utilize the most recent available data. This is thus not a prospective nor a historical LCA study (Arvidsson et al., 2024).

3.2.3 Impact categories

To assess the potential environmental impacts of this product, all impact categories in the impact assessment method ReCiPe 2016 are included, as shown in Table 1. The reason for this is that the nature of the environmental impact is unknown, and it is therefore interesting to investigate a wide range of impacts. After discussions with CPAC, the following impact categories were selected for a more in-depth analysis: *global warming*, *fossil resource scarcity*, *particulate matter formation*, *land use* and *water use*. In addition, the impact category *mineral resource scarcity* is assessed by two different impact indicators, the SOP and CSI. These categories were chosen for a more in-depth analysis as they are of the greatest interest for CPAC. The results from the other impact categories included in the ReCiPe 2016 method are provided in Appendix A3. All calculations are performed using the software OpenLCA.

3.2.4 Data requirements

To investigate the environmental impacts of the Hydra, there is need for a large amount of data about the different raw materials and components, as well as data from the different production steps. Since this LCA is performed on a specific product for a specific company, internal company data about this product is prioritized. For this purpose, the product's bill of materials (BOM) is considered, as well as information gathered about the material composition of each component from the International Material Data System (IMDS) for the Hydra.

It is important to principally use specific data in order to produce accurate results. However, not all necessary data is available through internal documents or from coworkers at CPAC. For example, not all suppliers of components for the Hydra provide sufficient data about their production. Therefore, the internal company data is supplemented with external data from datasets in the Ecoinvent database, as well as data in the scientific literature. For example, to approximate the screws used in the Hydra, an approximation developed by Oliveira et al. (2022) was used.

3.2.5 Assumptions

Several assumptions are made in order to calculate the environmental impact of the Hydra. Below is a list of more important assumptions:

- Most of the components in the Hydra are approximated using existing datasets in Ecoinvent. These datasets do not exactly match the composition and production of these components, but the level of detail is deemed sufficient for the scale of this study. The actual masses of the components in the Hydra are considered, and in cases where the material composition differs notably, the composition is altered to better match the component in question.
- For several components, no suitable approximations have been found in Ecoinvent. For these components, own approximations are made by combining existing datasets in Ecoinvent and data from literature review to generate suitable proxy datasets. This is true for the aluminium housing, connectors, gaskets, metal parts for hydra assembly and screws.
- Some production processes are missing energy inputs, and are thus only based on the materials used to create the product in question. These processes are therefore optimistically approximated and could in reality have a higher environmental impact. However, the products for which this is an issue constitute a minor share of the final product, so this approximation is therefore deemed appropriate as it should not majorly affect the final result.

3.2.6 Flowchart

Figure 4 shows a system flowchart with the main processes in the cradle-to-gate life cycle of the Hydra. The reference flow, marked in red, represents the specific product flow of 1 Hydra ready for transport, to which all the inputs and outputs of the system are related. This flowchart is more detailed than an initial flowchart, and therefore includes all processes and components within the part of the Hydra life cycle under study: the raw material extraction, the processing of materials into components, the assembly of the PCBA, the assembly of the Hydra in the factory in Slovakia, as well as the transport of the finished Hydra to CPAC's storage facility in Gothenburg. In Figure 4, each blue box represents the production process of a component required for the assembly of the product, or a process required to produce the final product. The assembly of the main PCBA requires the inflow of the components illustrated in the top of the figure, and the assembly of the Hydra requires the inflow of the PCBA, as well as all additional components illustrated in the left part of the figure.

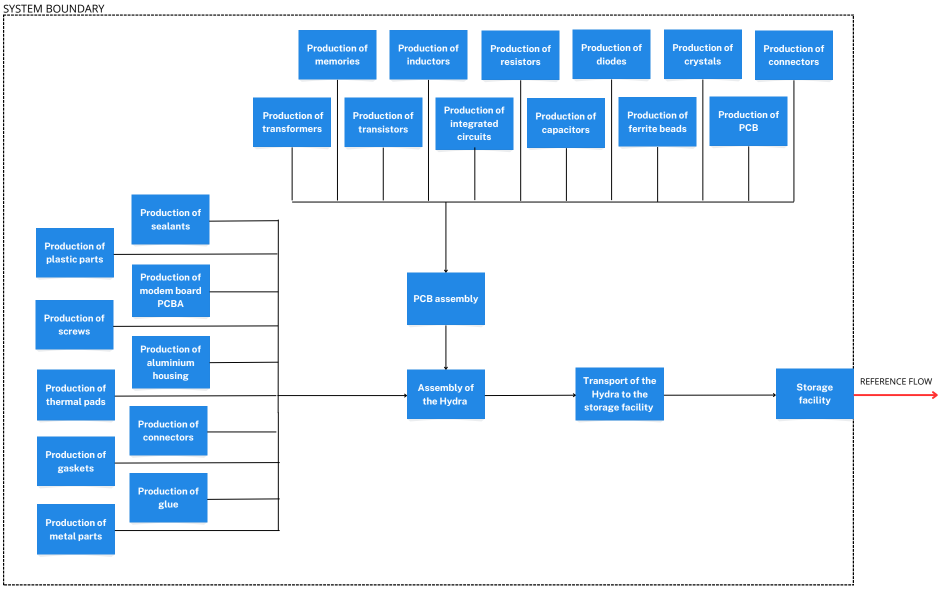

Figure 4: Flowchart providing a detailed overview of the life cycle for the Hydra, from cradle to gate. Each blue box represents the production of a component or a process step required to produce the final product, and the red arrow represents the reference flow out of the system.

4 Inventory analysis

The inventory analysis includes a description of the data collection procedure, as well as a description of all processes and components included in the cradle to gate life cycle of the studied product. For the data collection, the primary source of data is IMDS, which is a website that contains information about the material composition of all components in the product under study. However, using this information for LCA purposes requires additional data processing. First, all the components included in the BOM of the Hydra have been listed and categorised based on their function. This categorisation has been made to allow a simplified calculation. Then, the material composition of each component has been analyzed in IMDS, allowing the components to be matched with suitable approximations available in Ecoinvent, based on the components' material composition, function and size. This match is verified by a hardware technician at CPAC, to ensure that no components are incorrectly categorised or approximated. It can be noted that the material compositions of the components are not a complete match with the corresponding processes in Ecoinvent. However, most of the matches are deemed reasonable approximations for the scope of this study. To improve the accuracy of the approximations, the mass of the actual components is used, and some of the processes from Ecoinvent are partly modified to better suit the actual components, as described in more detail in Appendix A1. These modifications are applied to components with complex compositions, such as the connectors.

For components with no matching approximation in Ecoinvent, own approximations, presented in Appendix A2, are performed by studying the material composition and production processes for the components. Data has been compiled from different datasets available in Ecoinvent, and from other studies that have made approximations of similar parts.

Besides the modeling of the components included in the final product, there is also a need for modeling the production processes used to assemble the PCBA and the Hydra. For the modeling of these processes, information is supplied by CPAC on which steps are included in the processes, and an approximation is made using internal company data, scientific literature, and the alteration of datasets in Ecoinvent. These constructed unit processes are also presented in Appendix A2.

Presented in Figure 5 is an overview of the data sources used for each component and process included in the system under study. Components and processes marked with a purple box are approximated using solely unaltered existing datasets from Ecoinvent. Components and processes marked with a green box are modeled by the authors to create approximations truer to reality by altering and combining existing datasets in Ecoinvent, and complementing data from similar studies.

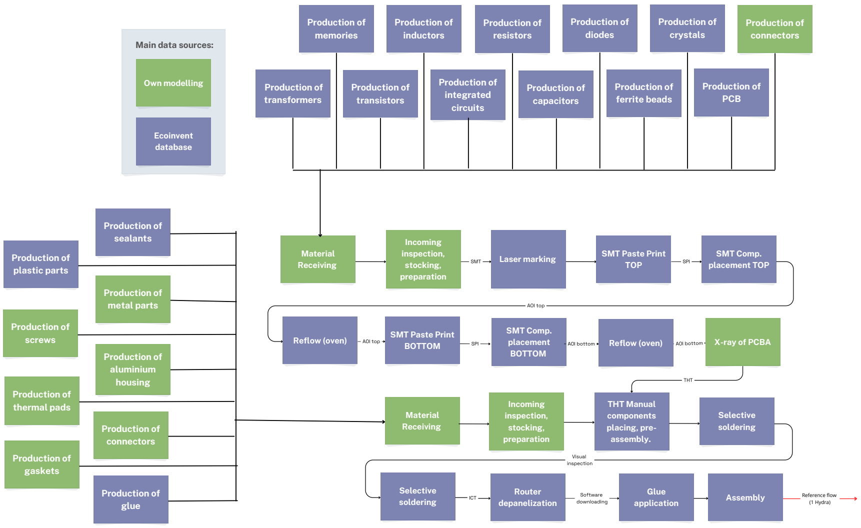

Figure 5: Flowchart providing an overview of the system under study, including all the components and the processing steps of the assembly of the Hydra, with main data sources shown.

4.1 Ecoinvent proxies

The Hydra is composed of multiple components, many of which, for the purpose of this study, are approximated using datasets available in Ecoinvent. This applies for the capacitors, diodes, inductors, ICs, plastic parts for hydra assembly, PCBs, resistors, sealants, transistors and transformers. In Appendix A1, descriptions of the approximations and datasets used for each of these components are presented. The components presented in this appendix are represented by the purple boxes in Figure 5.

4.2 Own modeling of components and processes

Not all components of the Hydra had adequate approximations available in Ecoinvent. Therefore, the inventory has been supplemented with own modeling for some specific components, such as the aluminium housing, connectors, screws and other metal parts used for the assembly of the Hydra. How these components have been modeled is described in more detail below. There are also two processes used to assemble the main PCBA and the Hydra, which have been modeled by the authors, and are described in further detail in this section. The components and processes presented in this section are represented by the green boxes in Figure 5.

4.2.1 Assembly of PCB

The assembly of the main PCBA for the Hydra is presented as a flowchart in Figure 5. The complete designed unit process for this step of the Hydra life cycle is illustrated in Table 9 in Appendix A2, and the unit process designed for the production process of the PCBA is shown in Table 10. The mounting of all components onto the PCB in the Hydra is done using surface mount technology (SMT) and through hole technology (THT) in a factory in Slovakia. All individual components are transported to the factory from the component suppliers. The smaller electrical components are mainly packaged using tape and reel, while the moisture sensitive components such as the processors are packaged in electrostatic discharge (ESD) protected plastic bags to avoid moisture exposure. To approximate the waste from these packaging materials, it has after discussions with CPAC been assumed that all components are delivered on plastic tape and reels, and that each tape and reel contains 3000 components. This approximation, together with the total number of components on the Hydra, and the weight and material composition of a tape and reel, gave an amount of plastic in grams that is assumed to be generated as waste for each Hydra. The corresponding amount of material waste has been added as a waste to the process modeled in Ecoinvent.

In order to approximate the energy use in each step of the assembly process, a step-by-step process chart has been supplied by CPAC, which shows each step of the assembly process along with the time required for each step to produce one Hydra. For each step, the machinery has been identified with help from the production facility in Slovakia, and by using the time schedule provided by CPAC and the energy consumption of each machine in each step the energy requirement was calculated.

In the first step of the assembly process, the materials are received for inspection, stocking and preparation. This step was approximated as a computer, to estimate the environmental impact of the stocking and marking system that is used to keep inventory of the received components. A dataset for computer use in Ecoinvent was used to represent this process.

The PCB is then placed in the first step of the manufacturing line, where it passes through a machine that performs laser marking. In this step, each PCB is uniquely marked to enable identification and tracking through the assembly process, as well as through its distribution and operation. Based on information regarding the machine used in the factory, the dataset *laser machining, metal, with* CO_2*-laser* from Ecoinvent was used for this process (Table 10).

Afterwards, the PCB is subject to SMT, in which solder paste is applied where components are to be placed to enable attachment of the components. The components themselves are placed on the board using a pick and place robot, which picks up the components from a tape and reel and places them on the PCB where the solder paste has been applied. Then, the PCB is heated in a re-flow oven, to melt the solder paste and thereby attach all components to the PCB. The PCBA used in the Hydra has components on both its sides, and thus this process is repeated for the bottom of the PCB. After each step of the SMT process, the board is subject to automated inspection, either solder paste inspection (SPI) or automated optical inspection (AOI) to ensure that all components have been placed correctly and that the PCB can progress to the next step of the assembly process. For the SMT process, there is a suitable dataset available in Ecoinvent that has been used. This dataset was thoroughly analyzed and compared to the actual process to ensure it was an adequate approximation. The dataset for *surface mounting, using lead-free solder paste*, in the Ecoinvent database includes the solder material used, the infrastructure for the mounting facility, as well as the mounting activity itself. The dataset for the mounting facility for SMT is comprised of five component placing machines, one inspection device and one reflow oven. The SMT process used by CPAC is, however, slightly different from the SMT dataset in Ecoinvent, and this dataset was therefore altered. Since the PCB passes through the SMT process twice to attach components to both the top and the bottom of the PCB, this had to be adjusted for by counting this process twice. The process under study also has more inspection steps than the dataset in Ecoinvent - after the re-flow oven, 20% of the PCBs are subjected to an X-ray inspection to ensure that the components have been mounted correctly. This step is energy demanding, and not included in the SMT-dataset in Ecoinvent. There is no suitable approximation of an X-ray in Ecoinvent, so this step had to be modeled anew. Using the time schedule provided by CPAC and the energy consumption of the X-ray machine used in the factory in Slovakia, a process was modeled in Ecoinvent that included the energy consumption and a process for machine production. The unit processes used to approximate this X-ray process are also shown in Table 10 in Appendix A2.

After the SMT, the PCB progresses to the next step of the assembly, namely the THT of larger components. This process includes manual placing of components on the PCB, selective soldering and visual inspection. In Ecoinvent there is no dataset available that represents the specific mounting techniques used to assemble the PCBA. Existing datasets consumed more energy and had higher emissions than the process in question. Therefore, this process was modeled using the necessary material inputs such as flux and solder paste, a computer for manual placement and inspection, a process for PCB mounting facility, and the necessary inputs of electricity and nitrogen, based on the specific THT machine used in the factory in Slovakia.

When the PCB has passed through the THT step, it is subject to integrated circuit testing (ICT), which is a test of the functionality of the PCBA that can detect whether the circuits in the PCBA work properly. This step is approximated as a computer used for a certain amount of time. The next step is the router depanelization, where the PCBA is cut out from its PCB frame. This step is modeled using the electricity consumption of the machine in the factory in Slovakia, along with a process for machine production. This step also generates waste in the form of left over PCB, which has been included in the modeled process as waste electronics. The final step of the PCBA process is software downloading, where the intended software of the ECU is downloaded to the finished PCBA. This step is also approximated as a computer used for a certain amount of time.

As mentioned in Section 2.2, the Hydra contains two different PCBA, one large that is the main PCBA in the unit, and a smaller PCBA that is included in the modem that is attached to the top of the Hydra. The assembly process for the smaller modem PCBA is the same as the assembly process for the main PCBA, which has been described above. The assembly of the modem PCBA is therefore modeled in the same way as the assembly of the main PCBA, but adjusted to match the production times for each step of the modem process, and the size of the modem.

4.2.2 Aluminium housing

Compared to many other parts present in the Hydra, CPAC has more detailed information about the aluminium housing, such as the country of origin and the production processes. The aluminium housing is mainly produced in China, using Chinese aluminium, and the process starts with raw material extraction of bauxite and conversion of this material to primary aluminium ingots. Through literature review, the article by Nunez and Jones (2016) was found, which shows the different steps of aluminium ingot production. This article was used to find relevant processes in Ecoinvent for this step, and a dataset for primary aluminium ingot production using Chinese data was selected. Compared with the aluminium composition in the dataset in Ecoinvent, the aluminium used in the housing of the Hydra contains more silicon. The share of silicon was altered accordingly.

The next step of the housing production is the casting of the aluminium ingots to the desired shape. This process is also done in China, using high-pressure die casting. Ecoinvent does not have any datasets for this process, only for other casting processes that are more energy demanding. Therefore, a new process was created by combining the dataset *aluminium casting facility construction* with a process for electricity consumption, to better match the environmental footprint of this production step. All the energy providers and locations were modeled to be Chinese. A value of the electricity consumption for high pressure die casting from Herrmann et al. (2016) was used. The resulting unit process is shown in Table 4 in Appendix A2.

After the housing has obtained the desired shape, it is surface treated using passivation, to get the desired finish. For this process, a matching dataset in Ecoinvent for anodising of aluminium was chosen, based on Chinese data. The housing is then transported to Sweden, where it undergoes metal working to create holes for screws and other desired features. To represent this process, a metal working process with European data in Ecoinvent was selected. Finally, the housing is transported to the production facility in Slovakia, where it is assembled with all other parts into the final product. For the transport from China to Sweden, it is assumed that the housing is transported by cargo ship, and for the transport from Sweden to Slovakia it is assumed that the housing is transported by truck. These assumptions, along with the assumed transport distances, are based on information provided by CPAC.

For each of the processes performed in China, a Chinese electricity mix for the Chinese aluminium industry has been used. This electricity mix is made from 90% coal and 10% hydro power, according to the process *market for electricity, high voltage, aluminium industry, China* available in Ecoinvent. The entire unit process designed and used to approximate the aluminium housing can be found in Table 3 in Appendix A2.

4.2.3 Connectors

There are several kinds of connectors present in the Hydra, which are used to connect the Hydra to for example different screens in the vehicle in which it is mounted after assembly. The connectors have been approximated as four different approximations in Ecoinvent, based on their material composition: IC logic type, glass fibre reinforced plastic, peripheral type electric connector and peripheral component interconnect buss connector. The categorisation of the connectors into each of these four categories was made together with a hardware technician at CPAC. For some connectors, the material composition of these approximations has been altered to better match the material composition of the connectors present in the Hydra, by for example decreasing the amount of gold. In these cases, an average amount of gold has been calculated using the material information for all relevant components in IMDS. The original amount of gold was 2.1 g gold/kg connectors, and this was reduced to 0.97 g gold/kg connectors. The missing amount (2.1-0.97 kg/connector) was compensated for by increasing the plastic input in Ecoinvent, leading to a better match with the amount of plastic in the connectors present in the Hydra.

4.2.4 Gaskets

There are different gaskets in the Hydra, which are components made of rubber used to seal gaps between metal surfaces, to prevent leakage between them (CPAC Systems, 2024b). Most gaskets are made of silicone, and approximated using a dataset for silicone product production from Ecoinvent.

There is also another type of gasket included in the Hydra called electromagnetic interference (EMI) shielding gasket, which is more complex and not matched by any dataset in Ecoinvent. This type of gasket is used to shield components in the Hydra from EMI (CPAC Systems, 2024b). It contains a polyurethane foam core, which is clad with polyester fabric, plated with copper and nickel plating, and is produced differently to silicone gaskets. EMI shielding gaskets were therefore modeled using datasets corresponding to the material inputs listed in IMDS. A literature study was performed to investigate what the production process for this type of gasket looked like, but no inventory data for the production could be found. After consulting the hardware technician, these gaskets were considered to be of secondary importance for the environmental impact of the Hydra, as they comprise less than a gram of the total weight of the Hydra and are not made from materials with a known high environmental impacts. Therefore, a choice was made to only model EMI shielding gasket based on its material inputs. The resulting unit process approximation is shown in Table 5 in Appendix A2.

4.2.5 Metal parts for Hydra assembly

The metal parts for Hydra assembly are a set of small metal components that are attached to the Hydra in the final assembly step, such as small shields that shield important electrical components from electromagnetic radiation, copper tape and washers. There were not any flows or processes in Ecoinvent that could be used as direct proxies for these components, and their material composition and production were quite simple. Therefore, these components were modeled as the material input of the materials they are composed of, and processes such as metal working were added to consider the energy use during the production of these components. The unit processes used to approximate the different metal parts included in the Hydra are shown in Tables 15 - 18 in Appendix A2.

4.2.6 Screws

Several different kinds of screws are used to assemble the different parts of the Hydra. There was no proxy dataset for screw production in Ecoinvent, and therefore own approximations had to be made. Through literature review, a previous study was found that presents an approximation of the production of a screw in Ecoinvent (Oliveira et al., 2022). The approximation included information about what datasets in Ecoinvent that could be combined to represent the production of a screw. This approximation was used to model the screws present in the Hydra, by combining the set of Ecoinvent processes recommended in the study and the different material inputs that matched the material composition of the screws used in the assembly of the Hydra. The resulting unit process approximations for the screws included in the Hydra are shown in Tables 11 - 14 in Appendix A2.

4.2.7 Assembly of the Hydra

In order to produce the finished ECU, all the parts included in the Hydra have to be assembled. This process is also performed in the factory in Slovakia, using two steps, glue application and assembly. The assembly of the finished Hydra is performed manually, with the use of different tools and computers. This process is therefore approximated as computers used for a certain amount of time. The resulting complete unit process is shown in Table 6 in Appendix A2, and the unit process designed to represent the production process for the assembly of the Hydra is shown in Table 7.

5 Impact assessment

In this section, the LCIA is presented. The impacts are presented for the cradle-to-gate life cycle of one Hydra, with three different graphs for each impact category.

The first graph shows an overview of the environmental impact of all the major components within the product life cycle. This includes one bar for the total environmental impact for the Hydra, one for the aluminium housing, one for the parts required for the assembly of the Hydra (aside from the PCBAs and the aluminium housing), one for PCBA Main, one for the modem PCBA, one for the assembly processes, i.e. the assembly of the PCBA as well as the final product, and finally one for the transportation of the finished Hydra to the storage facility in Gothenburg.

The second graph shows the environmental impact from each of the steps in the production of the aluminium housing. This includes the production of primary aluminium ingots, high pressure die-casting, metalworking, anodising and transport of the aluminium housing from China to Sweden for the metalworking and then from Sweden to the factory in Slovakia.

The third graph for each impact category shows the environmental impact from each of the component categories used in PCBA Main, as described in Appendix A1.

5.1 Global warming

The impact on global warming for the major parts of the Hydra are shown in Figure 6. As can be seen in the figure, the aluminium housing is contributing the most to the global warming impact, with the PCBA main also contributing substantially compared to the other parts of the Hydra. In total, one Hydra is responsible for emitting 154 kg CO_2-eq during its cradle-to-gate life cycle.

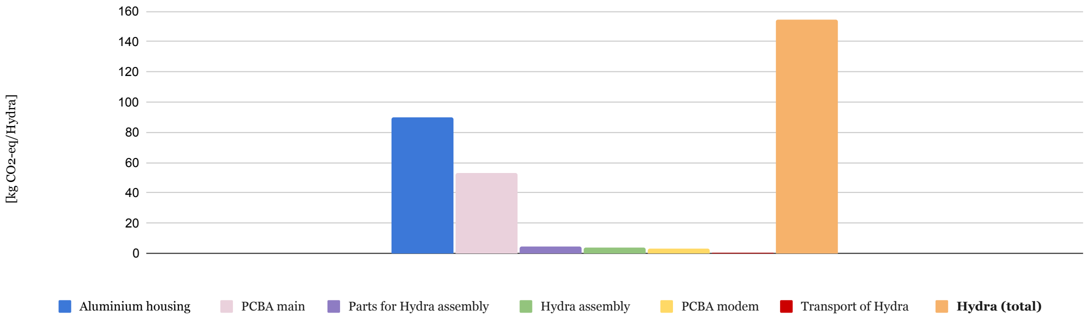

Figure 6: Global warming of the major components of the Hydra, as well as its assembly and transport.

Looking more closely at the two parts, Figure 7 shows the global warming impact related to each part of the aluminium housing production, while Figure 8 shows the impact related to each component on the PCBAs. For the aluminium housing, the primary ingot production is contributing the most to this impact category, followed by the die casting and metalworking.

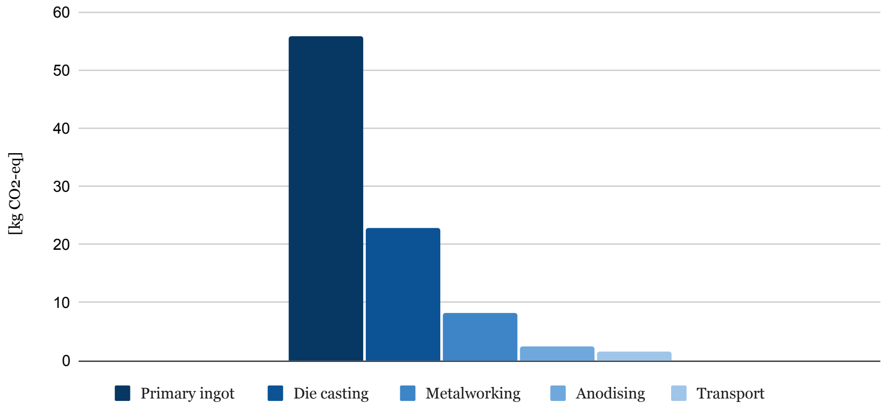

Figure 7: Global warming of the different phases of the aluminium-production, for producing the aluminium housing for one Hydra.

For PCBA Main, the component category contributing the most is the ICs, followed by the connectors, processors and PCB. Looking more closely at the ICs, it is the logic-type ICs that contribute to almost the entire impact of the ICs, while the impact of the memory-type ICs is much smaller. This can be explained by the fact that there is so much less IC memory type by weight compared to the IC logic type. The processors on PCBA Main are approximated as ICs of logic type, so therefore the high impact of these are explained in the same way as for the IC component.

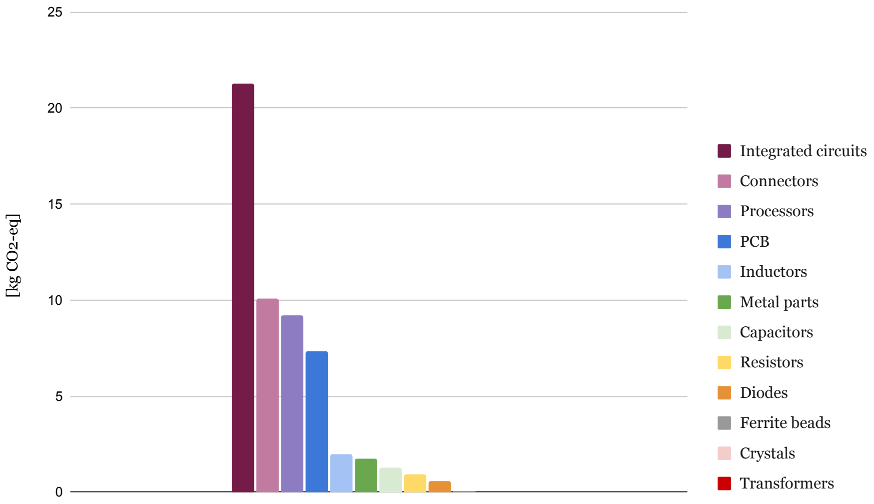

Figure 8: Global warming of the components mounted to PCBA Main.

5.2 Fossil resource scarcity

The results of this impact category for the Hydra and its major parts are shown in Figure 9, which shows a similar result as the global warming. The aluminium housing contributes the most, followed by PCBA Main.

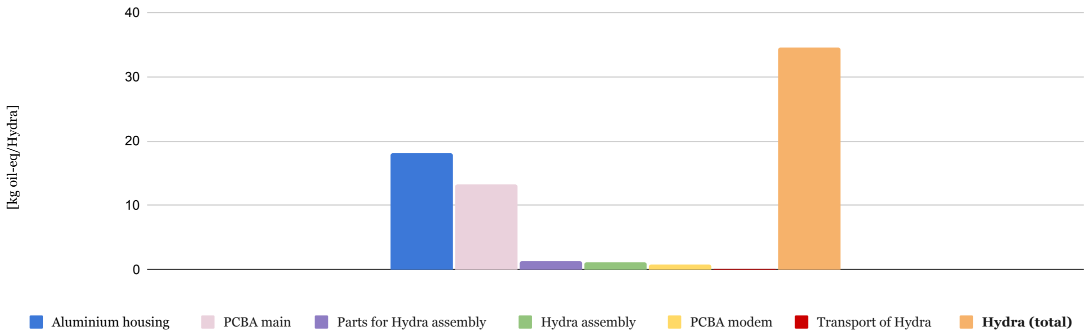

Figure 9: Fossil resource scarcity of the major components of the Hydra, as well as its assembly and transport.

For the aluminium housing, it is evident that the primary ingot production contributes the most to the fossil resource scarcity as seen in Figure 10, followed by die-casting and metal working.

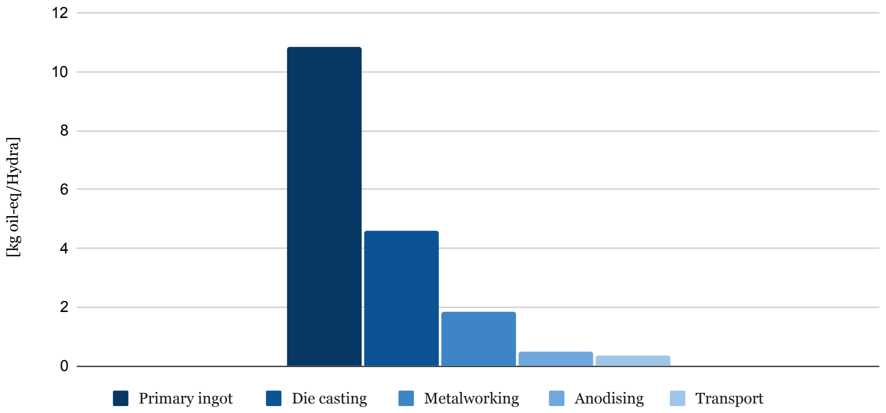

Figure 10: Fossil resource scarcity of the different phases of the aluminium-production, for producing the aluminium housing of one Hydra.

Figure 11 shows the fossil resource scarcity of PCBA Main and its components. The ICs contribute the most, followed by the connectors and the processors. The PCB itself is the fourth largest.

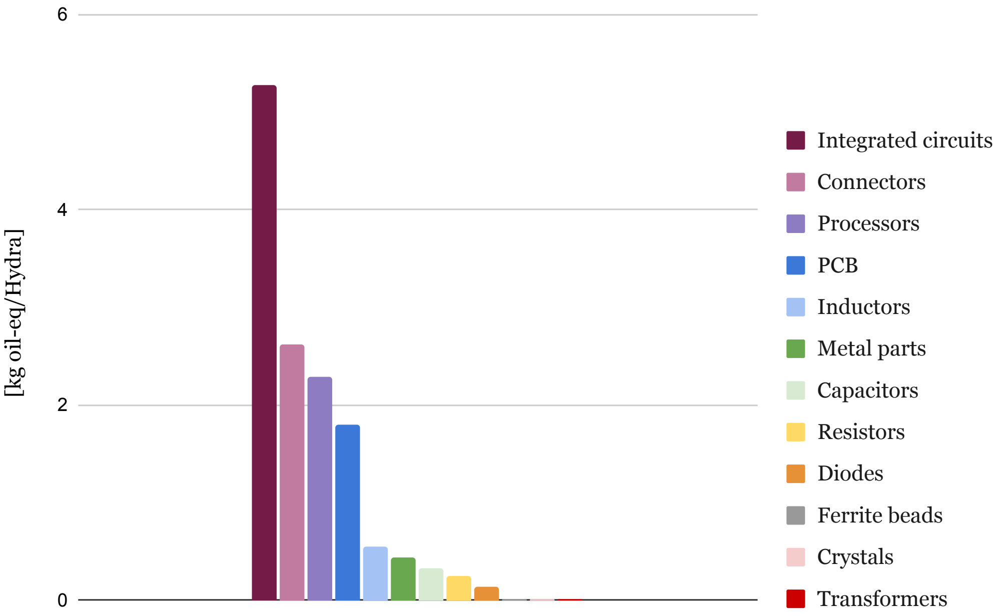

Figure 11: Fossil resource scarcity of the different components mounted to PCBA Main.

5.3 Particulate matter formation

Another impact category of interest is particulate matter formation from the emission of particulate matter to air. Figure 12 shows the impact of this category for the production of one Hydra. The aluminium housing, together with PCBA Main, contribute the most to this impact category.

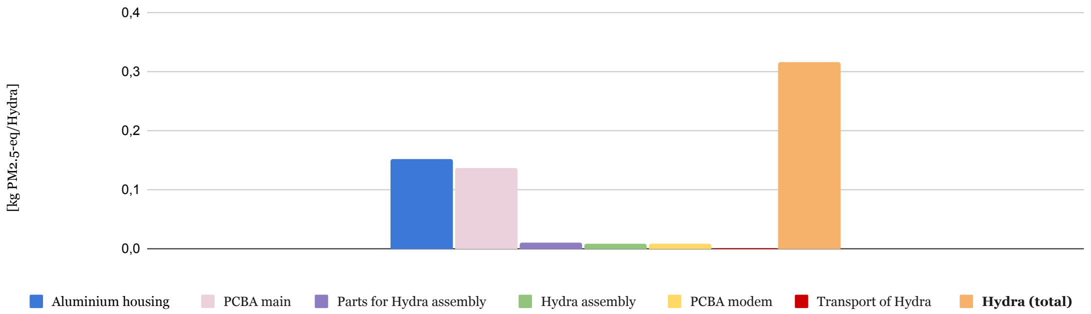

Figure 12: Particulate matter formation of the major components of the Hydra, as well as its assembly and transport.

When looking more closely at the production process for the aluminium housing in Figure 13, it can be seen that the largest contribution comes from the primary ingot production, followed by die casting.

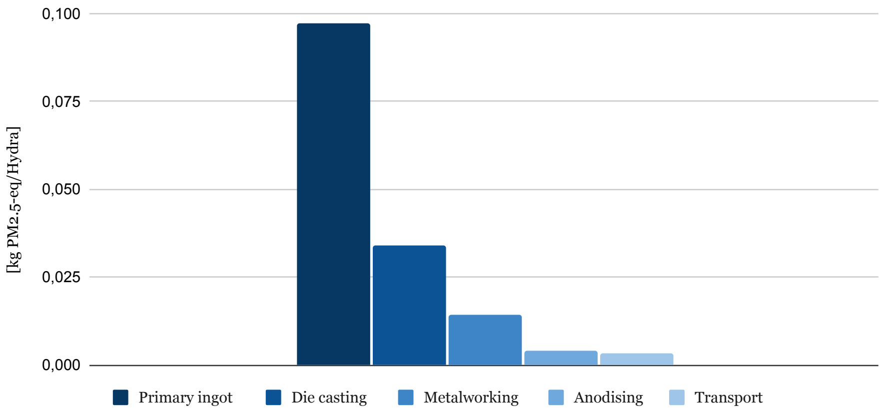

Figure 13: Particulate matter formation of the different phases of the aluminium-production, for producing the aluminium housing of one Hydra.

The impact of PCBA Main for particulate matter formation is shown in Figure 14. The impact of the ICs is the largest, followed by the connectors. In addition, the PCB, processors and resistors contribute notably.

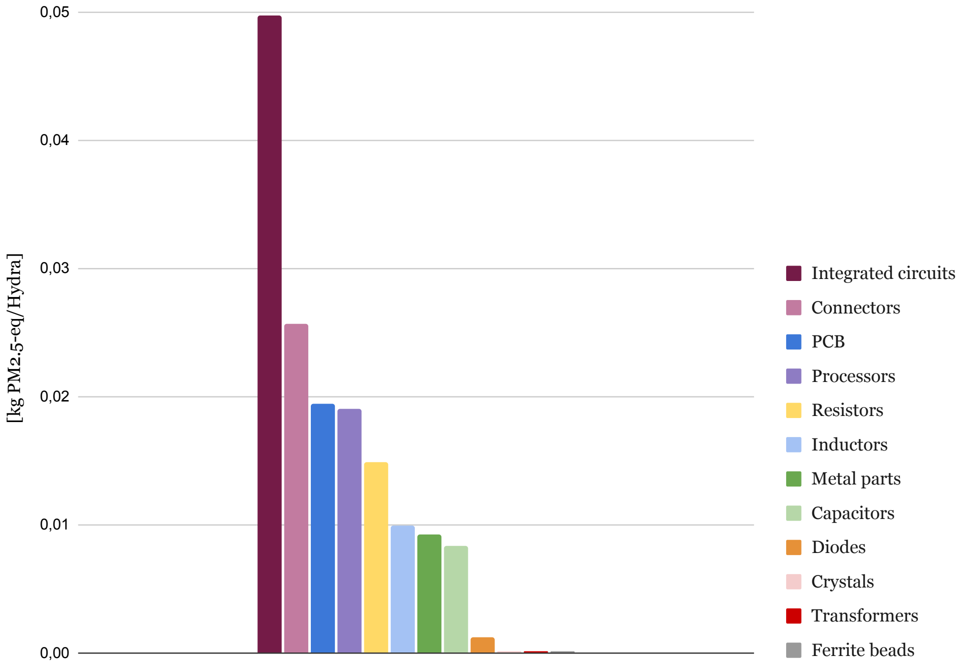

Figure 14: Particulate matter formation of the different components mounted to PCBA Main.

5.4 Mineral resource scarcity - SOP

The mineral resource scarcity is calculated using two different impact indicators in this study. The first to be presented is the SOP. The results are presented in Figure 15, which shows that the "PCBA Main" accounts for the most of the impact on mineral resource scarcity, followed by the aluminium housing and thirdly the production process of the Hydra.

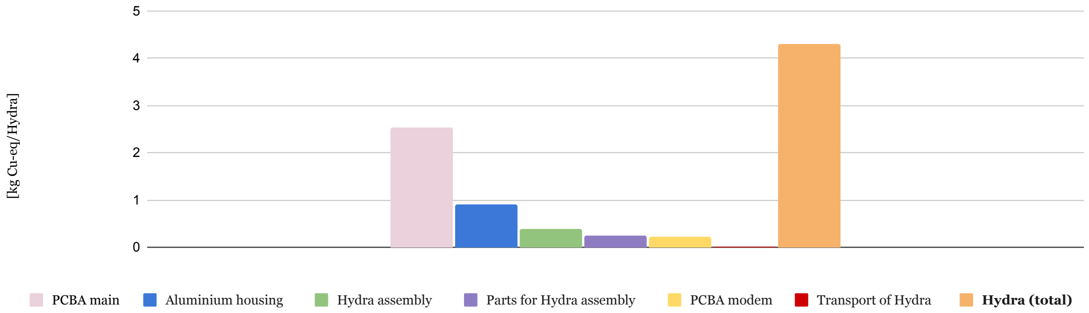

Figure 15: Mineral resource scarcity, using the SOP indicator, of the major components of the Hydra, as well as its assembly and transport.

When looking more closely at the aluminium production required for the aluminium housing, it is shown in Figure 16 that the primary ingot production accounts for most of the impact. This is because the mining of primary aluminium, in the form of bauxite, is very mineral-intensive and therefore has a high impact on mineral resource scarcity.

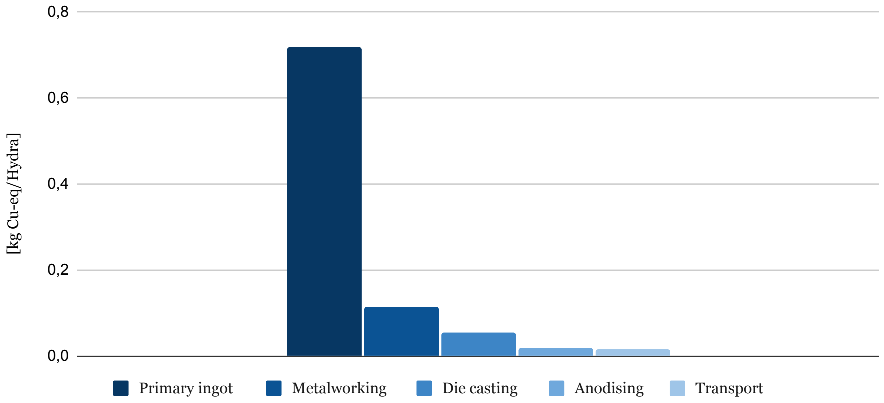

Figure 16: Mineral resource scarcity, using the SOP indicator, of the different phases of the aluminium-production, for producing the aluminium housing of one Hydra.

In addition to aluminium, other metals such as gold, cerium, silver, tin and copper contribute to this impact category. All these metals are present in the components on PCBA Main, and the impact of each component is illustrated in Figure 17. It shows that connectors have the largest impact, together with the ICs. In addition, the processors have a rather high impact, followed by the PCB.

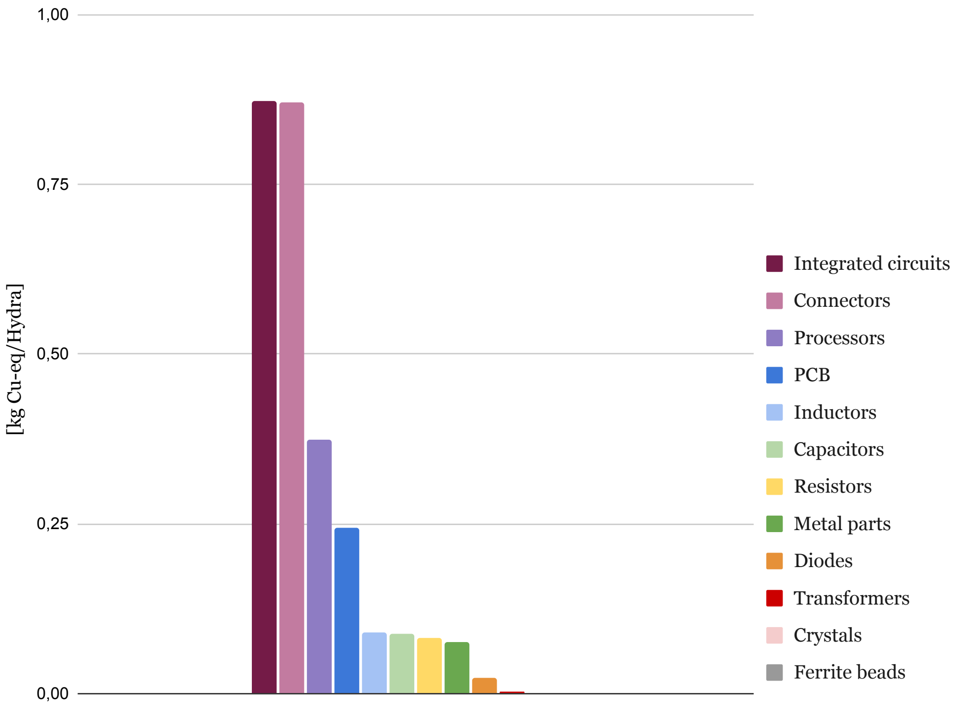

Figure 17: Mineral resource scarcity, using the SOP indicator, of the different components mounted to PCBA Main.

5.5 Mineral resource scarcity - CSI

The mineral resource scarcity can also be calculated using a different indicator, the CSI. In Figure 18 results calculated for the CSI are shown, showing that PCBA Main has the largest impact. This component contains larger amounts of gold, silver, tin and rhodium than other parts of the Hydra, and therefore accounts for the highest impact. The aluminium housing, which has high results for many other impact categories, does not have a high impact for this impact category since aluminium has a low characterisation factor in this method (Arvidsson et al., 2020).

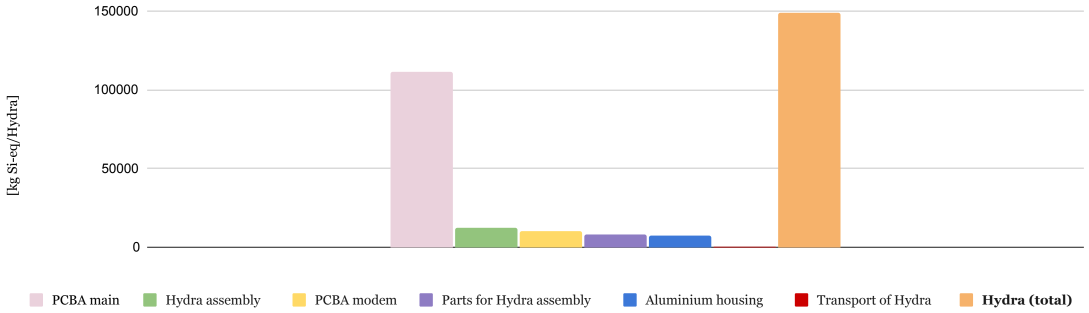

Figure 18: Mineral resource scarcity, using the CSI, of the major components of the Hydra, as well as its assembly and transport.

Even though the impact from the aluminium housing is negligible in comparison to PCBA Main, the impact related to each step in the aluminium production is shown in Figure 19, in order to be consistent in the presentation of impact categories and indicators. This figure shows that the primary ingot production contributes the most, followed by die casting.

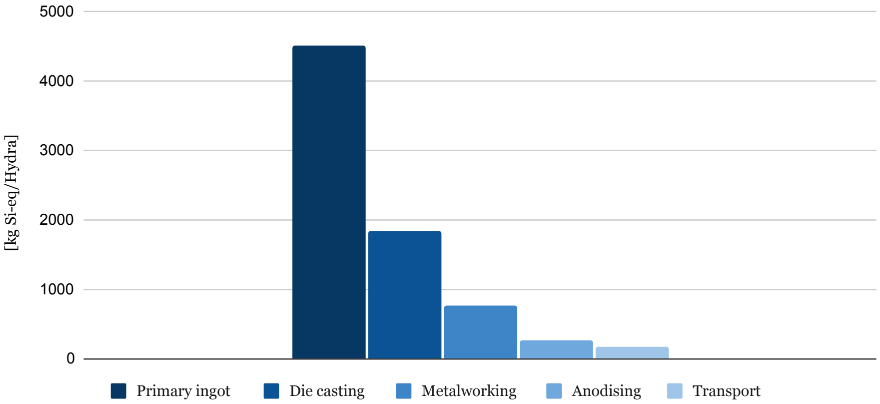

Figure 19: Mineral resource scarcity, using the CSI, of the different phases of the aluminium-production, for producing the aluminium housing of one Hydra.

The impacts of all the components of PCBA Main, which showed the largest contribution to the CSI, are shown in Figure 20. The component categories contributing the most to this impact are the connectors, the ICs and the processors. These components contain the largest amounts of mineral resources, primarily gold, which contributes to their high impact.

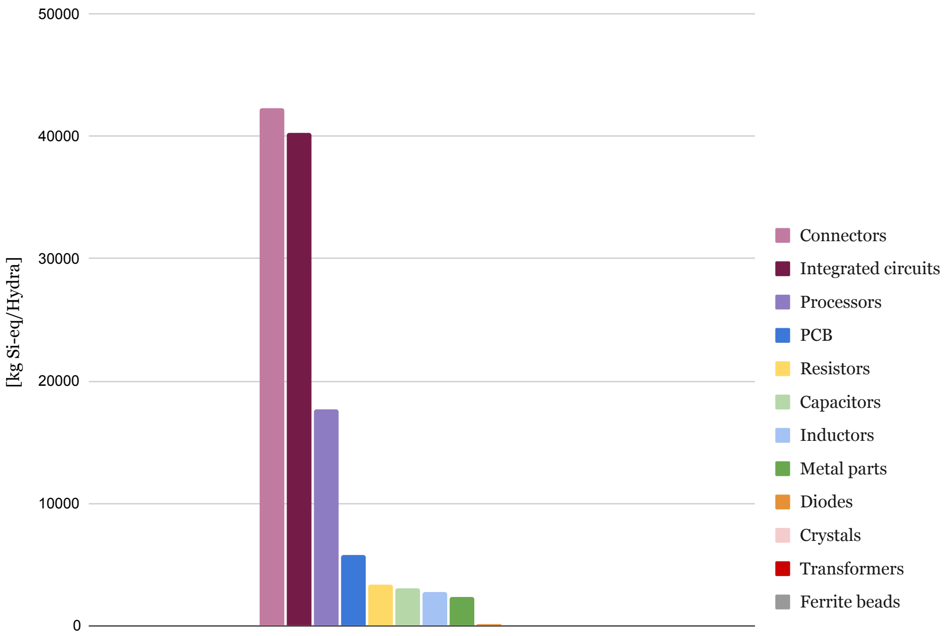

Figure 20: Mineral resource scarcity, using the CSI, of the different components mounted to PCBA Main.

5.6 Land use

The next impact category is land use, which covers the relative species loss caused by land use (Huijbregts et al., 2017). The land-use impact of the Hydra is shown in Figure 21. In this impact category, PCBA Main has the largest contribution, followed by the impacts from the aluminium housing.

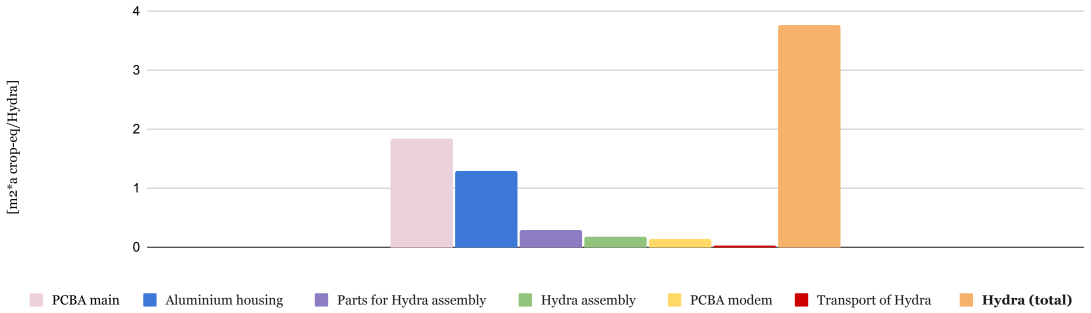

Figure 21: The impact on land use of the major components of the Hydra, as well as its assembly and transport.

The land-use impact of the aluminium housing production is shown in Figure 22, where the primary ingot production is again shown to account for the most of the impact, followed by the die casting and metalworking.

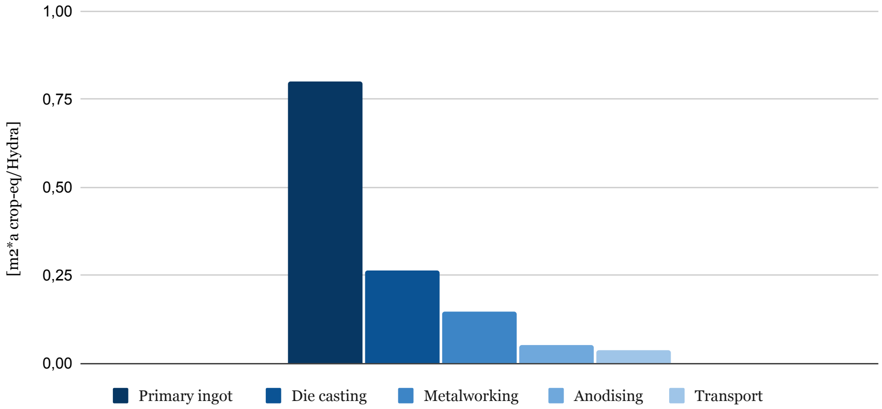

Figure 22: The impact on land use of the different phases of the aluminium-production, for producing the aluminium housing of one Hydra.

When considering the land-use impact of PCBA Main in Figure 23, it is shown that the ICs are contributing the most. In addition, the connectors have a notable impact, followed by the processors and the PCB.

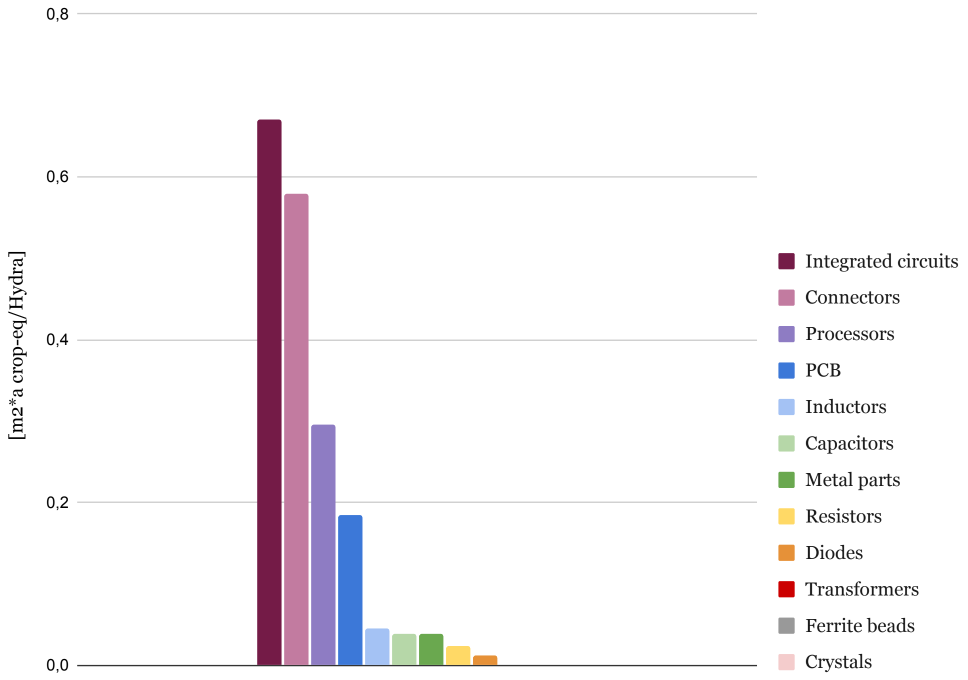

Figure 23: The impact on land use of the different components mounted to PCBA Main.

5.7 Water use

The final impact category covered in this section is water use. The water use related to the assembly of one Hydra from cradle-to-gate is shown in Figure 24. This figure shows that the two parts with the largest impact on this category are PCBA Main and the aluminium housing.

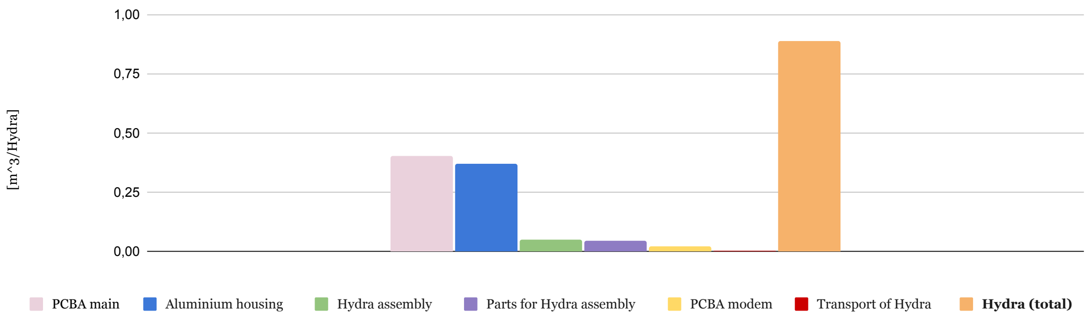

Figure 24: The impact on water use of the major components of the Hydra, as well as its assembly and transport.

The water use related to the production of the aluminium housing is shown in Figure 25, which presents the impact for each step in the production process. This result differs from the previous impact categories, since not only the primary ingot production has a large impact, but also the anodising-step.

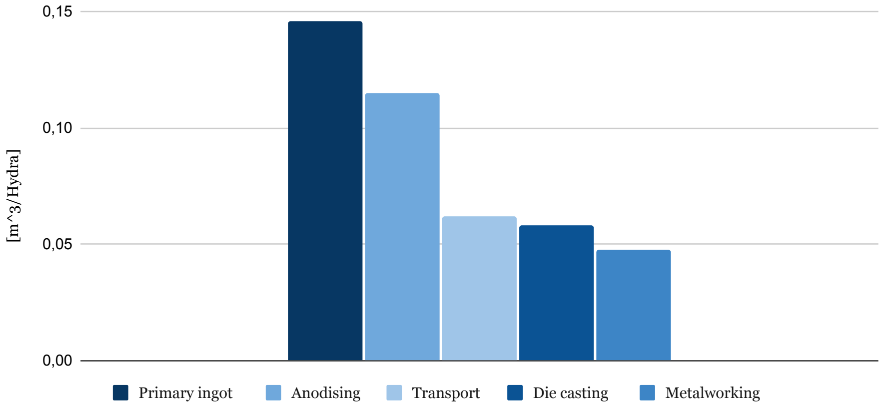

Figure 25: The impact on water use of the different phases of the aluminium-production, for producing the aluminium housing of one Hydra.

When assessing the impact of water use for PCBA Main, shown in Figure 26, this result is similar to the previously covered impact categories. For this impact category, the components with the largest impact are the ICs, the connectors, as well as the processors and the PCB.

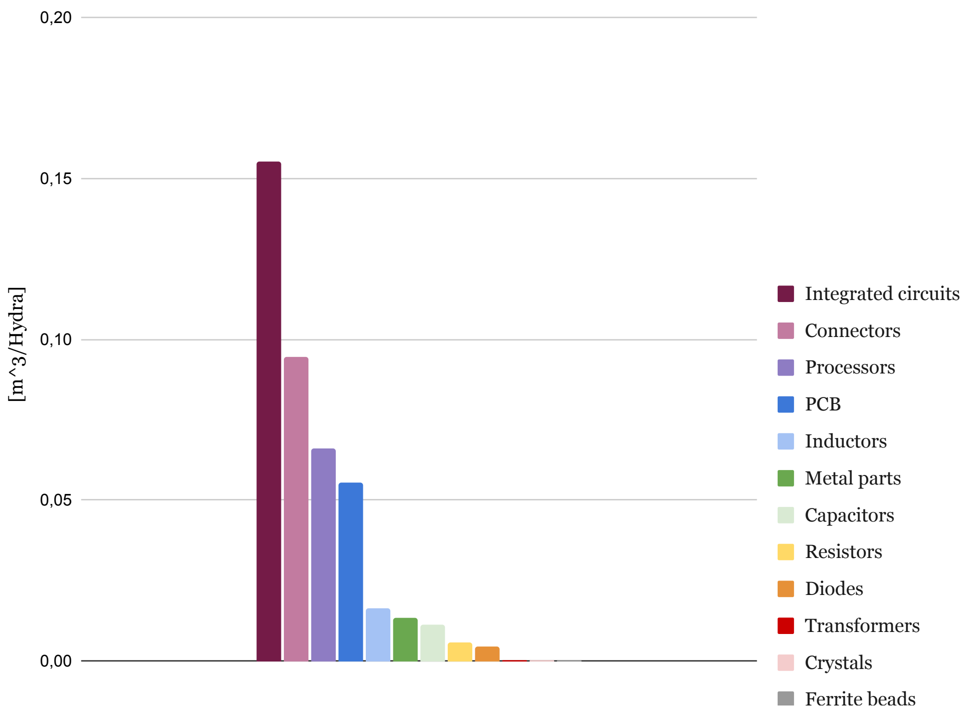

Figure 26: The impact on water use of the different components mounted to PCBA Main.

5.8 Other impact categories

The results of the remaining impact categories in the ReCiPe 2016-method, that have not been covered above, are presented in Appendix A3. All impact categories show similar results as the ones already discussed, where the main impact is related to the production of the aluminium housing and PCBA Main. The results from the following impact categories are presented: acidification, freshwater ecotoxicity, marine ecotoxicity and terrestrial ecotoxicity, freshwater eutrophication, marine eutrophication, carcinogenic and noncarcinogenic human toxicity, ionizing radiation, ozone depletion, photochemical oxidant formation (human health and terrestrial).

6 Interpretation

As concluded in the impact assessment, for most of the impact categories under study, the highest impact of the product is related to the aluminium housing and PCBA Main. Therefore, the following sections focus on the impact of these, discussing the reasons behind their impacts. Contrary, the modem PCBA, the parts used for the Hydra assembly, the Hydra assembly itself and the transportation of the finished product are of secondary importance from a cradle-to-gate life cycle perspective.

The reason for the modem PCBA having a smaller impact is largely attributed to its mass, since it weighs less than the main PCBA. The modem PCBA is almost a duplicate of PCBA Main, but contains only 121 components, compared to the 2424 components present in PCBA Main. The parts for Hydra assembly are also of secondary importance. These parts are all passive components of small size and simple composition. Thus, less energy and resources are required to produce these components as compared to other parts of the Hydra.

The assembly of the Hydra is a complex part of the Hydra's life cycle. However, as shown in Section 5, it does not contribute notably to the total impact of one Hydra. This is because all electronic components in the product are complex and demanding to produce, and hence the assembly of the Hydra contributes with a small environmental impact in comparison to this. The only indicator for which this production is somewhat greater than for other parts of the Hydra is the CSI. This is because the assembly of the PCBA requires solder paste to mount the components onto the PCB, which contains metals such as copper and silver. Finally, the transport of the finished product is also of secondary importance. This is also because the transport is much less energy-demanding than the processes required to produce many other components in the Hydra.

6.1 Aluminium housing

For all impact categories except water use and mineral resource scarcity, primary ingot production and die casting are the two processes that contribute the most. The reason is that they are energy intensive. As mentioned previously, the Chinese electricity mix used for these processes is fossil intensive, and thus contributes to high emissions and large environmental impacts. These results are confirmed by Nunez and Jones (2016), who concluded that electricity consumption during primary aluminium production has a notable environmental impact. The global warming impact from the production of 1 kg aluminium in the study by Nunez and Jones (2016) was 16.5 kg CO_2-eq, which is of the same magnitude as that of the dataset in Ecoinvent, namely 31 kg CO_2-eq. This difference is probably due to that the aluminium used in the Hydra is produced in China, while Nunez and Jones (2016) considered a global dataset.

6.2 PCBA main

For PCBA Main, the ICs and connectors are the main contributors to all impact categories. The IC component type has the highest environmental impact per mass unit, which is attributed to several factors. Firstly, the IC production process is energy intensive, thus electricity use constitutes a large share of the impact of the ICs. Secondly, there are two materials included in the IC approximation that account for a large share of the impact. Gold is one of them, since its production is material and energy-intensive and generates tailings that release toxicants. The other material is the wafer, as its production requires much energy and resources.

The significant contribution of connectors to the environmental impact of PCBA Main is twofold. Firstly, they contain materials such as gold, brass and plastic, whose energy- and waste-intensive production processes greatly contribute to this impact. Secondly, the electricity used in the production of connectors also makes a notable contribution.

There are three processors on PCBA Main, which also contribute notably. All the processors are categorised as ICs, and thus the reason for the processors contributing significantly is the same as for the ICs. The processors are of different sizes and the largest processor accounts for 74% of their total mass and thus also of the impacts of the processors.

The contribution of the PCB to the total environmental impact of the Hydra is foremost due to the PCB being a rather complex product. Since many materials, such as rare metals and plastic, are required for its production, its environmental impact is substantial. The energy requirements to produce the PCB also contribute to the high environmental impact. There is a large amount of hazardous waste generated in its production, and in addition to this the PCBs have a frame during production which goes directly to waste. The contribution of the above mentioned reasons to the environmental impact of the PCB is supported by the results in the LCA conducted by Nassajfar et al. (2021).

6.3 Scenario analysis

In this section, potential scenarios to reduce the environmental impact of the Hydra are analyzed. The scenarios have been modeled as systems identical to the base case in the previous calculations, except for alterations in line with the desired system change. Thus, this section presents a scenario analysis of the base case LCA. This has been done to identify impact reduction strategies in line with the second goal of this study (Section 3.1).

The scenario analysis includes three scenarios, all concerning the aluminium housing of the Hydra. As was concluded in Section 5, the aluminium housing and PCBA Main are the largest hotspots. Thus, these two parts are of largest interest for potentially reducing the impact of the Hydra. However, the three scenarios analyzed are all related to the aluminium housing or its production in some way, due to the practical feasibility of altering its composition and production.

6.3.1 Producing aluminium using the Norwegian electricity mix

The first improvement scenario considers a modification of the electricity mix used in the aluminium production. As discussed in Section 5, Chinese electricity has been identified as one of the main contributors to the environmental impact of the aluminium housing. Norwegian electricity has among the lowest climate impacts according to Kallitsis et al. (2024), who compared different electricity mixes for the production of batteries. This is due to its high share of renewable energy: 90% hydro power, 6% wind power and 4% imported electricity from neighboring countries. The Norwegian electricity mix is therefore applied in this scenario to investigate the importance of the electricity use in aluminium production for the overall impact of the Hydra.

The changes required for calculating this scenario are solely related to the electricity providers in the modeled processes for aluminium production. The provider used for the Ecoinvent dataset *electricity, medium voltage* is altered from China to Norway for the processes primary ingot production, die casting and anodising.

6.3.2 Replacing primary ingot with aluminium scrap

In the second improvement scenario modeled in this study, the primary aluminium ingot is replaced with recycled aluminium scrap. As shown in Section 5, the process of creating primary ingots has high impact on the total environmental impact of the Hydra, partly due to the mining of bauxite being energy-demanding. According to the International Aluminium Institute (2009), recycling of aluminium products requires as little as 5% of the energy and emits only 5% of the GHGs of primary aluminium production. Using recycled instead of primary aluminium in the housing is therefore one strategy for potentially decreasing the environmental impact without compromising the function of the Hydra. Aluminium is a metal that can be recycled many times over, without losing any of its initial properties (International Aluminium Institute, 2009). If the scrap is properly pre-treated and sorted, recycled aluminium can be used in almost all aluminium applications, as the metal's atomic structure is not altered during the melting process.

Finally, the aluminium recycling industry is well-developed, and this scenario should therefore be possible to implement. According to the International Aluminium Institute (2009), enough aluminium scrap has been generated in the EU and North America over the past decades to develop an economically strong and technically outstanding aluminium recycling industry. Recycled aluminium is thus already used in society to a large extent.

As for the practical aspects of modeling this scenario, the amount of primary aluminium in the housing is replaced by an equal amount of recycled aluminium, using the Ecoinvent process *treatment of aluminium scrap, post-consumer, prepared for recycling, at refinery* with global data. Except for this change, the same datasets are used as for the base case, with Chinese electricity mixes and otherwise using global datasets.

6.3.3 Changing housing material to glass fibre reinforced plastic

In the third improvement scenario, the aluminium housing of the Hydra is replaced with a glass fibre reinforced plastic housing. Many of CPAC's other ECUs also have protective housing, but for some ECUs this housing consists of a composite material instead of metal. Changing the aluminium housing to one made from a composite material is therefore a scenario that can be interesting to investigate. The composite material used in the modeling of this scenario is glass-fibre reinforced plastic, which has been used by CPAC in the housing of other ECUs. It is however important to note that this study only considers the difference in impact from the production of the two alternatives. When taking the whole life cycle of the two types of housing into account, the results may differ. Aluminium is, as mentioned previously, easy to recycle. Composite materials, on the other hand, are more difficult to recycle (Yang et al., 2012), which can affect the impact of the two alternatives.

One issue with this scenario is that the change of material from aluminium to a composite material may lead to the loss of important characteristics. Glass fibre reinforced plastic lacks many of the properties that aluminium has, such as thermal conductivity and protection from EMI and radio frequency interference (Alhamidi et al., 2022). A disclaimer that is worth noting is therefore that changing from aluminium to a glass fibre reinforced plastic housing could require the addition of other components, such as a thin protective metal layer to shield the inner components of the Hydra from EMI, and a fan to provide cooling. Discussions with a hardware technician at CPAC revealed that a more realistic scenario would be to change only a certain amount of the aluminium. The modeling of this scenario is however limited, considering the potential benefits of replacing all aluminium with glass fibre reinforced plastic in general.

The implementation of this scenario is made by replacing the aluminium by a corresponding volume of glass fibre reinforced plastic, using the density of aluminium (Nová et al., 2021) and of glass fibre reinforced plastic (Pereira et al., 2021). All the aluminium housing production processes are replaced by the Ecoinvent process *glass fibre reinforced plastic production, polyamide, injection moulded.*

6.4 Scenario analysis results

In this section, the impact assessment results of the scenario analysis are presented, with the results shown as the change in percent in comparison to the base case. The numerical results of the scenario analysis for all impact categories are presented in Appendix A4.

6.4.1 Global warming

When assessing the impact on global warming of the scenarios and the base case, it can be seen in Figure 27 that all three scenarios lead to a reduced impact. The impact reduction for each scenario is at least 30%, with the glass fibre reinforced plastic housing scenario giving a reduction of 50%. The glass fibre reinforced plastic housing is less energy intensive to produce than the aluminium housing and therefore shows a larger decrease in impact on global warming. The Norwegian electricity mix only uses renewable energy, hence the global warming impact is reduced using this scenario. For the scenario with recycled aluminium, the highly energy intensive primary aluminium production is avoided. Thus, there is also a reduction in global warming for this scenario.

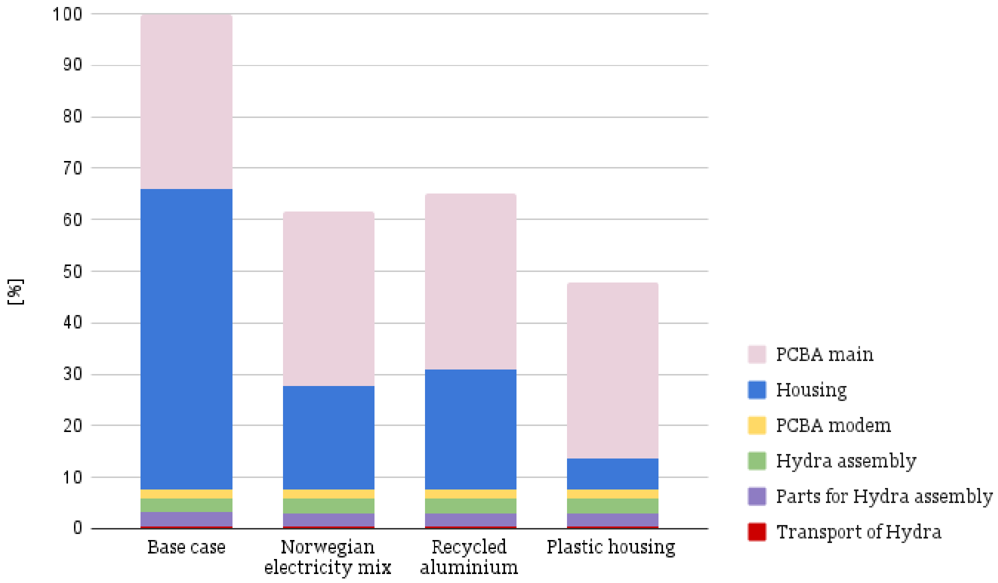

Figure 27: The change in impact associated with the three improvement scenarios in comparison to the base case, for global warming.

6.4.2 Fossil resource scarcity

The reduction of fossil resource scarcity related to each scenario is shown in Figure 28, with results similar to global warming. All three scenarios have a minimum reduction of 30%, with the scenario using glass fibre reinforced plastic housing having the largest reduction due to the large reduction of fossil energy use implied with shifting from aluminium to glass fibre reinforced plastic production.

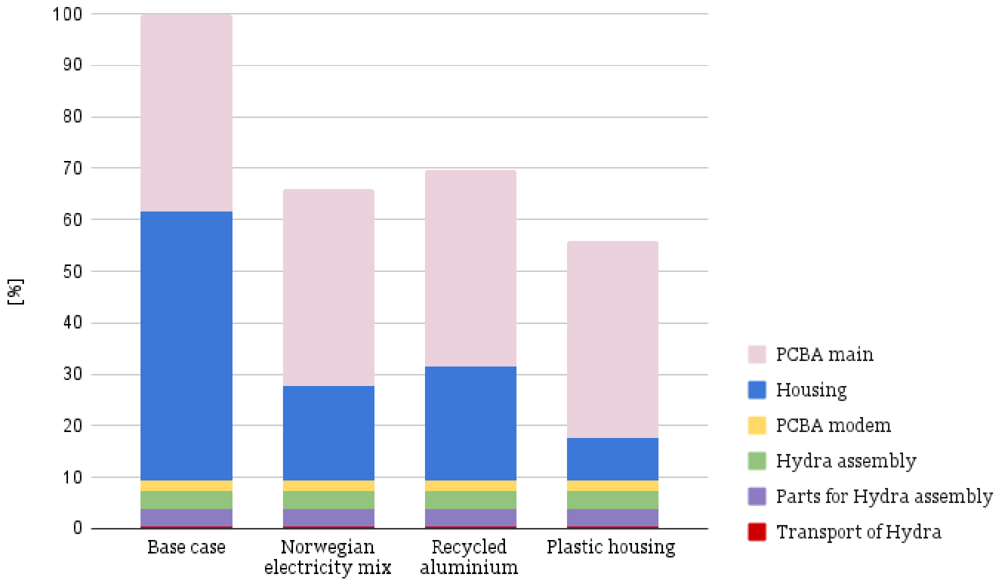

Figure 28: The change in fossil resource scarcity associated with the three improvement scenarios in comparison to the base case

6.4.3 Particulate matter formation

When assessing the impact on particulate matter formation for each scenario, the impact is reduced with almost 30% for all three scenarios, as seen in Figure 29. The same reasons as mentioned above apply to this impact category, as the particulate matter formation is correlated with fossil energy usage.

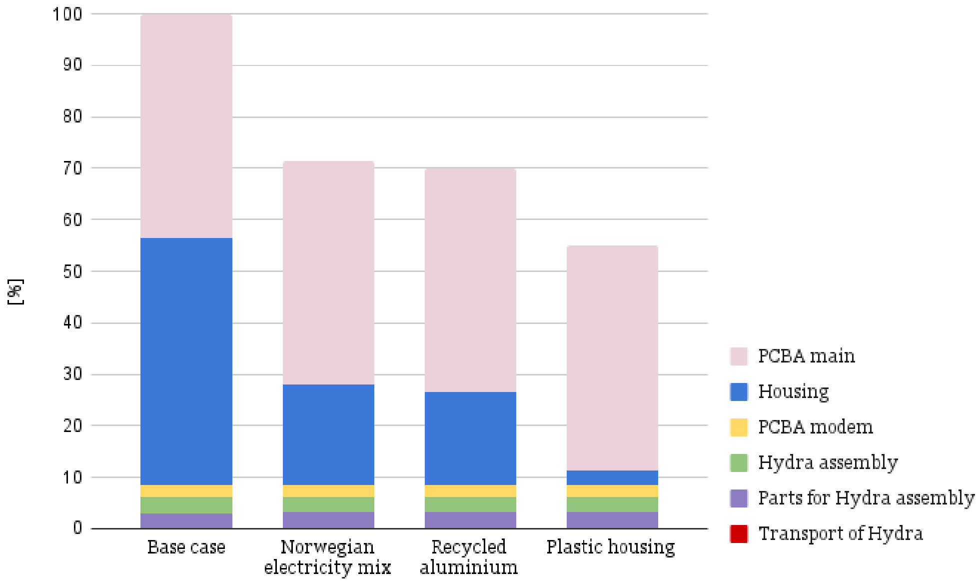

Figure 29: The change in particulate matter formation associated with the three improvement scenarios in comparison to the base case

6.4.4 Mineral resource scarcity - SOP

The reduction of mineral resource scarcity as per the SOP indicator, is not as large as for the previous impact categories. However, each scenario contributes to a slight improvement as seen in Figure 30. Since the impact on mineral resource scarcity depends on the materials used, changing the electricity mix for producing aluminium does not lead to a notable difference. Altering the primary ingot to recycled aluminium contributes to an impact reduction, as less aluminium is extracted from the earth's crust when using recycled aluminium. The third scenario performs best, since the glass fibre reinforced plastic housing does not require any rare minerals for its production.

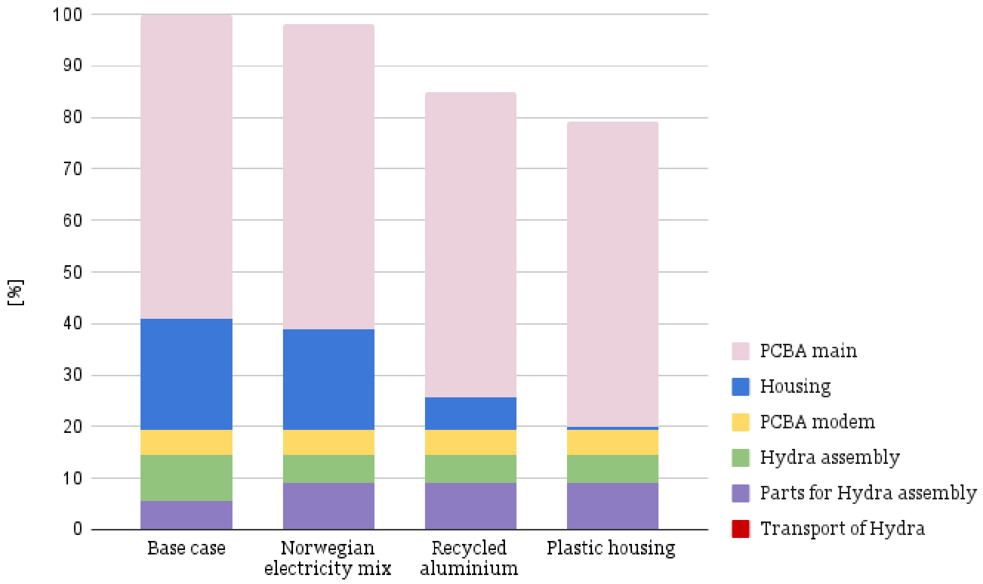

Figure 30: The change in mineral resource scarcity as per the SOP indicator associated with the three improvement scenarios in comparison to the base case

6.4.5 Mineral resource scarcity - CSI

When calculating the mineral resource scarcity with CSI, the results are as shown in Figure 31, the reduction for each scenario is smaller than for the SOP. This is because the CSI, unlike the SOP, does not attribute high impact to aluminium extraction, and thus changing the aluminium housing in any way does not contribute notably.

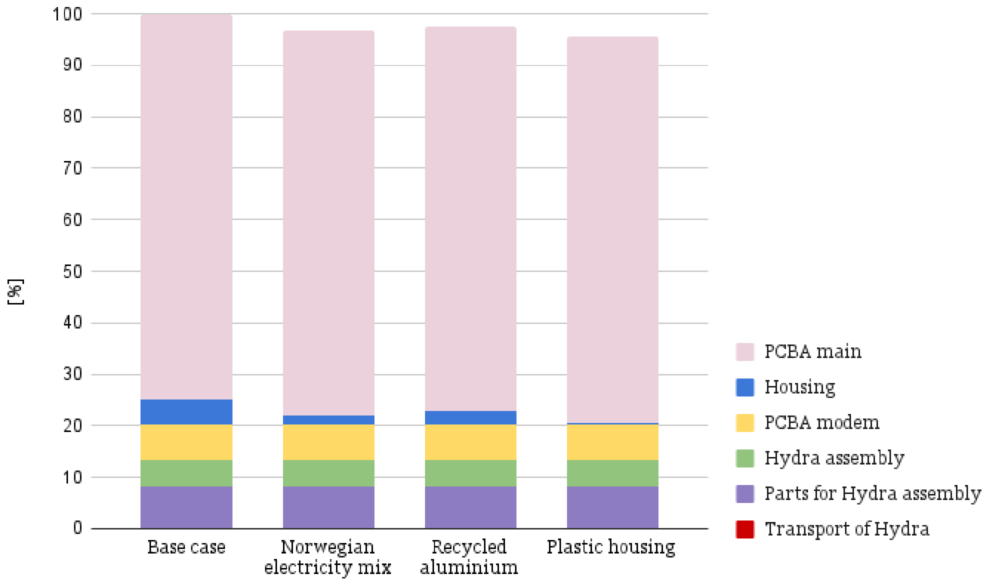

Figure 31: The change in mineral resource scarcity as per the CSI indicator associated with the three improvement scenarios in comparison to the base case

6.4.6 Land use

All three scenarios contribute to a reduction in impact on land use, as shown in Figure 32. For the first scenario, where the Norwegian electricity mix is used, the reduction is 18%, which is largely explained by the exclusion of coal mining. However, the land use related to the extraction and processing of aluminium still contributes to the total land use. When using recycled aluminium there is a reduction of 20%, which is primarily related to the elimination of aluminium extraction and the land it occupies. If the Hydra had a glass fibre reinforced plastic housing, the impact on land use would be reduced with approximately 30%, since the occupation of land by the whole process of aluminium production is eliminated.

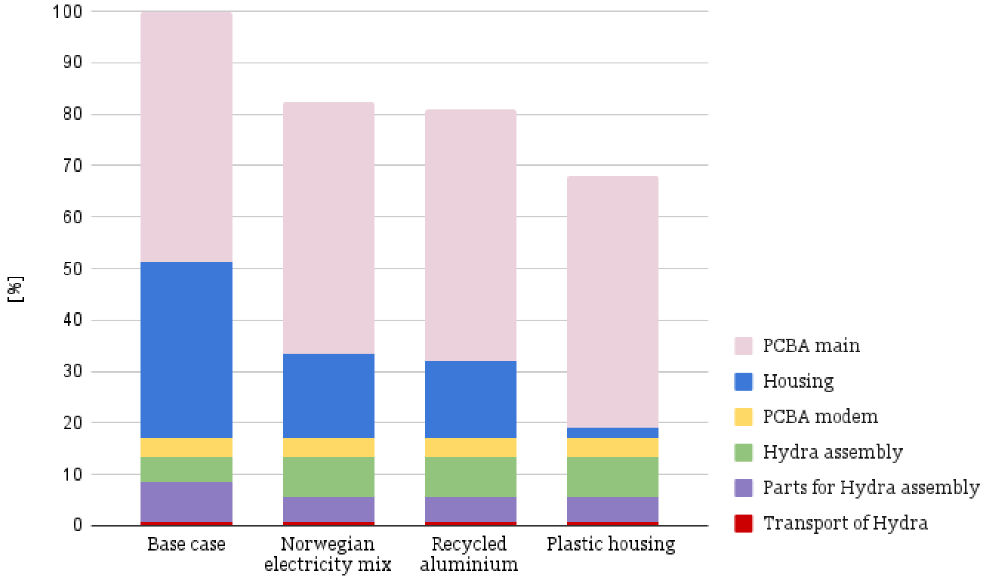

Figure 32: The change in land use associated with the three improvement scenarios in comparison to the base case

6.4.7 Water use

Water use is the only impact category where there is an increase of impact for one scenario, as seen in Figure 33. The Norwegian electricity mix increases the impact on water use, while the two other scenarios are similar to each other and lead to a slight impact reduction. The reason why the first improvement scenario increases the impact is due to the high share of hydro power in the Norwegian electricity mix. Hydro power generally has a high impact on water use, and utilizes water during the generation of electricity (Mekonnen & Hoekstra, 2011). ReCiPe 2016 considers this water in the calculation of water use impacts.

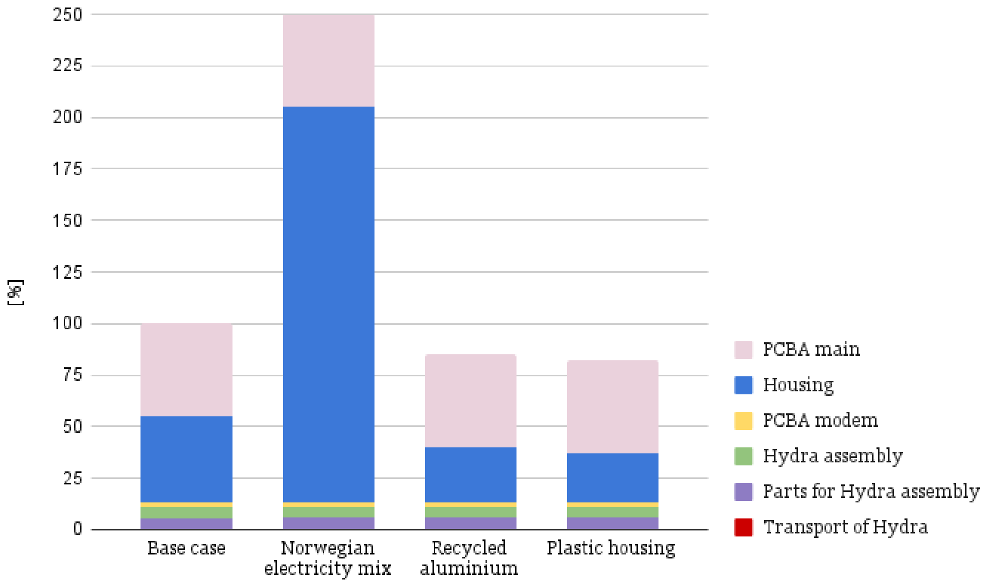

Figure 33: The change in water use associated with the three improvement scenarios in comparison to the base case

7 Discussion

The scenario analysis revealed the potential to achieve at least a 30% overall reduction in climate impact by modifying various aspects of housing design and production. For the scenario where the Norwegian electricity mix is used for producing aluminium, the overall environmental impact of the Hydra could decrease notably. This result is supported by a study performed by Farjana et al. (2019), which concluded that increasing the share of renewable energy in primary aluminium production leads to a decrease in environmental impact. A decrease in impact can be seen for all impact categories analyzed, except for water use. As mentioned in Section 6.4.7 , this is because of the high share of hydro power in the Norwegian electricity mix. When using recycled aluminium instead of primary ingot, the overall environmental impact of the Hydra shows a reduction similar in size to the first improvement scenario. This is due to the replacement of the energy intensive processes required to produce primary aluminium ingots with the less energy intensive processes used to recycle aluminium. This result is as expected, both in direction and magnitude, as available research on recycled aluminium shows that this material performs better from an environmental point of view than primary aluminium.

Lastly, the improvement scenario in which the material of the housing is changed from aluminium to glass fibre reinforced plastic is the only scenario that shows a higher impact reduction capacity potential than 30%. This is mainly explained by the elimination of the energy intensive aluminium production, which otherwise is the main contributor for most impact categories.

7.1 Practical feasibility

To make these scenarios practically applicable, it is important to note that the changes performed as a result of this study might not lead to the same results as presented. The scenario in which the electricity mix was changed, for example, is using the cleanest electricity mix in Europe. The scenario using recycled aluminium considers using 100% recycled aluminium, and the scenario using glass fibre reinforced plastic housing considers 100% composite material instead of 100% aluminium. The scenarios have thus been modeled as extreme versions of the practically possible. This was deemed appropriate to inspire towards impact reductions. However, CPAC may not be able to transfer their aluminium housing production to Norway or a location with similar low-impact electricity, implement the use of 100% recycled aluminium or change the housing material to 100% glass fibre reinforced plastic. Therefore, the actual impact reductions achieved by following the improvement scenarios would most likely be lower than the results that this report have shown.

One possibility to consider when analysing the scenarios is the combination of different scenarios, which results in even larger impact reductions that are easier to achieve in practice. A combination of 100% recycled aluminium and using the Norwegian electricity mix, both in the production of the aluminium housing from scrap and in the production of the recycled aluminium, revealed a 50% impact reduction for global warming. This alternative could therefore be even better than changing from aluminium to glass fibre reinforced plastic housing, from a cradle-to-gate perspective. It also means that to reach the 30% impact reduction aimed for by 2030, it is not necessary to use 100% recycled aluminium or 100% renewable electricity - a combination of lower percentages can still achieve the reduction target.

Another change that can be applied to the Hydra in a combined scenario including aluminium, is the removal of the anodised outer layer of the aluminium housing. All except two of the aluminium covers used in the Hydra are anodised through an electrolytic process, to create a matte surface finish. Discussions with employees at CPAC revealed that this surface is purely for aesthetic purposes, and does not serve any specific function. Removing this layer entirely would not compromise the product's function and can even lead decreased economic cost, making this scenario worth considering. In the LCIA, it could be seen that this layer is responsible for 1.5% of the total global warming impact of the Hydra (2.34 kg CO_2-eq/Hydra). Since this layer is so simple to remove, it could be used in combination with some of the above-mentioned improvements to achieve an even greater impact reduction.

7.2 Future research

Besides the improvement scenarios modeled in this study, the results and hotspots identified in this system indicate that there are other potential changes that could reduce the environmental impact of the Hydra. However, not all of these changes are currently practically feasible. These alterations are therefore discussed here as potential future improvements in environmental impact of the Hydra.

One improvement that is interesting to discuss is to remove the gold in the Hydra. There is in total about 80 mg gold in several different components on the main and modem PCBAs, which is one of the main reasons that some components on the PCBAs have larger environmental impacts than others. While only 0.0033% of the total mass of the Hydra, it accounts for a notably larger environmental impact. Removing the gold present in the Hydra could therefore be a strategy for decreasing the environmental footprint of the Hydra. For social justice reasons (Earthworks, 2024), as well as economic reasons (Mencho, 2022), it is also beneficial to remove the gold.

However, implementation of this scenario would involve some difficulties. The gold in the Hydra is primarily used as a thin conductive plating layer to shield electronic components from oxidation and corrosion. In some components, it is also used as conductive elements. Altering the amounts of gold in the components of the Hydra is therefore not as simple as for example altering the aluminium housing, as the use of gold provides important functions that are not easily replaced or omitted (Aindow et al., 2010). Also, since the development of gold-free electronic components is still mostly in the research phase, there are still no viable gold-free alternatives available on the market. Finding less expensive but equally durable and efficient alternatives to gold is therefore an important long-term aim within the electronics industry. It is possible that similarly to the movement towards lead-free electronics, in the future we might see a movement towards gold-free electronics. As gold-free components become more available on the market, it will become easier to decrease the amount of gold in the Hydra, and thereby potentially decrease its environmental impact further.

As the use and end-of-life phases of the Hydra were not studied, no improvement scenario has thus been suggested for these life cycle phases. However, as mentioned in Section 1, the electronics industry has a large environmental impact, and is known for creating large amounts of waste. According to Peng and Shehabi (2022), only 17% of global electronic waste is properly recycled. However, electronics at their end-of-life contain many valuable materials that, if properly taken care of could lead not only to sustainability benefits, but also to economic benefits. There is thus a potential future scenario in which CPAC, by collecting old ECUs, can extract valuable materials and components that they once invested in, to reuse them in new products. By converting to a more circular business model where recycling is an explicit part of CPAC's business strategy, CPAC can thus not only achieve a more sustainable way of doing business, but also a more economical. This transformation is therefore suggested as a valuable area for future research.

As shown in Section 5, the PCB is one of the main contributors to the environmental impacts of PCBA Main. This is also widely recognized within the electronics industry, and many studies investigate other substrates for producing PCBs. One such substrate is paper, usually coated with cellulose nanocrystals (Sudheshwar et al., 2023). Manufacturing of the paper-based board is performed using additive manufacturing, which minimizes waste and the use of chemicals. The results of the LCA performed by Sudheshwar et al. (2023) shows promising advantages using paper-based PCBs, lowering the overall environmental impact of the board. The same conclusion was reached by Nassajfar et al. (2021), which compares the environmental impact of manufacturing conventional PCBs with four alternative substrates, where paper is one of them. The LCA conducted in their study showed a notable decline in overall environmental impact for paper-based PCBs in comparison with the conventional PCB. However, direct replacement with paper is not suitable in all applications, and with the present technology it is not possible to construct complex multilayer PCBs using paper as the substrate (Sudheshwar et al., 2023). Although this cannot be implemented by CPAC at the moment, this topic should be continuously monitored as a potential strategy to reducing the environmental impacts of the PCB.

7.3 Limitations

Several sources of error may have affected the results of this study. Firstly, the calculations are mainly based on Ecoinvent datasets that serve as proxies for the actual components in the Hydra. However, several of the approximations differ in material composition and processing compared to those in the Hydra. The connectors, for example, is one component type that did not completely match its proxy.

Secondly, it is important to mention that the scope of this study limits the conclusions that can be drawn. Since the results are only calculated for the cradle to gate of the Hydra, the impact of the use and end-of-life phases are not taken into account. Thus it is important to note that the environmental impact calculated in this study does not represent the entire life cycle of the Hydra. In the use phase, the Hydra is installed in a vehicle and used to control certain systems of the vehicle (CPAC Systems, 2024b). When the vehicle reaches the end of its lifetime, the Hydra is scrapped along with the vehicle. These phases also contribute with emissions and resource use that can be attributed to the Hydra, but their magnitude is unknown. Thus, a potential future study is to broaden the scope of this study to also include the use and end-of-life phase of the Hydra.

The results of this study should be validated by comparing to results from similar products, in this case ECUs with similar function and composition. However, this is difficult since the availability of such studies is limited. One relevant study identified is an LCA of an ECU used for safety control in cars, with a weight of 427 g and 83 components in total (Suyang & Jingjing, 2010). To make the comparison more relevant, the results of both studies are recalculated to 1 kg of ECU, resulting in 60 kg CO_2-eq/kg for the Hydra. The corresponding global warming impact from Suyang and Jingjing (2010) is approximately 24 kg CO_2-eq/kg from cradle to gate. The results are within the same order of magnitude, which can be seen as a partial validation of the results of this study. However, the ECUs are not completely comparable due to the difference in complexity.

8 Conclusions

The electronics industry faces many sustainability challenges, which need to be tackled during the coming years. CPAC aims for a 30% impact reduction until 2030 and in order to accomplish this it is of importance to know the current environmental impact related to their products.

In this study, an LCA was performed of one of CPAC's ECUs with the aim to determine the environmental hotspots in its life cycle from cradle-to-gate, as well as to formulate potential strategies to reduce its environmental impact with 30%. The LCA showed that the overall environmental impact of this product is mainly attributed to the aluminium housing and the main PCBA.

To answer the second research question, a scenario analysis was performed, from which two impact reducing strategies can be formulated. These strategies can be considered to reach the goal of a 30% impact reduction, although the exact size of the resulting reduction will depend on the ambition of the undertaken actions.

The first strategy is to change the aluminium housing. This can be done in several ways:

- Increasing the share of renewable energy in the electricity mix used for aluminium production
- Using recycled aluminium in the housing of the Hydra
- Excluding the process of anodising the aluminium housing

Reconsidering the choice of supplier for the Hydra's housing is crucial, with a focus on selecting a supplier that utilizes a higher share of renewable energy in their electricity mix. For example, this could involve choosing a supplier with manufacturing facilities located in a country with a high share of renewable energy or exerting pressure on the current aluminum supplier to invest in local renewable energy. Another promising action is to incorporate recycled aluminum in the housing of the Hydra, as this has been proven to improve environmental performance. Switching from primary to recycled aluminum would not negatively affect the function of the Hydra and would therefore be a viable alternative from a product performance perspective. Furthermore, there is a possibility to remove the anodised layer of the housing since it is only used for aesthetic purposes. This would also reduce the impact on global warming, and provide a straightforward solution to begin taking action.

The second alternative is to redesign the Hydra by using glass fibre reinforced plastic instead of aluminium in the housing. This would entail a halving of the product's impact on global warming from a cradle-to-gate perspective, which is more than enough to reach the 2030 targets. However, a housing made entirely from a composite material lacks certain functions that the housing made from aluminium provides, so to provide the same functions, it would need to be complemented with other materials.

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Appendix

A1. Component descriptions

The Hydra is composed of multiple components, which, for the purpose of this study, are approximated using datasets available in Ecoinvent. Bellow follow short descriptions of the approximations and datasets used for each of these components.

Capacitors

Within electric circuits, there are usually capacitors included that function as energy-storage (Hischier et al., 2007). This is also the case for the Hydra, where there are two types of capacitors, surface mounted device (SMD) type and electrolyte type. For these two types there are also available datasets in the Ecoinvent database. Most of the capacitors in the Hydra are SMD type, which offers maximum capacitance within the smallest space and is usually applied in advanced microelectronics (Hischier et al., 2007). The electrolyte type capacitors are included due to their high current handling capability, as well as their high capacitance per unit volume.

Crystals are another electronic component used in the Hydra, for which the SMD type capacitor dataset in Ecoinvent has been used as a proxy. Crystals are used on the PCBA to determine the oscillation frequency for certain timing signals (Crecraft & Gergely, 2002). A comparison between their material composition in IMDS and the material composition of SMD type capacitors in the Ecoinvent dataset showed that their material compositions are very similar to that of capacitors.

The production effort for capacitors in the Ecoinvent database is a rough approximation for all types of capacitors, which includes the input of auxiliaries (mainly methyl ethyl ketone and ethyl acetate) and energy, outputs such as emissions and waste (non-used raw material), as well as transportation, infrastructure and land-use (Hischier et al., 2007).

Diodes

Diodes are also used in the Hydra, to restrict the direction of movement of charge carriers, only allowing electric current flow in one direction (Hischier et al., 2007). In the Hydra there are two types of semiconductor diodes; surface mounted diodes and light emitting diodes (LED), where the LED emits light when electricity passes through it in a certain direction. These two components are available as datasets in Ecoinvent, where the SMD diode is a glass diode. The composition of the datasets of the diodes are accurate when compared with the components present in the Hydra, while the production effort is approximated with an average production effort over all types of diodes. The production effort for diodes in the datasets includes the input of auxiliaries (mainly nitrogen, oxygen and hydrogen) and energy, outputs such as emissions and waste (mainly from auxiliaries, water and raw materials), as well as transportation, infrastructure and land-use.

Inductors

An inductor is used as a passive device within electrical circuits to hinder changes in electrical currents. In Ecoinvent there are available datasets for three types of inductors, which can all be found in the Hydra. These are a ring core choke type, a miniature radio frequency chip type and a low value multi-layer chip type (Hischier et al., 2007).

In the Hydra there are also multiple components categorised as ferrite beads, which is a type of inductor. They have been categorised as low value multi layer chip inductors, after discussion with a hardware technician at CPAC.

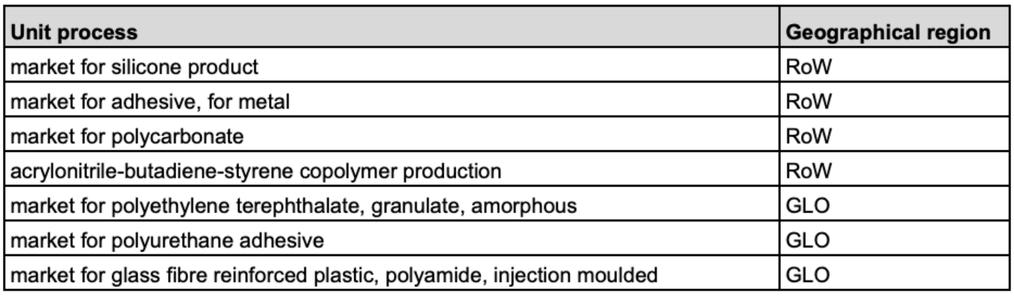
The material composition differs between the three different datasets, while the production effort is generalized for all three inductors. It includes the input of auxiliaries (mainly methyl ethyl ketone and ethyl acetate) and energy, outputs such as emissions and waste, as well as transportation, infrastructure and land-use.

Integrated circuits
The Ecoinvent database differentiates ICs into two types, one logic type and one memory type (Hischier et al., 2007). The logic type performs specified logical operations, such as processing and passing on incoming data, while the memory type stores the data. These two categories of ICs, and the two datasets, have been used in this study for several different components that do not fit into any of the other component categories. This categorization was done in collaboration with a hardware technician at CPAC, to ensure that it was done reasonably. The components classified as memory type ICs are the memories located on both the main and the modem PCBAs. The components classified as logic type ICs are the following:

- Amplifiers
- Controllers
- Converters
- Drivers
- Expanders
- Inverters
- Processors
- Protectors
- Radios
- Receivers
- Regulators
- Sensors
- SIM card
- Switches
- Transceivers
- Translators
- Voltage references

Plastic parts for Hydra assembly
There are several plastic parts included in the Hydra, ranging from O-rings to dust caps and labels, which are used for shielding or decorative purposes. These parts have been approximated using different datasets in Ecoinvent, based on their material composition and the complexity of the production processes used to produce them. Datasets used to approximate these components are shown in Table 2. All these datasets include the raw material inputs and process energy consumption, as well as waste and emissions.

Table 2: Datasets from Ecoinvent used to approximate plastic parts for Hydra assembly



Unit process	Geographical region
market for silicone product	RoW
market for adhesive, for metal	RoW
market for polycarbonate	RoW
acrylonitrile-butadiene-styrene copolymer production	RoW
market for polyethylene terephthalate, granulate, amorphous	GLO
market for polyurethane adhesive	GLO
market for glass fibre reinforced plastic, polyamide, injection moulded	GLO

Printed circuit boards

One of the larger components present in the Hydra is the PCB. The PCB is an interconnective electrical structure that all electrical components are mounted onto (Hischier et al., 2007). It thus serves as the foundation for the function of the Hydra, and consists of multiple electrical current conducting and non-conducting layers. There are many different PCBs for different intended applications. The main PCB of the Hydra consists of 10 layers, and has a total area of $0.049\,\mathrm{m}^2$, while the PCB of the modem module consists of 4 layers and has an area of $0.0039\,\mathrm{m}^2$. Both PCBs present in the Hydra are prepared for surface mounting, since this is the technology used for mounting most of electrical components onto the board. In Ecoinvent there are two datasets available for the process of producing PCBs, one for SMT and one for THT. In addition, there are also options for either a lead-free or lead-containing surface of the PCB. There is no lead present in the PCBs included in the Hydra, and they are both prepared for surface mounting. Hence, the dataset for this type of PCB is most representative. This dataset includes data for the raw materials, infrastructure, energy consumption, emissions and waste (Hischier et al., 2007).

One thing that should be noted is that the PCB represented in the chosen dataset is a 6-layer board, which is not the same number of layers as either of the two PCBs used in the Hydra. However, the thickness of both boards is approximately the same as the thickness used in the approximation in Ecoinvent. After consultation with a hardware technician, the approximation available in Ecoinvent was thus decided to be a sufficient proxy for the PCBs in the Hydra.

Resistors

In the Hydra there are many resistors of different kinds and sizes. A resistor is an electronic component that produces a voltage drop between its two terminals and thereby resists an electric current (Hischier et al., 2007). In this study, the resistors have been divided into two categories: surface mounted resistors and resistors mounted with THT. The two most similar resistor datasets available in Ecoinvent are the resistor SMD type, which was chosen to represent all the resistors in the Hydra that are mounted using SMT, and the resistor metal-film type, which was chosen to represent resistors mounted with THT. The same production effort is considered for both types of resistors, while the material composition differs. The production effort includes the input of auxiliaries (solvents, hardeners and ethyl cellulose) and energy, outputs such as emissions and waste (non-used raw material, mainly hardener), as well as transportation, infrastructure and land use.

Sealants

The Hydra is glued together in the final assembly using different kinds of sealants. The sealants in the final product have been approximated based on their material composition using two datasets available in Ecoinvent, namely datasets for metal adhesive and silicone product production. The dataset for metal adhesive production incorporates the basic materials used in the production, but excludes energy consumption in the production phase (Hischier et al., 2007). The dataset for silicone product production is calculated as an average of the production of 2000 different silicone products, and includes data on the raw material inputs, the production facility infrastructure, the energy consumption, waste and emissions.

Transformers

A transformer is an electrical device that transfers energy between circuits by magnetic coupling (Hischier et al., 2007). In the Hydra there is one type of transformer present, which is used for low voltages. These transformers have been approximated using a dataset for low voltage transformers in Ecoinvent. The available dataset includes the production efforts for producing a low voltage transformer. The inventory is not based on data for one specific production plant. Instead, the energy consumption is indirectly accounted for by the specific processing datasets for the raw materials. The inventory also includes data for standard transport distances and waste streams of non-used-materials. However, no emission flows are included in the inventory of transformers due to lack of information (Hischier et al., 2007). Therefore, the uncertainty of this dataset is considered high.

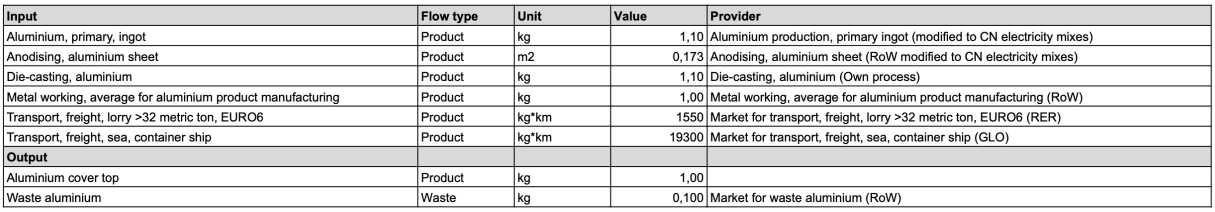
Transistors

The Hydra also contains several transistors, which are semiconductor devices that can act as current amplifiers, voltage controllers or regulators, and oscillators (Hischier et al., 2007). In Ecoinvent, there are datasets available for different types of transistors. The production efforts are identical for all the datasets, comparative to the average production efforts, while the composition of the devices differ between the available approximations. Most of the transistors in the Hydra are SMD type, and the chosen dataset in Ecoinvent represents a typical SMD transistor. The production effort included in the dataset includes the input of auxiliaries (mainly nitrogen, as process gas) and energy, outputs such as emissions and waste (non-used raw material such as epoxy, lead frame and solder), as well as transportation, infrastructure and land-use.

A2. Unit processes

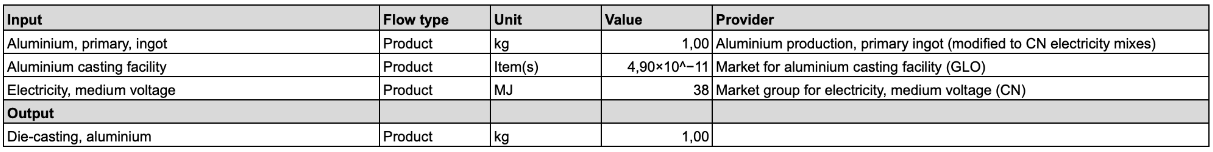
In this Appendix the unit processes for the components and processes modeled by the authors are shown (Tables 3-18).

Table 3: Unit process for the production of 1 kg aluminium housing, using the top cover as an example.



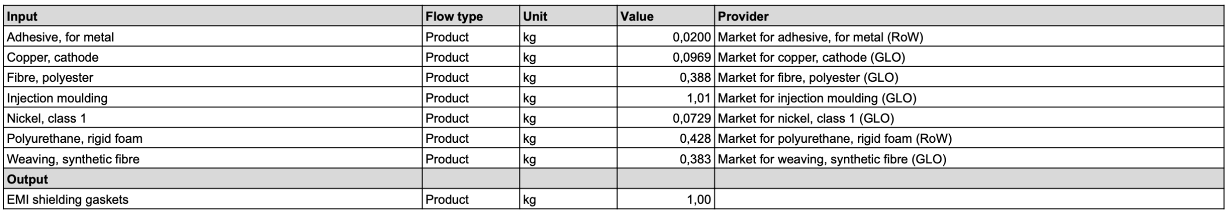
Input	Flow type	Unit	Value	Provider
Aluminium, primary, ingot	Product	kg	1,10	Aluminium production, primary ingot (modified to CN electricity mixes)
Anodising, aluminium sheet	Product	m2	0,173	Anodising, aluminium sheet (RoW modified to CN electricity mixes)
Die-casting, aluminium	Product	kg	1,10	Die-casting, aluminium (Own process)
Metal working, average for aluminium product manufacturing	Product	kg	1,00	Metal working, average for aluminium product manufacturing (RoW)
Transport, freight, lorry >32 metric ton, EURO6	Product	kg*km	1550	Market for transport, freight, lorry >32 metric ton, EURO6 (RER)
Transport, freight, sea, container ship	Product	kg*km	19300	Market for transport, freight, sea, container ship (GLO)
Output				
Aluminium cover top	Product	kg	1,00	
Waste aluminium	Waste	kg	0,100	Market for waste aluminium (RoW)

Table 4: Unit process for aluminium die casting.



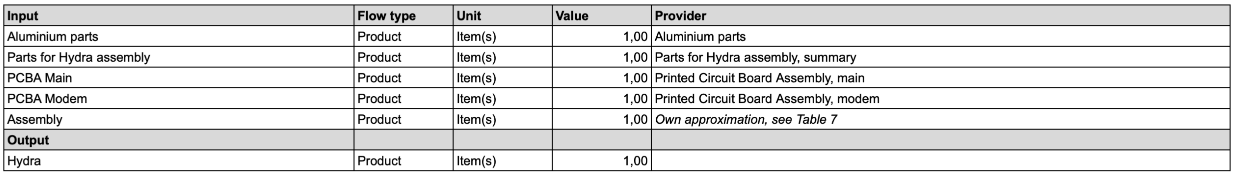
Input	Flow type	Unit	Value	Provider
Aluminium, primary, ingot	Product	kg	1,00	Aluminium production, primary ingot (modified to CN electricity mixes)
Aluminium casting facility	Product	Item(s)	4,90×10^−11	Market for aluminium casting facility (GLO)
Electricity, medium voltage	Product	MJ	38	Market group for electricity, medium voltage (CN)
Output				
Die-casting, aluminium	Product	kg	1,00	

Table 5: Unit process for the production of 1 kg EMI shielding gaskets.



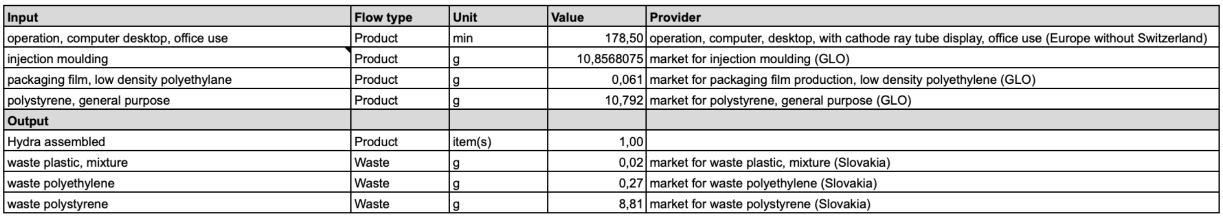
Input	Flow type	Unit	Value	Provider
Adhesive, for metal	Product	kg	0,0200	Market for adhesive, for metal (RoW)
Copper, cathode	Product	kg	0,0969	Market for copper, cathode (GLO)
Fibre, polyester	Product	kg	0,388	Market for fibre, polyester (GLO)
Injection moulding	Product	kg	1,01	Market for injection moulding (GLO)
Nickel, class 1	Product	kg	0,0729	Market for nickel, class 1 (GLO)
Polyurethane, rigid foam	Product	kg	0,428	Market for polyurethane, rigid foam (RoW)
Weaving, synthetic fibre	Product	kg	0,383	Market for weaving, synthetic fibre (GLO)
Output				
EMI shielding gaskets	Product	kg	1,00	

Table 6: Unit process for the assembly of one Hydra.



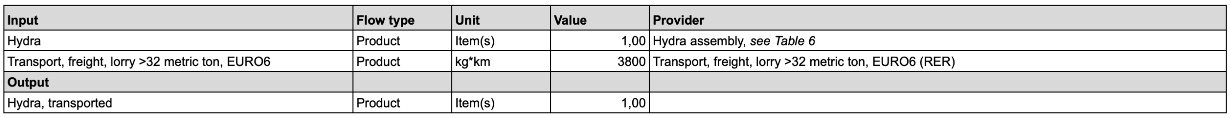
Input	Flow type	Unit	Value	Provider
Aluminium parts	Product	Item(s)	1,00	Aluminium parts
Parts for Hydra assembly	Product	Item(s)	1,00	Parts for Hydra assembly, summary
PCBA Main	Product	Item(s)	1,00	Printed Circuit Board Assembly, main
PCBA Modem	Product	Item(s)	1,00	Printed Circuit Board Assembly, modem
Assembly	Product	Item(s)	1,00	*Own approximation, see Table 7*
Output				
Hydra	Product	Item(s)	1,00	

Table 7: Unit process for the production process of one Hydra.



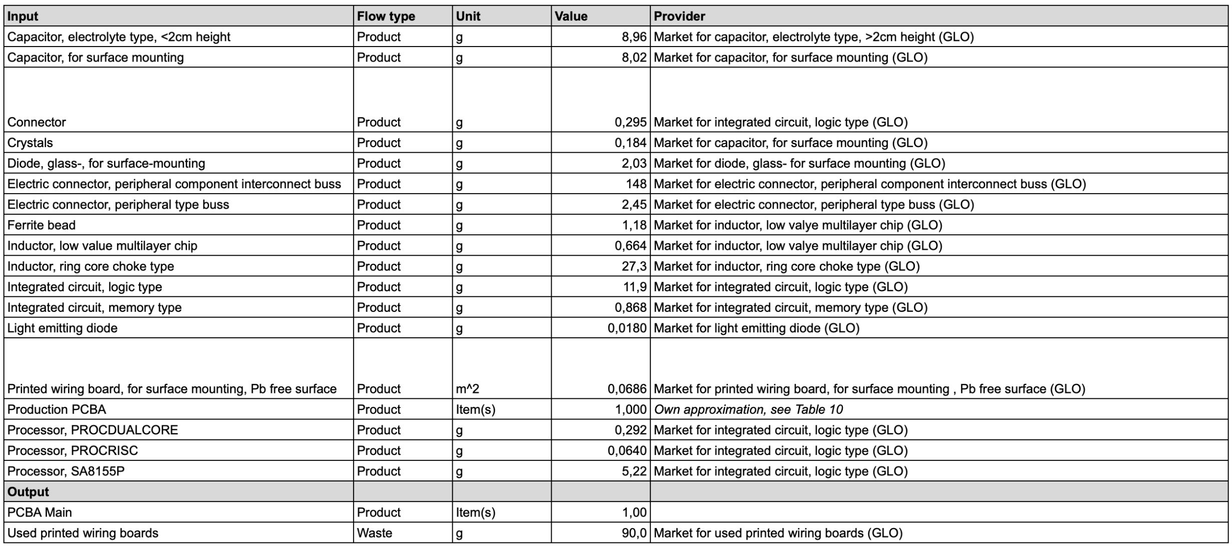
Input	Flow type	Unit	Value	Provider
operation, computer desktop, office use	Product	min	178,50	operation, computer, desktop, with cathode ray tube display, office use (Europe without Switzerland)
injection moulding	Product	g	10,8568075	market for injection moulding (GLO)
packaging film, low density polyethylane	Product	g	0,061	market for packaging film production, low density polyethylene (GLO)
polystyrene, general purpose	Product	g	10,792	market for polystyrene, general purpose (GLO)
Output				
Hydra assembled	Product	item(s)	1,00	
waste plastic, mixture	Waste	g	0,02	market for waste plastic, mixture (Slovakia)
waste polyethylene	Waste	g	0,27	market for waste polyethylene (Slovakia)
waste polystyrene	Waste	g	8,81	market for waste polystyrene (Slovakia)

Table 8: Unit process for the transport of one assembled Hydra, from the factory in Slovakia to the storage unit in Sweden.



Input	Flow type	Unit	Value	Provider
Hydra	Product	Item(s)	1,00	Hydra assembly, *see Table 6*
Transport, freight, lorry >32 metric ton, EURO6	Product	kg*km	3800	Transport, freight, lorry >32 metric ton, EURO6 (RER)
Output				
Hydra, transported	Product	Item(s)	1,00	

Table 9: Unit process for PCBA Main. The modem PCBA contains the same components but with varying amounts.



Input	Flow type	Unit	Value	Provider
Capacitor, electrolyte type, <2cm height	Product	g	8,96	Market for capacitor, electrolyte type, >2cm height (GLO)
Capacitor, for surface mounting	Product	g	8,02	Market for capacitor, for surface mounting (GLO)
Connector	Product	g	0,295	Market for integrated circuit, logic type (GLO)
Crystals	Product	g	0,184	Market for capacitor, for surface mounting (GLO)
Diode, glass-, for surface-mounting	Product	g	2,03	Market for diode, glass- for surface mounting (GLO)
Electric connector, peripheral component interconnect buss	Product	g	148	Market for electric connector, peripheral component interconnect buss (GLO)
Electric connector, peripheral type buss	Product	g	2,45	Market for electric connector, peripheral type buss (GLO)
Ferrite bead	Product	g	1,18	Market for inductor, low valye multilayer chip (GLO)
Inductor, low value multilayer chip	Product	g	0,664	Market for inductor, low valye multilayer chip (GLO)
Inductor, ring core choke type	Product	g	27,3	Market for inductor, ring core choke type (GLO)
Integrated circuit, logic type	Product	g	11,9	Market for integrated circuit, logic type (GLO)
Integrated circuit, memory type	Product	g	0,868	Market for integrated circuit, memory type (GLO)
Light emitting diode	Product	g	0,0180	Market for light emitting diode (GLO)
Printed wiring board, for surface mounting, Pb free surface	Product	m^2	0,0686	Market for printed wiring board, for surface mounting , Pb free surface (GLO)
Production PCBA	Product	Item(s)	1,000	*Own approximation, see Table 10*
Processor, PROCDUALCORE	Product	g	0,292	Market for integrated circuit, logic type (GLO)
Processor, PROCRISC	Product	g	0,0640	Market for integrated circuit, logic type (GLO)
Processor, SA8155P	Product	g	5,22	Market for integrated circuit, logic type (GLO)
Output				
PCBA Main	Product	Item(s)	1,00	
Used printed wiring boards	Waste	g	90,0	Market for used printed wiring boards (GLO)

Table 10: Unit process for the production of PCBA Main. The modem PCBA contains the same processes but with varying amounts.

Input	**Flow type**	**Unit**	**Value**	**Provider**	**Step in production**
laser machining, metal, with CO2-laser, 4000W power	Product	h	0,00833	laser machining, metal, with CO2-laser, 4000W powwer (GLO)	Laser marking
mounting, surface mount technology, Pb-free solder	Product	m2	0,09705	mounting, surface mount technology, Pb-free solder (GLO)	Surface mounting
operation, computer desktop, office use	Product	h	0,688	operation, computer, desktop, with cathode ray tube display, office use (Europe without Switzerland)	Material recieving, in circuit testing, software downloading
electricity, medium voltage	Product	kWh	0,012400	market for electricity, medium voltage (Slovakia)	Router depaneling
metal working machine, unspecified	Product	kg	00.47	market for metal working machine, unspecified (GLO)	Router depaneling
injection moulding	Product	g	212,7065725	market for injection moulding (GLO)	Tape and reel
packaging film, low density polyethylane	Product	g	1,200	market for packaging film production, low density polyethylene (GLO)	Tape and reel
polystyrene, general purpose	Product	g	211,430	market for polystyrene, general purpose (GLO)	Tape and reel
electricity, medium voltage	Product	kWh	1,137	market for electricity, medium voltage (Slovakia)	THT selective soldering
flux, for wave soldering	Product	g	0,150	market for flux, for wave soldering (GLO)	THT selective soldering
nitrogen, liquid	Product	kg	0,781	market for nitrogen, liquid (RER)	THT selective soldering
operation, computer desktop, office use	Product	h	0,084	operation, computer, desktop, with cathode ray tube display, office use (Europe without Switzerland)	THT selective soldering
printed wiring board mounting facility	Product	item(s)	1,01×10^−08	market for printed wiring board mounting facility (GLO)	THT selective soldering
solder paste, Sn95.5Ag3.9Cu0.6, for electronics industry	Product	kg	0,021	market for solder, paste, Sn95.5,Ag3.9Cu0.6, for electronics industry (GLO)	THT selective soldering
electricity, medium voltage	Product	kWh	0,019	market for electricity, medium voltage (Slovakia)	X-ray of PCBA
metal working machine, unspecified	Product	kg	0,006	market for metal working machine, unspecified (GLO)	X-ray of PCBA
Output					
assembled PCBA main	Product	item(s)	1,00		
waste plastic, mixture	Waste	g	0,45	market for waste plastic, mixture (Slovakia)	Tape and reel
waste polyethylene	Waste	g	5,33	market for waste polyethylene (Slovakia)	Tape and reel
waste polystyrene	Waste	g	172,60	market for waste polystyrene (Slovakia)	Tape and reel

Table 11: Unit process for the production of 1 kg of screw-type 1.

Input	**Flow type**	**Unit**	**Value**	**Provider**
Glass fibre reinforced plastic, polyamide, injection moulded	Product	kg	0,000345	Market for glass fibre reinforced plastic, polyamide, injection moulded (GLO)
Hard chromium coat, electroplating, steel substrate, 0.14 mm thickness	Product	m2	0,360	Market for Hard chromium coat, electroplating, steel substrate, 0.14 mm thickness (GLO)
Hot rolling, steel	Product	kg	1,00	Market for Hot rolling, steel (GLO)
Metal working, average for steel product manufacturing	Product	kg	1,00	Market for Metal working, average for steel product manufacturing (GLO)
Steel, low-alloyed	Product	kg	1,00	Market for Steel, low-alloyed (GLO)
Wire drawing, steel	Product	kg	1,00	Market for Wire drawing, steel (GLO)
Zinc coat, pieces	Product	m2	0,360	Market for Zinc coat, pieces (GLO)
Output				
Screws	Product	kg	1,00	

Table 12: Unit process for the production of 1 kg of screw-type 2.

Input	**Flow type**	**Unit**	**Value**	**Provider**
Hot rolling, steel	Product	kg	1,00	Market for Hot rolling, steel (GLO)
Metal working, average for steel product manufacturing	Product	kg	1,00	Market for Metal working, average for steel product manufacturing (GLO)
Steel, low-alloyed	Product	kg	1,00	Market for Steel, low-alloyed (GLO)
Wire drawing, steel	Product	kg	1,00	Market for Wire drawing, steel (GLO)
Zinc coat, pieces	Product	m2	0,100	Market for Zinc coat, pieces (GLO)
Output				
Screws	Product	kg	1,00	

Table 13: Unit process for the production of 1 kg of screw-type 3.

Input	Flow type	Unit	Value	Provider
Glass fibre reinforced plastic, polyamide, injection moulded	Product	kg	0,002	Market for glass fibre reinforced plastic, polyamide, injection moulded (GLO)
Hot rolling, steel	Product	kg	0,998	Market for Hot rolling, steel (GLO)
Metal working, average for steel product manufacturing	Product	kg	0,998	Market for Metal working, average for steel product manufacturing (GLO)
Steel, low-alloyed	Product	kg	0,998	Market for Steel, low-alloyed (GLO)
Wire drawing, steel	Product	kg	0,998	Market for Wire drawing, steel (GLO)
Zinc coat, pieces	Product	m2	0,360	Market for Zinc coat, pieces (GLO)
Output				
Screws	Product	kg	1,00	

Table 14: Unit process for the production of 1 kg of screw-type 4.

Input	Flow type	Unit	Value	Provider
Hard chromium coat, electroplating, steel substrate, 0.14 mm thickness	Product	m2	0,360	Market for Hard chromium coat, electroplating, steel substrate, 0.14 mm thickness (GLO)
Hot rolling, steel	Product	kg	1,00	Market for Hot rolling, steel (GLO)
Metal working, average for steel product manufacturing	Product	kg	1,00	Market for Metal working, average for steel product manufacturing (GLO)
Steel, low-alloyed	Product	kg	1,00	Market for Steel, low-alloyed (GLO)
Wire drawing, steel	Product	kg	1,00	Market for Wire drawing, steel (GLO)
Zinc coat, pieces	Product	m2	0,360	Market for Zinc coat, pieces (GLO)
Output				
Screws	Product	kg	1,00	

Table 15: Unit process for the production of 1 kg shield clip.

Input	Flow type	Unit	Value	Provider
Iron-nickel-chromium alloy	Product	kg	1,00	Market for iron-nickel-chromium alloy (GLO)
Metal working, average for chromium steel product manufacturing	Product	kg	1,00	Market for metal working, average for chromium steel product manufacturing (GLO)
Tin plating, pieces	Product	m2	1,20	Market for tin plating (GLO)
Output				
Shield clip	Product	kg	1,00	

Table 16: Unit process for the production of 1 kg shielding can.

Input	Flow type	Unit	Value	Provider
Brass	Product	kg	1,00	Brass production (RoW)
Metal working, average for metal product manufacturing	Product	kg	1,00	Market for metal working, average for metal product manufacturing (GLO)
Output				
Shielding can	Product	kg	1,00	

Table 17: Unit process for the production of 1 kg of shielding for the LTE module.

Input	Flow type	Unit	Value	Provider
Brass	Product	kg	1,00	Brass production (RoW)
Metal working, average for metal product manufacturing	Product	kg	1,00	Market for metal working, average for metal product manufacturing (GLO)
Output				
Shielding LTE	Product	kg	1,00	

Table 18: *Unit process for the production of 1 kg of washer.*

Input	Flow type	Unit	Value	Provider
Iron-nickel-chromium alloy	Product	kg	1,00	Market for iron-nickel-chromium alloy (GLO)
Metal working, average for chromium steel product manufacturing	Product	kg	1,00	Market for metal working, average for chromium steel product manufacturing (GLO)
Output				
Washer	Product	kg	1,00	

A3. Impact assessment

In this appendix the results from the LCIA of the base case are shown (Figures 34-45), for each of the impact categories not discussed in detail in Section 5.

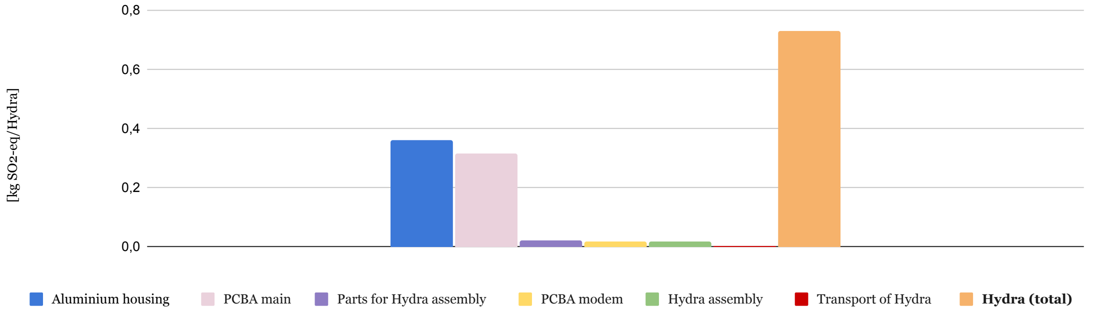


Figure 34: Acidification of the major components of the Hydra, as well as its assembly and transport.

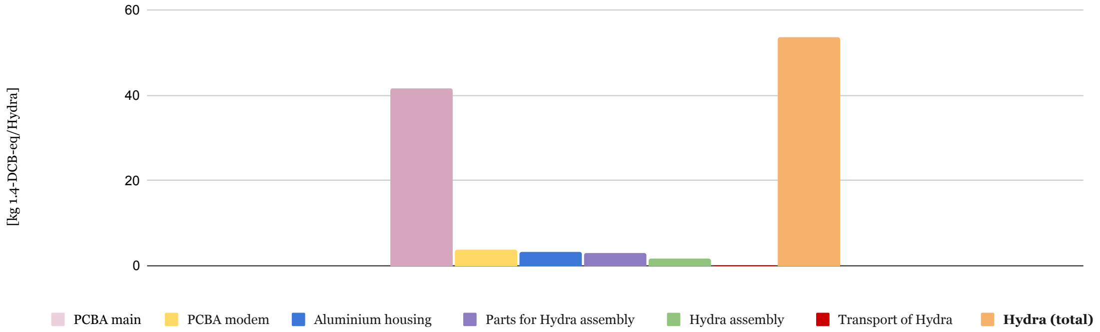


Figure 35: Ecotoxicity: freshwater of the major components of the Hydra, as well as its assembly and transport.

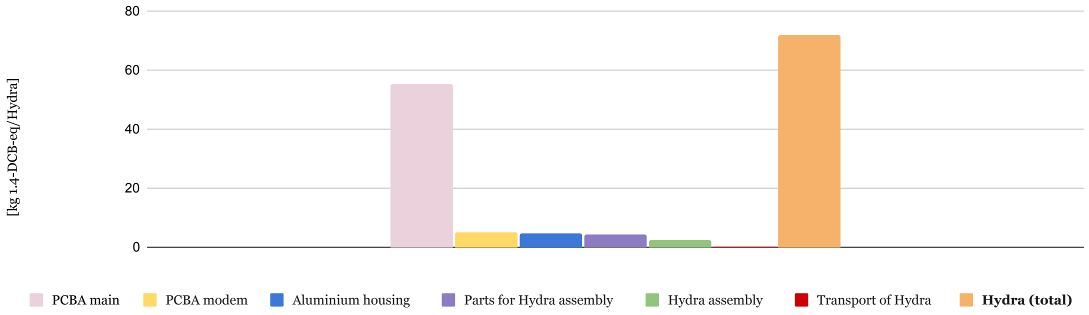


Figure 36: Ecotoxicity: marine of the major components of the Hydra, as well as its assembly and transport.

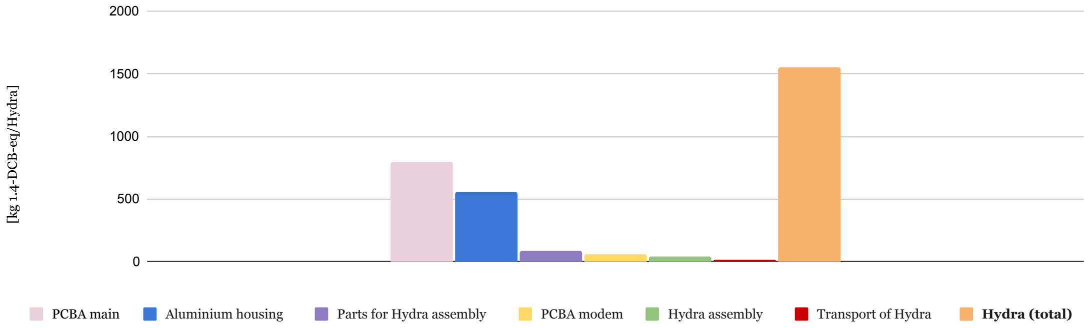


Figure 37: Ecotoxicity: terrestrial of the major components of the Hydra, as well as its assembly and transport.

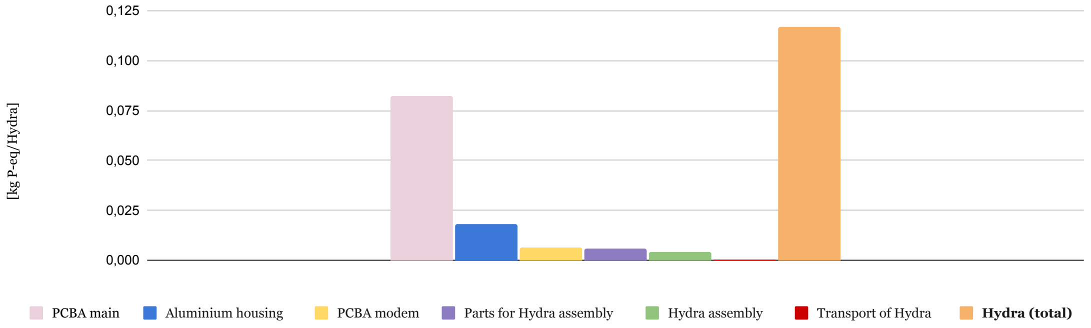


Figure 38: Eutrophication: freshwater of the major components of the Hydra, as well as its assembly and transport.

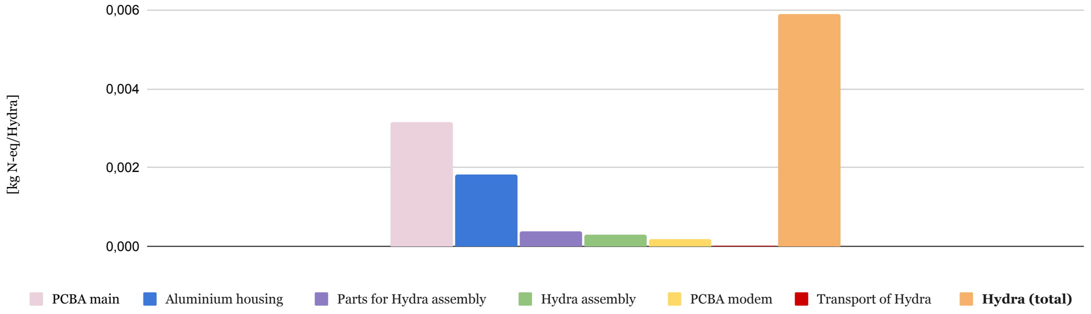


Figure 39: Eutrophication: marine of the major components of the Hydra, as well as its assembly and transport.

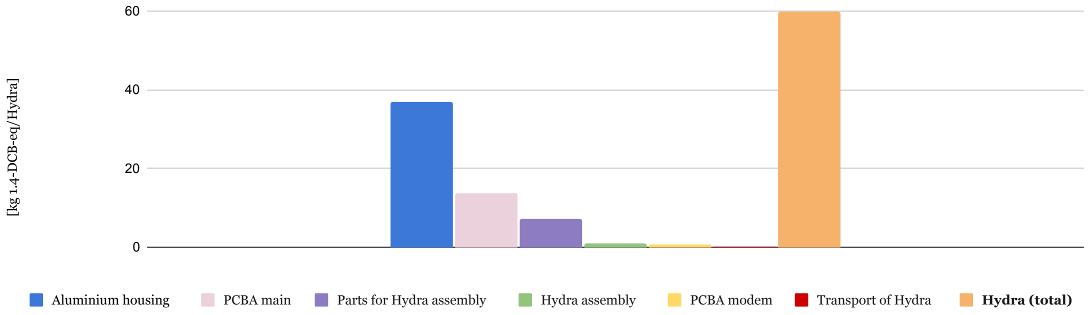


Figure 40: Human toxicity: carcinogenic of the major components of the Hydra, as well as its assembly and transport.

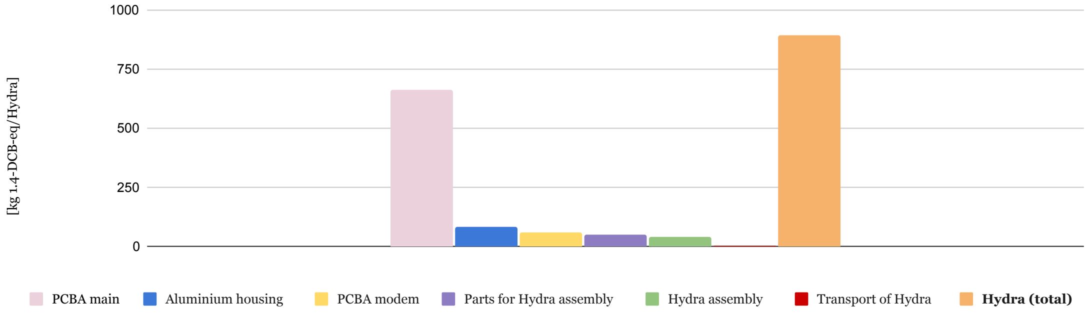


Figure 41: Human toxicity: non-carcinogenic of the major components of the Hydra, as well as its assembly and transport.

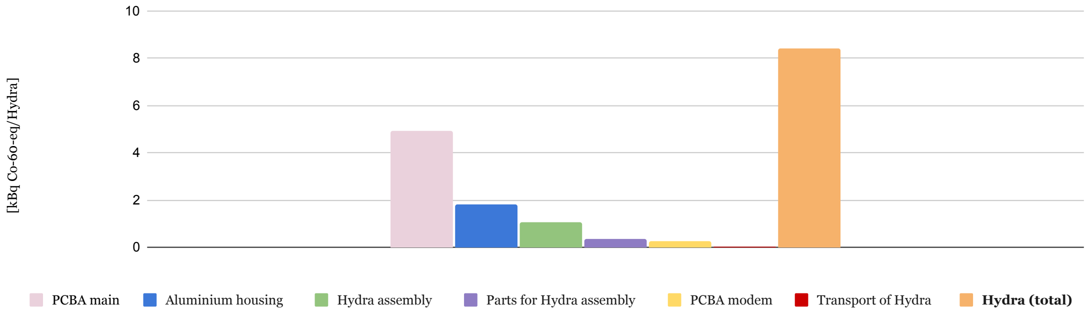


Figure 42: Ionizing radiation of the major components of the Hydra, as well as its assembly and transport.

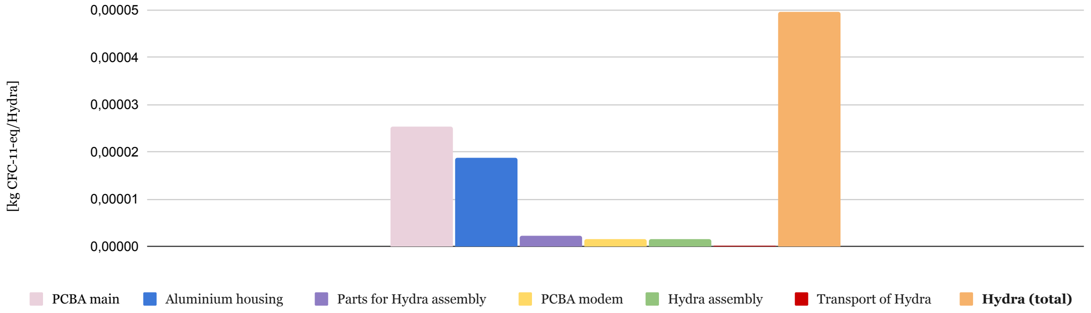


Figure 43: Ozone depletion of the major components of the Hydra, as well as its assembly and transport.

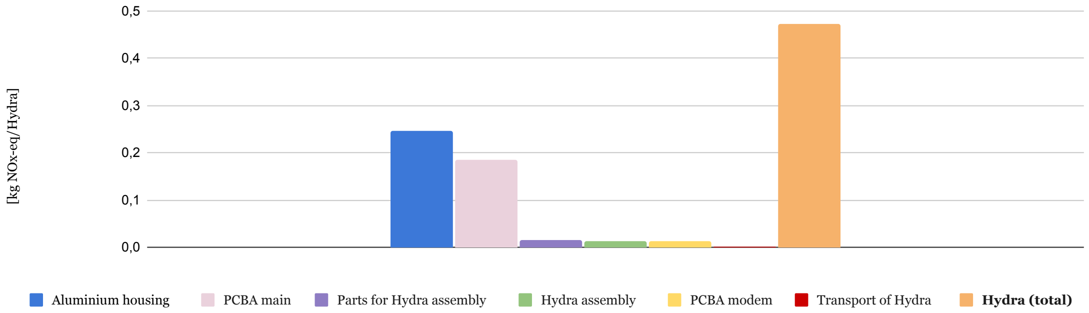


Figure 44: Photochemical oxidant formation: human health of the major components of the Hydra, as well as its assembly and transport.

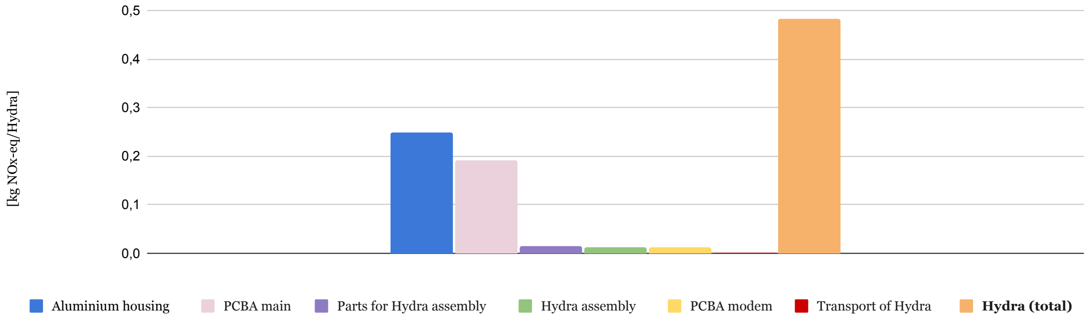
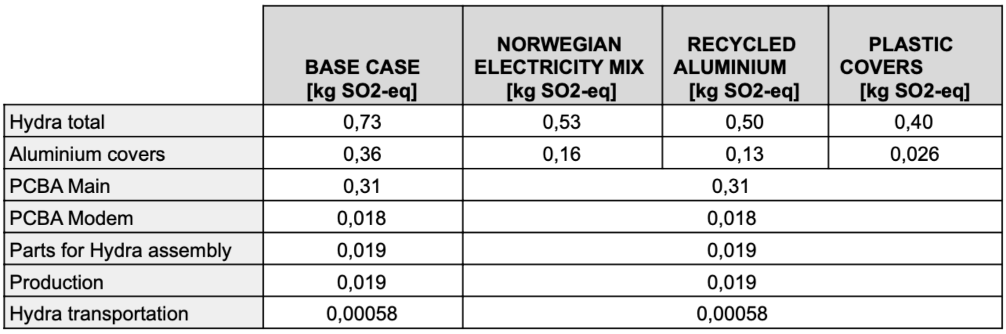


Figure 45: Photochemical oxidant formation: terrestrial of the major components of the Hydra, as well as its assembly and transport.

A4. Results of the scenario analysis

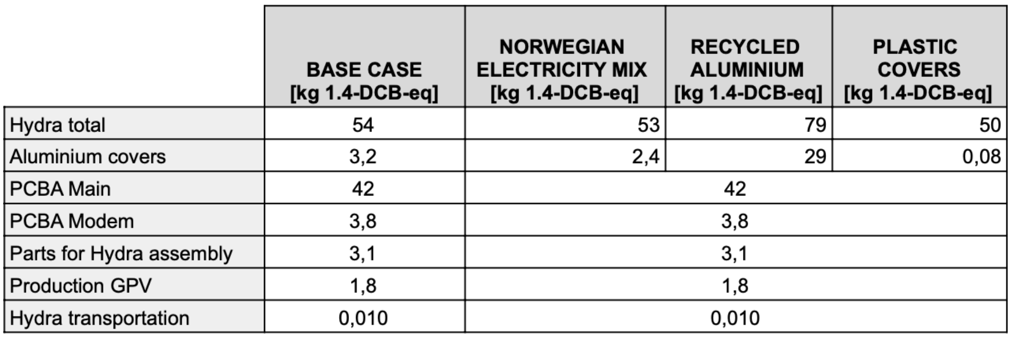
In this appendix the results for the base case and three improvement scenarios are shown (Tables 19-37) for all impact categories studied, the results are calculated per Hydra.

Table 19: Acidification for the base case and the three improvement scenarios



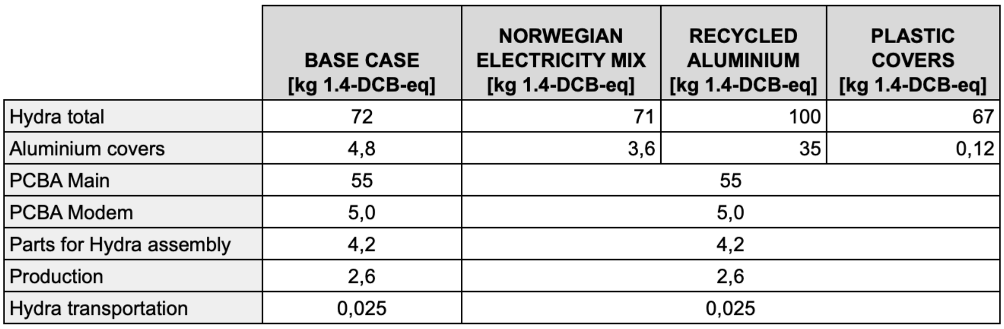
	BASE CASE [kg SO2-eq]	NORWEGIAN ELECTRICITY MIX [kg SO2-eq]	RECYCLED ALUMINIUM [kg SO2-eq]	PLASTIC COVERS [kg SO2-eq]
Hydra total	0,73	0,53	0,50	0,40
Aluminium covers	0,36	0,16	0,13	0,026
PCBA Main	0,31	0,31		
PCBA Modem	0,018	0,018		
Parts for Hydra assembly	0,019	0,019		
Production	0,019	0,019		
Hydra transportation	0,00058	0,00058		

Table 20: Ecotoxicity: freshwater for the base case and the three improvement scenarios



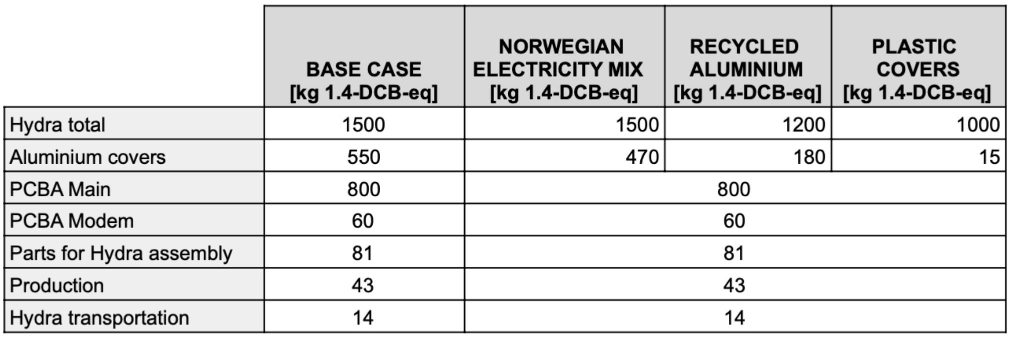
	BASE CASE [kg 1.4-DCB-eq]	NORWEGIAN ELECTRICITY MIX [kg 1.4-DCB-eq]	RECYCLED ALUMINIUM [kg 1.4-DCB-eq]	PLASTIC COVERS [kg 1.4-DCB-eq]
Hydra total	54	53	79	50
Aluminium covers	3,2	2,4	29	0,08
PCBA Main	42	42		
PCBA Modem	3,8	3,8		
Parts for Hydra assembly	3,1	3,1		
Production GPV	1,8	1,8		
Hydra transportation	0,010	0,010		

Table 21: Ecotoxicity: marine for the base case and the three improvement scenarios



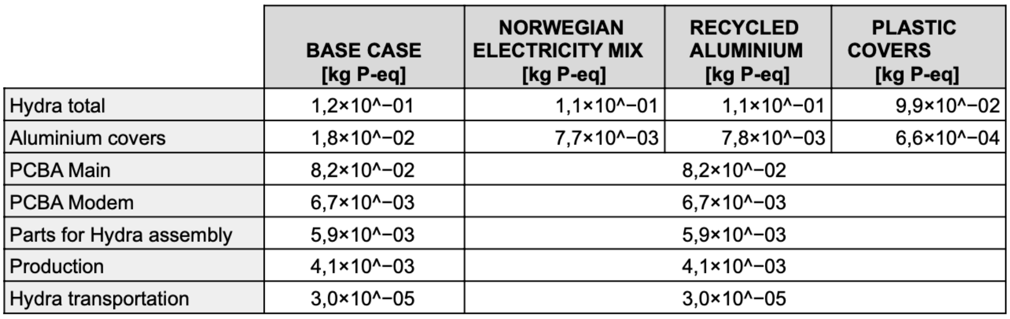
	BASE CASE [kg 1.4-DCB-eq]	NORWEGIAN ELECTRICITY MIX [kg 1.4-DCB-eq]	RECYCLED ALUMINIUM [kg 1.4-DCB-eq]	PLASTIC COVERS [kg 1.4-DCB-eq]
Hydra total	72	71	100	67
Aluminium covers	4,8	3,6	35	0,12
PCBA Main	55	55		
PCBA Modem	5,0	5,0		
Parts for Hydra assembly	4,2	4,2		
Production	2,6	2,6		
Hydra transportation	0,025	0,025		

Table 22: Ecotoxicity: terrestrial for the base case and the three improvement scenarios



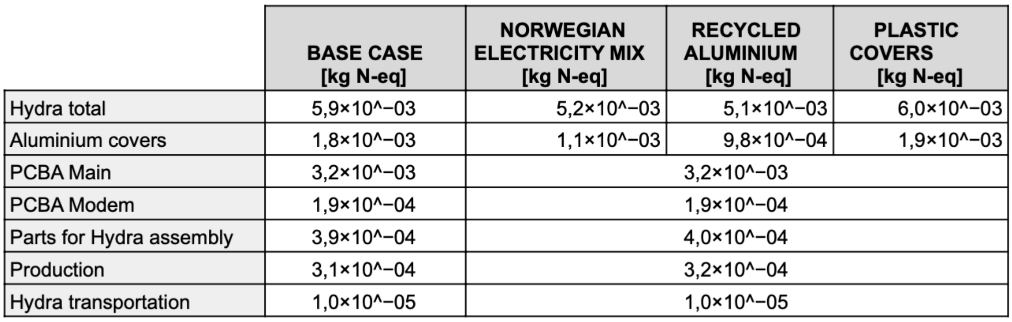
	BASE CASE [kg 1.4-DCB-eq]	NORWEGIAN ELECTRICITY MIX [kg 1.4-DCB-eq]	RECYCLED ALUMINIUM [kg 1.4-DCB-eq]	PLASTIC COVERS [kg 1.4-DCB-eq]
Hydra total	1500	1500	1200	1000
Aluminium covers	550	470	180	15
PCBA Main	800	800		
PCBA Modem	60	60		
Parts for Hydra assembly	81	81		
Production	43	43		
Hydra transportation	14	14		

Table 23: Eutrophication: freshwater for the base case and the three improvement scenarios



	BASE CASE [kg P-eq]	NORWEGIAN ELECTRICITY MIX [kg P-eq]	RECYCLED ALUMINIUM [kg P-eq]	PLASTIC COVERS [kg P-eq]
Hydra total	1,2×10^−01	1,1×10^−01	1,1×10^−01	9,9×10^−02
Aluminium covers	1,8×10^−02	7,7×10^−03	7,8×10^−03	6,6×10^−04
PCBA Main	8,2×10^−02	8,2×10^−02		
PCBA Modem	6,7×10^−03	6,7×10^−03		
Parts for Hydra assembly	5,9×10^−03	5,9×10^−03		
Production	4,1×10^−03	4,1×10^−03		
Hydra transportation	3,0×10^−05	3,0×10^−05		

Table 24: Eutrophication: marine for the base case and the three improvement scenarios



	BASE CASE [kg N-eq]	NORWEGIAN ELECTRICITY MIX [kg N-eq]	RECYCLED ALUMINIUM [kg N-eq]	PLASTIC COVERS [kg N-eq]
Hydra total	5,9×10^−03	5,2×10^−03	5,1×10^−03	6,0×10^−03
Aluminium covers	1,8×10^−03	1,1×10^−03	9,8×10^−04	1,9×10^−03
PCBA Main	3,2×10^−03	3,2×10^−03		
PCBA Modem	1,9×10^−04	1,9×10^−04		
Parts for Hydra assembly	3,9×10^−04	4,0×10^−04		
Production	3,1×10^−04	3,2×10^−04		
Hydra transportation	1,0×10^−05	1,0×10^−05		

Table 25: Fossil resource scarcity for the base case and the three improvement scenarios

	BASE CASE [kg oil eq]	NORWEGIAN ELECTRICITY MIX [kg oil eq]	RECYCLED ALUMINIUM [kg oil eq]	PLASTIC COVERS [kg oil eq]
Hydra total	35	23	24	19
Aluminium covers	18	6,3	7,6	2,8
PCBA Main	13	13		
PCBA Modem	0,71	0,71		
Parts for Hydra assembly	1,2	1,2		
Production	1,2	1,2		
Hydra transportation	0,13	0,13		

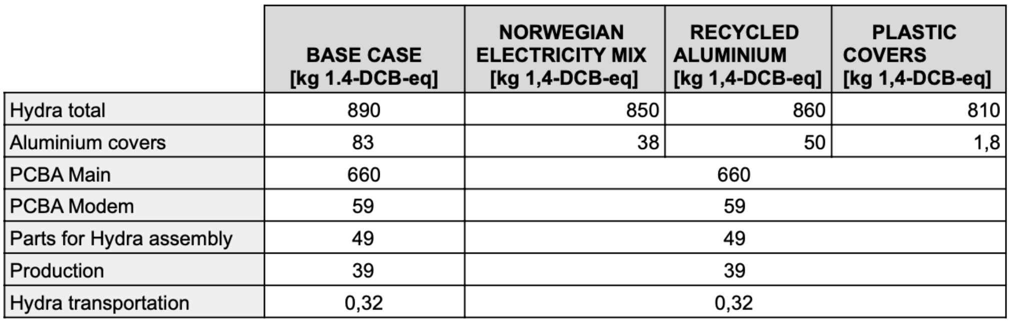
Table 26: Global warming for the base case and the three improvement scenarios

	BASE CASE [kg CO2-eq]	NORWEGIAN ELECTRICITY MIX [kg CO2-eq]	RECYCLED ALUMINIUM [kg CO2-eq]	PLASTIC COVERS [kg CO2-eq]
Hydra total	150	96	101	74
Aluminium covers	90,1	31	36	9,3
PCBA Main	53	53		
PCBA Modem	2,8	2,8		
Parts for Hydra assembly	4,5	4,5		
Production	4,1	4,1		
Hydra transportation	0,40	0,40		

Table 27: Human toxicity: carcinogenic for the base case and the three improvement scenarios

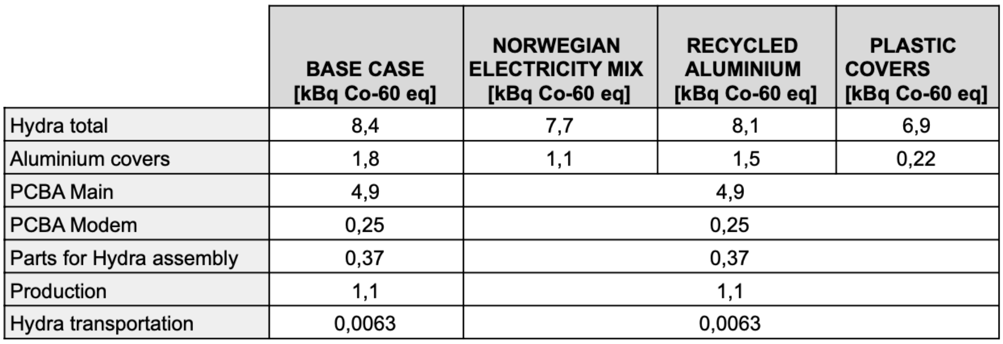
	BASE CASE [kg 1.4-DCB-eq]	NORWEGIAN ELECTRICITY MIX [kg 1,4-DCB-eq]	RECYCLED ALUMINIUM [kg 1,4-DCB-eq]	PLASTIC COVERS [kg 1,4-DCB-eq]
Hydra total	60	54	30	23
Aluminium covers	37	31	7,3	0,41
PCBA Main	14	14		
PCBA Modem	0,60	0,60		
Parts for Hydra assembly	7,3	7,3		
Production	1,1	1,1		
Hydra transportation	0,072	0,072		

Table 28: Human toxicity: non-carcinogenic for the base case and the three improvement scenarios



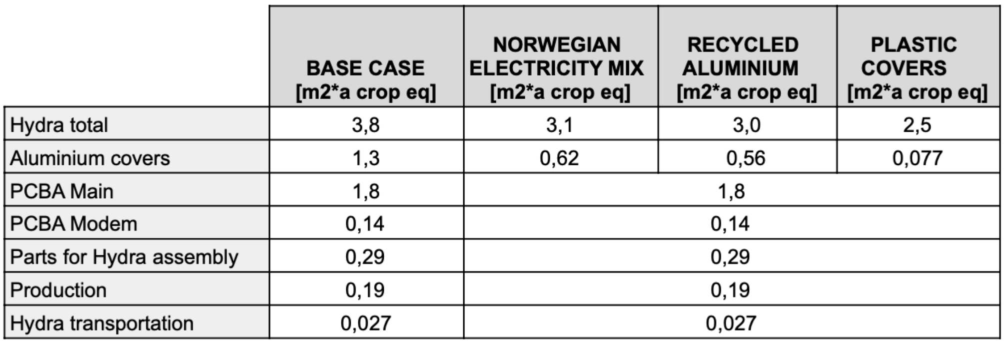
	BASE CASE [kg 1.4-DCB-eq]	NORWEGIAN ELECTRICITY MIX [kg 1,4-DCB-eq]	RECYCLED ALUMINIUM [kg 1,4-DCB-eq]	PLASTIC COVERS [kg 1,4-DCB-eq]
Hydra total	890	850	860	810
Aluminium covers	83	38	50	1,8
PCBA Main	660	660		
PCBA Modem	59	59		
Parts for Hydra assembly	49	49		
Production	39	39		
Hydra transportation	0,32	0,32		

Table 29: Ionizing radiation for the base case and the three improvement scenarios



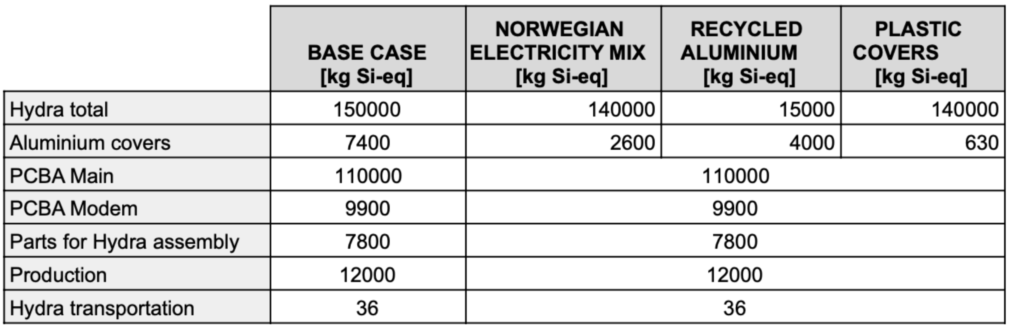
	BASE CASE [kBq Co-60 eq]	NORWEGIAN ELECTRICITY MIX [kBq Co-60 eq]	RECYCLED ALUMINIUM [kBq Co-60 eq]	PLASTIC COVERS [kBq Co-60 eq]
Hydra total	8,4	7,7	8,1	6,9
Aluminium covers	1,8	1,1	1,5	0,22
PCBA Main	4,9	4,9		
PCBA Modem	0,25	0,25		
Parts for Hydra assembly	0,37	0,37		
Production	1,1	1,1		
Hydra transportation	0,0063	0,0063		

Table 30: Land use for the base case and the three improvement scenarios



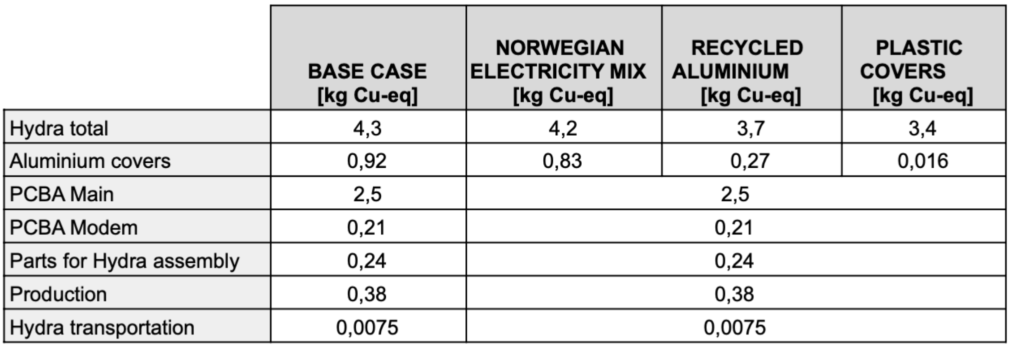
	BASE CASE [m2*a crop eq]	NORWEGIAN ELECTRICITY MIX [m2*a crop eq]	RECYCLED ALUMINIUM [m2*a crop eq]	PLASTIC COVERS [m2*a crop eq]
Hydra total	3,8	3,1	3,0	2,5
Aluminium covers	1,3	0,62	0,56	0,077
PCBA Main	1,8	1,8		
PCBA Modem	0,14	0,14		
Parts for Hydra assembly	0,29	0,29		
Production	0,19	0,19		
Hydra transportation	0,027	0,027		

Table 31: *Mineral resource scarcity for the base case and the three improvement scenarios*



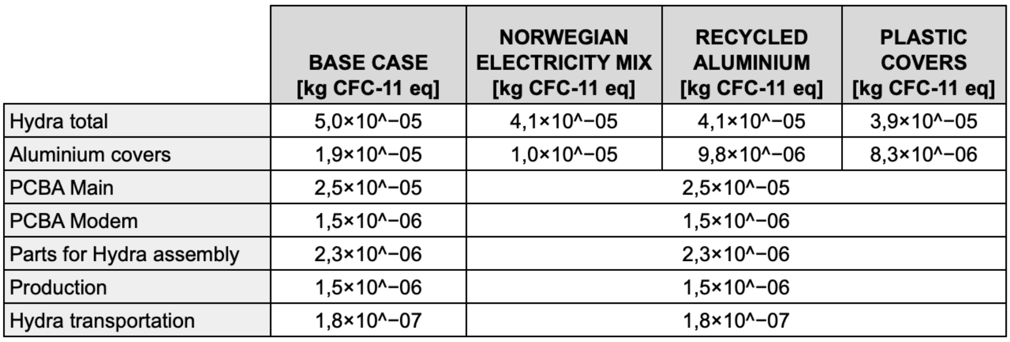
	BASE CASE [kg Si-eq]	NORWEGIAN ELECTRICITY MIX [kg Si-eq]	RECYCLED ALUMINIUM [kg Si-eq]	PLASTIC COVERS [kg Si-eq]
Hydra total	150000	140000	15000	140000
Aluminium covers	7400	2600	4000	630
PCBA Main	110000	110000		
PCBA Modem	9900	9900		
Parts for Hydra assembly	7800	7800		
Production	12000	12000		
Hydra transportation	36	36		

Table 32: *Mineral resource scarcity for the base case and the three improvement scenarios*



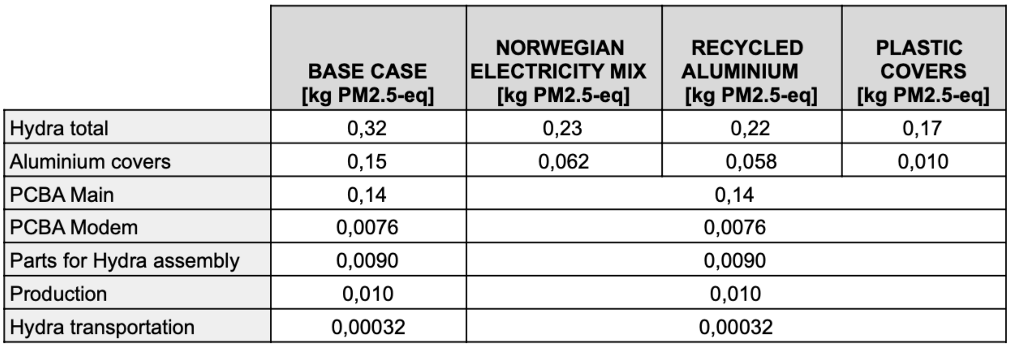
	BASE CASE [kg Cu-eq]	NORWEGIAN ELECTRICITY MIX [kg Cu-eq]	RECYCLED ALUMINIUM [kg Cu-eq]	PLASTIC COVERS [kg Cu-eq]
Hydra total	4,3	4,2	3,7	3,4
Aluminium covers	0,92	0,83	0,27	0,016
PCBA Main	2,5	2,5		
PCBA Modem	0,21	0,21		
Parts for Hydra assembly	0,24	0,24		
Production	0,38	0,38		
Hydra transportation	0,0075	0,0075		

Table 33: *Ozone depletion for the base case and the three improvement scenarios*



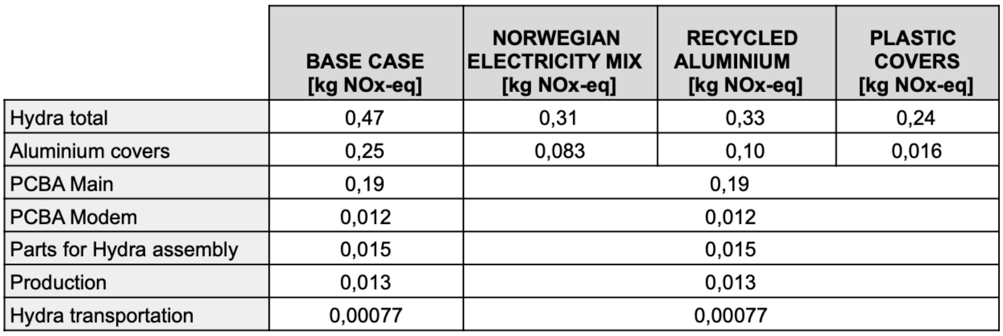
	BASE CASE [kg CFC-11 eq]	NORWEGIAN ELECTRICITY MIX [kg CFC-11 eq]	RECYCLED ALUMINIUM [kg CFC-11 eq]	PLASTIC COVERS [kg CFC-11 eq]
Hydra total	5,0×10^−05	4,1×10^−05	4,1×10^−05	3,9×10^−05
Aluminium covers	1,9×10^−05	1,0×10^−05	9,8×10^−06	8,3×10^−06
PCBA Main	2,5×10^−05	2,5×10^−05		
PCBA Modem	1,5×10^−06	1,5×10^−06		
Parts for Hydra assembly	2,3×10^−06	2,3×10^−06		
Production	1,5×10^−06	1,5×10^−06		
Hydra transportation	1,8×10^−07	1,8×10^−07		

Table 34: Particulate matter formation for the base case and the three improvement scenarios



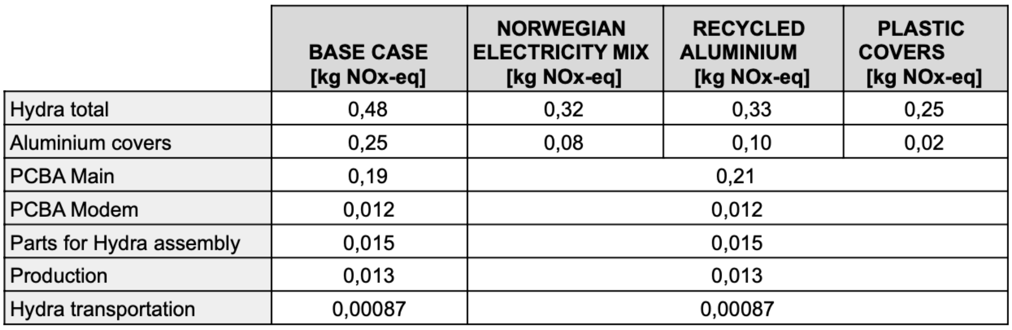
	BASE CASE [kg PM2.5-eq]	NORWEGIAN ELECTRICITY MIX [kg PM2.5-eq]	RECYCLED ALUMINIUM [kg PM2.5-eq]	PLASTIC COVERS [kg PM2.5-eq]
Hydra total	0,32	0,23	0,22	0,17
Aluminium covers	0,15	0,062	0,058	0,010
PCBA Main	0,14	0,14		
PCBA Modem	0,0076	0,0076		
Parts for Hydra assembly	0,0090	0,0090		
Production	0,010	0,010		
Hydra transportation	0,00032	0,00032		

Table 35: Photochemical oxidant formation: human health for the base case and the three improvement scenarios



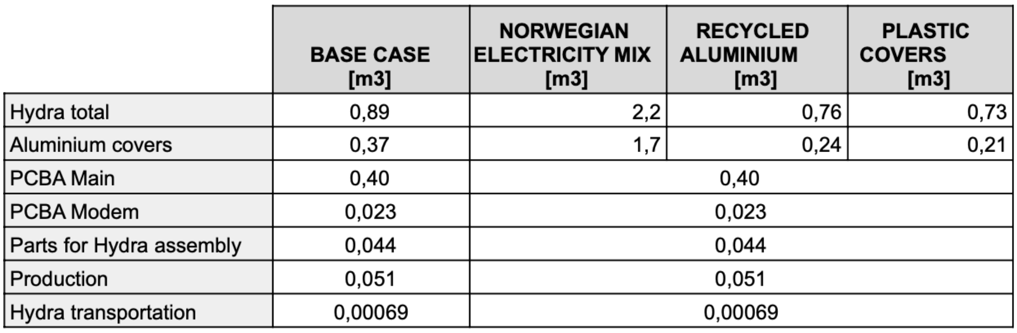
	BASE CASE [kg NOx-eq]	NORWEGIAN ELECTRICITY MIX [kg NOx-eq]	RECYCLED ALUMINIUM [kg NOx-eq]	PLASTIC COVERS [kg NOx-eq]
Hydra total	0,47	0,31	0,33	0,24
Aluminium covers	0,25	0,083	0,10	0,016
PCBA Main	0,19	0,19		
PCBA Modem	0,012	0,012		
Parts for Hydra assembly	0,015	0,015		
Production	0,013	0,013		
Hydra transportation	0,00077	0,00077		

Table 36: Photochemical oxidant formation: terrestrial for the base case and the three improvement scenarios



	BASE CASE [kg NOx-eq]	NORWEGIAN ELECTRICITY MIX [kg NOx-eq]	RECYCLED ALUMINIUM [kg NOx-eq]	PLASTIC COVERS [kg NOx-eq]
Hydra total	0,48	0,32	0,33	0,25
Aluminium covers	0,25	0,08	0,10	0,02
PCBA Main	0,19	0,21		
PCBA Modem	0,012	0,012		
Parts for Hydra assembly	0,015	0,015		
Production	0,013	0,013		
Hydra transportation	0,00087	0,00087		

Table 37: Water use for the base case and the three improvement scenarios



	BASE CASE [m3]	NORWEGIAN ELECTRICITY MIX [m3]	RECYCLED ALUMINIUM [m3]	PLASTIC COVERS [m3]
Hydra total	0,89	2,2	0,76	0,73
Aluminium covers	0,37	1,7	0,24	0,21
PCBA Main	0,40	0,40		
PCBA Modem	0,023	0,023		
Parts for Hydra assembly	0,044	0,044		
Production	0,051	0,051		
Hydra transportation	0,00069	0,00069		

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