CHALMERS
UNIVERSITY OF TECHNOLOGY

Exploring Life Cycle Impact Assessment As A Prioritisation Strategy

With a focus on climate change and mineral resource depletion in the automotive sector

Master's thesis in Industrial Ecology

VINCENT BUNKE
SARA RUTFJÄLL

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
www.chalmers.se
Report No. E2023:145

REPORT NO. E2023:145

Exploring Life Cycle Impact Assessment As A Prioritisation Strategy

With focus on climate change and mineral resource depletion in the automotive sector

VINCENT BUNKE
SARA RUTFJÄLL

Department of Technology Management and Economics
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024

Exploring Life Cycle Impact Assessment As A Prioritisation Strategy
With focus on climate change and mineral resource depletion in the automotive sector
VINCENT BUNKE
SARA RUTFJÄLL

Report no. E2023:145
Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover:
Image displaying a model of the Aurobay mild-hybrid VEP Gen 3 engine.

Gothenburg, Sweden 2024

Exploring Life Cycle Impact Assessment As A Prioritisation Strategy
With focus on climate change and mineral resource depletion in the automotive sector

VINCENT BUNKE
SARA RUTFJÄLL

Department of Technology Management and Economics
Chalmers University of Technology

SUMMARY

With the release of the 6th assessment report from IPCC, there is a larger need than ever to invest in climate change mitigation. This can be seen in the company Aurobay which develops combustion engines primarily for Volvo Cars. Last year they conducted an LCA on the mild-hybrid VEP MP Gen3, and are now aiming to understand and quantify the impact of the emissions based on the results.

This thesis explores the possibility of directly comparing the impacts of climate change and mineral resource depletion. A literature study was conducted evaluating midpoint impact categories by using the RACER criteria. Three methods suitable for climate change (IPCC, Environmental Footprint and ILCD) and mineral resource depletion (CML, Environmental Footprint and ILCD) were found during an organised workshop. The next step focused on endpoint methods, where the aim was to find two methods able to incorporate both impact categories. Context-specific criteria were derived for this purpose. A second workshop was organised where it was decided to use Environmental Footprint and Ecological Scarcity.

Normalisation approaches for the two selected endpoint categories were presented and used to calculate final scores. For climate change, yearly budgets and total budgets based on IPCC's SSP1 scenarios 1.9 and 2.6 were used. For mineral resource depletion, yearly budget and total budget based on the different reserve estimates, ultimate, reserve base and economic reserve were used. In addition, an Aurobay approach was created, based on their sustainability targets using simple linear reduction. The results showed that the chosen normalisation reference alters the severity to a high degree where larger budgets result in lower impacts. This can also be seen in the way that there are clear budgets for climate change in contrast to mineral resource depletion where there are no such targets. It was concluded that at this stage, this should not be used as an indicator within development, more research is needed along with extensive work on other impact categories. However, this approach could be applied when comparing different substances within an impact category, if one were to use the same method and budget.

Keywords: LCIA, climate change, mineral resource depletion, ADP, SSP, normalisation, engine, midpoint, endpoint, impact categories

Acknowledgements

We would like to thank Aurobay for the opportunity to write our thesis at your company. We want to give special thanks to our supervisor Joshua Dudley for providing guidance and always being open for discussions. Another big thanks to Christoffer Thuve who provided the model which has been the basis for our results as well as partaking in numerous discussions.

Lastly, we would also like to thank our examiner at Chalmers University of Technology, Matty Jansen for taking the time and making this thesis possible.

Vincent Bunke, Gothenburg, 2024
Sara Rutfjäll, Gothenburg, 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ADP	Abiotic Depletion Potential
AGWP	Absolute Global Warming Potential
AoP	Area of Protection
ASOP	Absolute Surplus Ore Potential
CC	Climate Change
CF	Characterisation Factor
COP	UN Climate Change Conference
CRM	Critical Raw Materials
GHG	Greenhouse Gases
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MRD	Mineral Resource Depletion
NGO	Non-governmental organisation
RCB	Remaning Carbon Budget
SOP	Surplus Ore Potential
SSP	Shared Socio-economic Pathways
USGS	United States Geological Survey

Contents

List of Figures

List of Tables

1

Introduction

This chapter aims to introduce the reader to the topic and provide a basis for understanding the aim and question framing of the thesis.

1.1 Background

With the release of the 6th assessment report from the IPCC, there is a larger need than ever to invest in climate change mitigation. Contribution from all different kinds of actors, from transnational cooperation down to individual level, are needed to reach the current climate targets as the world is currently on the path towards failing the Paris Agreement [1]. However, in the current public discourse, there is a lack of focus on other environmental targets. This is illustrated by some of the currently defined planetary boundaries such as biosphere integrity, nitrogen, and phosphorus emissions from use in industry and agriculture [2], that have already crossed the boundary of what is considered safe.

Sustainable development entails that future generations should not be limited by our actions today. The impact of the current resource use must be properly assessed in comparison to the climate change mitigation techniques being adopted, to realise how to preserve the planet most optimally for future generations.

In the automotive sector, where road transport is responsible for 11.9% [3] of the global greenhouse gas (GHG) emissions, the current electrification strategy is widespread to combat climate change and accelerated by regulations such as the ban on fossil-fueled cars in the EU [4]. However, it lacks the nuance of other targets, in particular mineral resource depletion which is highly relevant. Battery electric vehicles are usually favoured compared to pure internal combustion engine vehicles in terms of life cycle GHG emissions [5]. However, in terms of resource use and contribution to mineral resource depletion, and especially critical raw materials such as cobalt, neodymium, nickel, graphite, and lithium [6], the internal combustion engine vehicle impacts are generally lower.

Aurobay has recently conducted an LCA of their most sold engine, the mild-hybrid petrol (VEP) middle power (MP) Gen3 [7] and has assessed seven midpoint impact categories achieving an overview of life cycle emissions and impacts. However, to be able to prioritise the impacts that are causing the most damage, there is a need to understand how the impact categories compare with each other by using comparable endpoint categories. Several different midpoint and endpoint categories are being used by several different methods related to all or some of the environmental emissions and damages. For climate change and ozone depletion categories there is consensus on which method should be used [8] for calculation but the outcome can still vary quite a bit depending on the approach in using the methods [9].

Understanding which methods and emissions that are most relevant for a specific industry is key to acquiring reliable results, and can enable data-driven sustainability. This is precisely what Aurobay is after; information to guide them in their efforts to become sustainable and knowing where their efforts should be focused to achieve the most efficient damage reduction. To be able to do this, a comparison of the impact categories is needed and an indicator that includes all relevant impact categories has to be used [10].

1.2 Aim

This thesis aims to explore and understand how the selection of life cycle impact assessment methods influences the result of analysed inventory data of an engine, and to determine what criteria should be used when choosing a method in an automotive context. Furthermore, the thesis aims to find environmental boundaries as a normalisation reference to be able to compare the severity between climate change and mineral resource depletion. The resulting approach will be applied to a cradle-to-grave life cycle inventory analysis already conducted on Aurobay's mild-hybrid engine, VEP MP Gen3, to determine within which impact category mitigation efforts should be focused.

1.3 Question framing

With previous background as a basis, the following questions have been constructed in line with the aim.

- What LCIA methods are available for product evaluation which are suitable for the automotive industry and how can they be selected?
- Using normalisation; can climate change and mineral resource depletion impact categories be directly compared?
- Is it possible for Aurobay to use impact assessment as a prioritisation strategy in product development?

2

Theory

The following chapter describes concepts which increase the understanding of both the background as well as the topic itself. It is assumed that the reader has basic knowledge of climate science.

2.1 Life Cycle Assessment

The life cycle assessment (LCA) is a standardised methodology which is developed to calculate and identify environmental impacts associated with a specific product or service [11]. The LCA methodology is divided into four steps where each contributes with different parts that together cover the entire life cycle. These are the goal and scope definition, inventory analysis, impact assessment and interpretation of the result [12]. Together the four steps can identify and educate industry, non-governmental organisations (NGOs), and other notified bodies which are described in more detail below.

The first step of the LCA, the goal and scope definition, aims at defining the study [11]. This includes the methodology as well as the system boundary amongst other details such as functional units and data required [13].

The second step of the LCA is the life cycle inventory analysis (LCI). The purpose of this step is to collect all data necessary for the study but also to work as an inventory of all the input and output related to the life cycle [11]. This could for example include emissions, raw material or other environmental aspects [13].

The life cycle impact assessment (LCIA) aims to provide information about the impact categories and indicators to get a better understanding in regards to the LCI result [11]. Here, LCIA methods are used as a tool which can be applied at both the midpoint level which is emission-oriented and the endpoint level which is damage-oriented to get a final indicator which is more convenient for comparison [13].

The LCIA consists of two mandatory steps, classification, and characterisation, and two optional steps normalisation and weighting. The classification is used to categorise different emissions, such as CO_2 and CH_4 which are included in the impact category climate change or different raw materials included in mineral resource depletion [14]. Next, the characterisation is used to calculate the magnitude of each substance included in each category, which results in a total impact from the categories in equivalent units, i.e. CO_2 *eq.* or *Sb eq.*. The normalisation is then used to calculate and compare the magnitude of each impact category in relation to a target, budget, or such. Lastly, the weighting, which is an optional stage is where the normalised results are multiplied by a weighting factor (%) which represents the relative importance of the category.

The final stage of the LCA is the interpretation where the result from the LCI and LCIA is concluded [11]. This is done in accordance with the goal and scope definition and is the part of the LCA that works as a basis for conclusion and discussion [13].

2.2 Aurobay and OpenLCA Model

Aurobay develops and produces powertrain solutions and originates from Volvo Cars and Geely. Their mild-hybrid VEP middle power (MP) Gen3 engine was modelled in an SUV-type car. They have two main assembly sites, one located in Skövde, Sweden and another site located in Zhangjiakou, China. They are on a journey to completely transform into a circular business and reach net zero emissions by 2040 [15].

Open LCA is an open-source software designed for sustainability assessment and life cycle modelling. Creating a model makes it possible to investigate the total impact as well as the different processes included in the life cycle. The software provides the model; however, the data comes from a database for both the underlying manufacturing processes and the resulting impacts.

Aurobay used this software to create a model of the mild-hybrid VEP MP Gen3 engine to assess its environmental impact in a previous project. The model uses a weight allocation to derive impacts related to the user phase. The car that the engine powers and the basis for the use phase weight allocation is the Volvo XC60 AWD 2020. It was modelled with a total life cycle driven distance of 200,000 km using the Worldwide Harmonised Light Vehicles Test Procedure (WLTP) as the driving cycle.

For a manageable workload during the creation of the model in OpenLCA, the authors made a cut-off of components weighing less than 1 gram meaning these were not included in the final midpoint impact calculations [7]. For most impact categories this is an effective approach to minimise work while still retaining most of the results, which was found in a study by Volvo using a 1 % cutoff. For climate change, the results were almost unchanged for some of the other impact categories in the worst case. For mineral resource depletion, however, the results were rendered close to unusable when evaluating an internal combustion engine with the most simplified approach [16]. Although the 1-gram cutoff is not directly comparable to the 1 % cutoff in the study, the results show that caution is advisable when aggregating and/or removing substances when modelling products. It also shows that the results from this thesis will have considerable uncertainties from the starting point hence the main focus will be on the overall approach rather than specific numbers at this stage.

2.3 RACER

Deciding on methods suitable to evaluate impact categories at midpoint should be based on well-defined criteria which disclose the choice of methods. By using such criteria, it can be ensured that the methods are suitable for the impact categories considered, i.e. climate change and mineral resource depletion. The RACER method for impact assessment was recommended by the European Commission in 2006 and is a method to assess and compare impact methods. The approach entails that each method should be evaluated from the perspectives of Relevance, Acceptability, Credibility, Easiness, and Robustness with relevant sub-criteria within each perspective [17]. These criteria can be used to decide on methods suitable for evaluating climate change and mineral resource depletion at midpoint and will be described further below.

The first criterion, *relevance*, focuses on how well a method covers the life cycle of a specific product or sector [18] [19]. This implies that the evaluation method should be closely linked to the objectives and be suitable for the intended impact categories, i.e. climate change and mineral resource depletion [17] [20]. It also implies that the specific method can be applicable on the relevant endpoint or planetary boundaries, i.e., same functional unit, similar scope, etc.

The second criterion, *acceptability*, aims at that the method should be widespread and well-known within the industry or scientific community as well as used by other relevant stakeholders such as policymakers and regulatory bodies [18] [20]. This criterion also highlights the importance of well-defined roles and responsibilities for the indicator [17].

The *credibility* criterion can be described as how well defined the method is, for example, is the method clear and can it easily be interpreted by non-expert [17]. This could also aim at the method should not be any older than ten years unless there are standards such as the IPCC [8]. Apart from that the method should be transparent in regards to where the data is sourced [18].

The perspective of *easiness* aims at simplicity. Meaning, easy to access data, limited workload, has low costs and in this case, specifically, is compatible with relevant software [17] [18].

Lastly, there is the perspective of *robustness*. This criterion highlights how the method responds to input change but also its comparability via normalisation [18]. Furthermore, the robustness focuses on how reliable the method is, including how it responds to manipulation, i.e., if the method will perform as intended [17] [20].

With the perspectives above as a basis, sub-criteria have been adopted to identify each method's characteristics. These can be found in table A.1 and work as a method to find suitable LCIA methods.

2.4 Climate Change impact assessment

The International Panel on Climate Change (IPCC) measures climate change contribution from greenhouse gases (GHG) into the atmosphere which are published as AR reports. Their latest report, AR6, has updated the characterisation factors which are used to convert every other contributing GHG into carbon dioxide equivalents, $CO_2\ eq.$ to have a more manageable basis for understanding and comparison. Each gas remains in the atmosphere for a different amount of time which depends on several factors such as how reactive it is with other gases in the atmosphere, what natural processes incorporate these gases removing or changing them in the process, and many others. Even the warming effect of these gases can impact the uptake of them in a wide variety of ecosystems and Earth processes. The IPCC has modelled these processes to estimate the impact the release of GHG has on Earth's climate in the shared socioeconomic pathways, SSPs which are further described in section 2.7.1 [21].

Even though AR6 has brought many major improvements over the last report, uncertainties are still unavoidable. To give a few examples, the projected amount and timing for ice loss from Antarctica still have a low confidence which will directly affect the sea-level rise projections in turn. Some uncertainties regarding aerosol projections and trends are also still present due to, among other things, a lack of adequate observations. One of the dominating uncertainties when projecting global warming is the future anthropogenic CO_2 emissions which surpasses the uncertainties in climate-feedback projections [21].

2.5 Mineral Resource Depletion impact

To measure the amount of minerals in the crust there are different methodologies available. These methods could be based on different factors, such as the estimated total amount of minerals in the crust, or be based on the future effort to extract minerals or even future competitiveness. The most common one is Abiotic Depletion Potential (ADP) used in several life cycle impact methods within the LCA community.

ADP was first proposed by Guinée & Heijungs in 1995 [22] and is a method to measure the severity of depletion of a specific substance within an LCA context. It utilises yearly extraction rates along with reserve estimates of the substance in question to derive a depletion potential. Antimony is used as a reference substance to which all other resources are converted by using an equivalency factor, similar to Global Warming Potential in the climate change category.

The depletion equation is defined as follows:

$$ADP_{res}(u_{ref} \cdot u_{res}^{-1}) = \frac{production_{res}(u_{res} \cdot yr^{-1})}{production_{ref}(u_{ref} \cdot yr^{-1})} \cdot \frac{reserve_{ref}(u_{ref})^2}{reserve_{res}(u_{res})^2} \tag{2.1}$$

Where u_{res} defines the unit of the resource evaluated and u_{ref} denotes the reference resource unit for yearly production of the resource and the estimated reserves for said resource. By calculating the ADP for each relevant mineral within a product an aggregated ADP value can be derived according to the equation:

$$equivalent\ abiotic\ use(u_{ref}) = \Sigma\ ADP_{res}(u_{ref} \cdot u_{res}^{-1}) \cdot extraction_{res}(u_{res}) \tag{2.2}$$

The abiotic reserves are considered non-regenerative meaning that no new natural formation of these substances is incorporated into the above equations [22].
CML 2002 which is an impact method from Leiden University, uses a 500-year time horizon where, just as Guinée & Heijungs stated, no regeneration of any mineral reserve will occur [23]. CML mentions three different reserve types that can be used for deriving an ADP value of a mineral. *Ultimate reserves* which is based on the concentration of that substance in Earth's crust with a constant assumed crust depth. This assumes no limitation on the accessibility of the substance. *Reserve base* is another way of measuring which is based on current mining capabilities and identified resources that fulfil the mining requirements. The last type is *Economic reserves* which is the part of the reserve base that can be economically mined. This approach will be subject to not only mining capabilities but also market variations at the time of reporting [23].

The incorporation of anthropogenic stocks can also be included according to the authors but raises a few difficulties in properly implementing these stocks. Estimating the quality and amount available for use is not trivial and was deemed out of the scope of this report.

The term *ultimate extractable reserves* has also been up for discussion in the literature where it is proposed as an alternative to the ultimate reserves. This estimate would take into account only the upper crustal reserves, approximately 3 km, that would reasonably be available for extraction by humans in the coming centuries [24].

The method has since updated its characterisation factors and reserve estimates from several different contributors. In 2019, van Oers and colleagues updated the reserve and production estimates to better handle the time variation of these variables on a yearly basis. This revisit was partly done to provide a more robust basis for the Product Environmental Footprint (PEF) guidance that utilises the category total ADP for impact assessment. Moving average of production and cumulative production are considered as potential improvements but for use of longer term with ultimate reserves cumulative approach is recommended although the two approaches vary by only small amounts. The choice of reference substance was found to be less relevant compared to antimony and tantalum which varied by a factor of 4 and 3 respectively [25]. The updated characterisation factors along with the older numbers are available in appendix F.

Using ADP in a policy context requires the characterisation factors to be regularly updated to represent the current situation properly and accurately. A proposal to update ADP characterisation factors every fifth year similar to global warming potential (GWP) by the IPCC was made by van Oers in 2019 to make it suitable for use in PEFs or Environmental Product Declarations (EPDs). The update also included new basic earth data among other things, an average upper crust estimation of 12 km was used [25].

2.6 Normalisation and Weighting

Normalisation is a way to achieve comparable impacts when dealing with multiple different impact categories and units [26]. It can be described by the below equation:

$$NI = \frac{CI}{NR} \tag{2.3}$$

where NI is the normalised impact, CI is the characterised impact from an impact category and NR is the normalisation reference within that impact category. The result is the unit-less score that can be compared to other normalised results from other impact categories, given that the references and underlying model have been matched. It is strongly recommended to weigh the scores when comparing across impact categories and even more so between entire product systems to ensure proper aggregation [26].

An example of a complete weighting set has been provided by the Environmental Footprint method which is based on several surveys and workshops with scientists, industry representatives and NGOs [27].

Impact Categories	**WF** [%]
Acidification	6.20%
Climate change	21.06%
Ecotoxicity, freshwater	1.92%
EF-partuculate matter	8.96%
Eutrophication, freshwater	2.80%
Eutrophication, marine	2.96%
Eutrophication, terrestrial	3.71%
Human toxicity, cancer	2.13%
Human toxicity, non-cancer	1.84%
Ionising radiation	5.01%
Land use	7.94%
Ozone depletion	6.31%
Photochemical ozone formation	4.78%
Resource depletion, fossils	8.32%
Resource depletion, minerals and metals	7.55%
Water use	8.51%

Table 2.1: Weighting set by the LCIA method Environmental Footprint.

It can be seen that climate change is by far the highest-ranking impact category with 21.06% and mineral depletion ranks 6th with 7.55%. These percentages are used in the aggregation step where climate change in this case will contribute almost three times as much towards the final aggregated score compared to the mineral depletion impact category results.

2.7 Environmental boundaries

This section aims to describe current boundaries for climate change and mineral resource depletion categunitlesst could potentially be used as normalisation references.

2.7.1 Climate Change

During the UN Climate Change Conference (COP21) in 2015, the Paris Agreement was agreed on by 195 nations [28]. Here, it was decided and also legally binding that the temperature on earth should stay well below 2 degrees with an aim at 1.5 compared to pre-industrial levels. These temperatures can be described according to the Shared Socio-economic Pathways (SSPs) scenario 1-1.9 and 1-2.6 [29]. The SSPs were first introduced in 2017 by the IPCC to function as a prediction of how developments in society can affect the level of GHG emissions [30]. That means that the 1.5-degree target can be described using a very low SSP1-1.9 scenario and the 2-degree target using a low SSP1-2.6 scenario and are both a part of the SSP1 scenario.

The SSP1, also referred to as *Taking the Green Road*, is described as a scenario where all parts of society work towards sustainable development by investing in both education and health [31]. This implies that the industry shifts towards more sustainable materials resulting in a more sustainable consumption which eventually will reach financial turnover. Lastly, inequality will be reduced, both in countries but also across the world. For SSP1-1.9, this means that the radiative forcing on earth must be kept below 1.9 W/m^2 or a remaining carbon budget (RCB), calculated from the beginning of 2020, estimated to be around 510 $GtCO_2$ with a 50% likelihood [29]. For the SSP1-2.6 scenario that instead implies that the radiative forcing should be kept below 2.6 W/m^2 and that the RCB should stay within 890 $GtCO_2$ with a likelihood of 67%. Depending on non-$\mathrm{CO_2}$ warming, such as methane and nitrous oxide, this implies that scenarios would result in net zero sometime around 2050-2070.

The planetary boundaries (PB) are another way of potentially gaining a normalisation reference and were first developed in 2009 by Johan Rockström together with 28 internationally renowned scientists. The aim was to identify nine processes that regulate the stability and resilience of the Earth's system [32]. The purpose of the boundaries is to determine global environmental limits and from that guide in regards to keeping man-made damage within a safe operating space [33]. As an example, out of the three zones, safe, increasing risk and risk, climate change is identified as an increasing risk. Even though nine processes have been identified, some of them remain to be quantified such as biotic integrity within biosphere integrity as well as atmospheric aerosol loading [32]. However, not all impact categories are seen as a process within the PBs such as mineral and metal scarcity as they do not have direct Earth-regulatory properties [34]. The proposed boundary for carbon dioxide concentration by Rockström was 350 ppm with pre-industrial levels of 280 ppm and for radiative forcing, a proposed boundary of 1 W/m^2 increase compared to pre-industrial levels.

2.7.2 Mineral Resource Depletion

As stated previously, the planetary boundaries do not include mineral resource depletion which requires other forms of references for normalisation. The Environmental Footprint method proposes normalisation based on global emissions and global resource use according to the normalisation set developed by Sala et al [27]. The different reserve estimates used by the ADP methodology is another basis that provides a budget-like approach similar to that of carbon budgets widely used in current literature [23].

3

Method

The following chapter covers the necessary steps of deciding on methods for both midpoint and endpoint as well as budgets and normalisation which is a necessary part of the result. The workshops as well as the RACER criteria will be described briefly during this chapter and are described in depth in Appendix, A, C and, D.

3.1 Selection of midpoint methods

The selection of midpoint methods was conducted out of two steps. The first was to gain an understanding of which midpoint LCIA methods applied to the model and the automotive context. A literature study of available methods was conducted where two criteria were used for a first screening: the method along with its database had to be freely available in OpenLCA and GaBi software, and also that the method should not be outdated hence a 10-year limit was set. A collection of all methods explored can be found in Appendix B.

After the first screening was done a workshop was conducted together with representatives from Aurobay based on the RACER approach conducted by the European Commission. The approach lists five main criteria, Relevance, Applicability, Credibility, Easiness, and Robustness with sub-criteria which can be found in Appendix A. From the workshop, three methods were selected for climate change and mineral resource depletion.

The workshop focused on comparing all impact methods and evaluating them. Each midpoint method that was deemed suitable for evaluation, was evaluated on each of the RACER criteria. A pair-wise comparison was used which put every method against every other method for the categories of climate change and mineral scarcity respectively. In the end, the top three methods were selected based on a win rate, meaning one point was awarded for each match-up win between the methods. Then they were used in the OpenLCA software to derive midpoint impact results that could then be used in the subsequent steps. The Midpoint workshop is only described briefly during this chapter and can be read in further detail in Appendix C.

Based on the results from the midpoint workshop, results for the different impact categories using the different methods came directly from the OpenLCA cradle-to-grave model. The results were derived using the 'middle' calculation accuracy which is the step below Monte Carlo simulation to save time. Then the calculation was done for each of the midpoint methods selected to extract climate change- and mineral resource depletion impacts in GWP100, CO_2 *eq.* and *Sb eq.* using ultimate reserves, reserve base and, economic reserve estimates where available. The methods were either available in the Ecoinvent 3.8 and 3.9.1 database or the OpenLCA LCIA methods v2.2.1 pack.

3.2 Selection of endpoint methods

The selection process for endpoint impact methods was somewhat similar to the previous step but due to the nature of the endpoint methods, there were significant differences as well. The similar criteria used from the previous step were frequency of updates, age, responsible body/organisation, availability of relevant software and transparency. However, endpoint-specific criteria had to be derived as well. These were, that the methods had to be able to assess both impact categories while minimising workload. At the same time, the normalisation and weighting approaches needed to be easily accessible which by extension means more useful for Aurobay. These were, in addition to those criteria, the ability to utilise some form of environmental boundary was also included in the evaluation and comparison between these endpoint methods.

Here a workshop was conducted which was done in the same way as for the midpoint. For endpoint evaluation, two methods were selected which needed to work together with all the midpoint methods. Compared to the midpoint, the results from the endpoint had to be calculated by hand, which uses normalisation described further below together with targets that are also described below. The Endpoint workshop is further described in Appendix D.

3.3 Normalisation

Environmental Footprint and Ecological Scarcity were chosen for endpoint evaluation. Environmental Footprint normalise impacts based on current global emissions or current resource use which was one of the adopted approaches for deriving the single score indicator. The method itself had normalisation values which can be found in table B.1 and are based on emissions and resource extraction in the year 2010. Normalisation using budgets based on SSP1-1.9 and SSP1-2.6 for climate change, and three reserve estimates for mineral resource depletion were also approaches adopted to reflect environmental boundaries. In addition to these approaches, a budget approach based on Aurobay 2040 targets was also adopted reflecting company targets of net zero emissions and zero primary material dependency, further described in section 3.3.3.

The normalisation in the Ecological Scarcity method was applied through the critical flows which corresponded to reduction targets for climate change and mineral resource depletion. The different targets for climate change were SSP1-1.9 and SSP1-2.6

scenarios due 2050 and current emissions represented by the year 2020.

3.3.1 Yearly budgets and targets

When modelling the yearly emissions for climate change the SSP1-1.9 and SSP1-2.6 were used. CO_2, CH_4 and, N_2O which are the largest contributors to the total GHG in the atmosphere were calculated for the year 2020 according to the CIMP6 data [35] used for AR6, see Appendix E. Based on that, the yearly emissions in $CO_2\ eq.$ could be calculated according to;

$$Emissions_{2020} = CO_{2,2020,X} \cdot CF_{CO_2} + CH_{4,2020,X} \cdot CF_{CH_4} + N_2O_{2020,X} \cdot CF_{N_2O} \tag{3.1}$$

where X represents the emissions in 2020 given the SSP scenario and CF is the characterisation factor for each of the anthropogenic gases. In addition to the calculated yearly emissions, Environmental Footprints' normalisation factors could be applied, both for climate change and mineral resource depletion. These can be found in table B.1 and are based on emissions and resource extraction in 2010.

Mineral resource depletion could also be modelled with the yearly extraction, based on the different approaches according to ADP, ultimate reserves, reserve base, and economic reserve. The modelling of the total yearly mineral resource extraction based on different reserve estimates and figures from CML, uses the reference year of 2000. The total resource extraction for that year concerning ultimate reserves was given but the total for the economic reserves and reserve base was lacking. The total production of each substance in antimony equivalents was available however and could be easily summed up for a total mineral resource depletion (MRD) estimate for that year [36], according to equation 3.2.

$$MRD_{yearly\ total} = \sum_{i}^{I} P_i \tag{3.2}$$

Where P is the yearly global production in $kg\ Sb\ eq.$ of a specific mineral i for a given year and I is the total number of included minerals. Only an estimate for world production using ultimate reserves for 2015 was available in the literature and directly provided by the report in which the ADP method was updated [25]. Similar numbers for the other reserve estimates were not available.

3.3.2 Total budgets

By using the CIMP6 data covering the SSP1-1.9 and SSP1-2.6 scenarios for the years 2020, 2030, 2040 and, 2050 a simplified model of the total remaining $CO_2\ eq.$ budget until 2050 could be calculated. This was done by summarising the top three anthropogenic gases, CO_2, NH_4 and, N_2O for each year according to equation 3.1 followed by a simple linear extrapolation which estimated a cumulative budget for each target that was used to normalise the results from each midpoint category. The linear extrapolation was calculated according to equation 3.3.

$$\frac{\sum_{n=1}^{3} Y_n + Y_{n+1}}{2} \cdot 10 = 5 \cdot (Y_1 + 2 \cdot (Y_2 + Y_3) + Y_4) \tag{3.3}$$

where Y represents the years 2020, 2030, 2040 and 2050. The result, i.e. a total budget until 2050, could be applied to both endpoint methods. For Environmental Footprint by dividing on the normalised budget and for Ecological Scarcity by using the 2050 budget as a critical flow and the emissions in 2020 as a reference and normalisation flow.

For mineral resource depletion the total reserves in *Sb eq.* were estimated and used as a normalisation basis according to ADP, ultimate reserves, ultimate recoverable reserves and economic reserves using 2015 reference year. The ultimate reserves were estimated using available data belonging to the updated ADP method [25]. Estimations for total available mass $M_{crust,i}$ of each mineral i in the Earth's crust were available along with the updated characterisation factors, CF_i making it possible to estimate the total ultimate reserves in mass of antimony equivalents as seen in the equation 3.4.

$$Ultimate\ reserve_{crust\ total} = \sum M_{crust,i} \cdot CF_i \tag{3.4}$$

As the concentration of each substance is assumed evenly distributed in the crust, the ultimate extractable reserves are a simple re-scaling of the ultimate reserves with a ratio of 1/10000 solely based on the difference in crustal depth and the resulting volume. The total economic reserves for 2015 are based on a summary of the reported reserves for each mineral from the Mineral Commodity Summaries from the United States Geological Surve (USGS) [37]. Due to the lack of updated ADP values using economic reserves, the ADP values concerning ultimate reserves were used in combination with the total economic reserve estimates for each mineral to create a total economic reserve estimate in antimony equivalents for the year 2015. Where reserves were absent, a 20 times yearly production was used as an estimate for those specific minerals which are described in the equation 3.5.

$$Economic\ reserve_{2015\ total} = \sum R_{2015,i} \cdot CF_i \tag{3.5}$$

Where $R_{2015,i}$ is the estimated economic reserve for the reference year 2015 for a specific mineral i and CF_i is the characterisation factor converting the reserve estimate to antimony equivalents for that mineral.

3.3.3 Aurobay Targets

Aurobay has a goal of reaching net zero GHG emissions by 2040 and independence of primary materials in the manufacturing of its products. To reflect these goals in the normalisation process, a budget was created by assuming a linear reduction each year from 2020 levels down to zero in 2040 based on 2020 world emissions of GHG and 2015 world use of minerals. The 2020 GHG emissions were based on the SSP1-1.9 scenario and the 2015 ADP yearly mineral usage based on the latest available world production numbers for which the method was updated. Equation 3.6 describes the simple linear reduction model which is used to estimate the world GHG budget when applying Aurobay targets.

$$Aurobay_{\,GHG-Budget} = \frac{SSP1-1.9_{\,2020}}{2} \cdot 20 \tag{3.6}$$

Using the same approach as for climate change, the mineral budget can be calculated using ADPs CFs for ultimate reserve based on the reference year 2015 as can be seen in equation 3.7.

$$Aurobay_{\,Mineral\ Budget\ 2015} = \frac{P_{ultimate,\,2015}}{2} \cdot 20 \tag{3.7}$$

The same calculation is conducted in equation 3.8. However, instead of using 2015 as the reference year, the year 2000 is used, together with updated ADP CFs in antimony equivalents using ultimate reserves.

$$Aurobay_{\,Mineral\ Budget\ 2000} = \frac{P_{ultimate,\,2000}}{2} \cdot 20 \tag{3.8}$$

To introduce a few more results on the mineral side, economic reserves and reserve base can be used where world production from the year 2000 was available. The below two equations, eq 3.9 and eq 3.10, will assume that the current production is replaced by that of the year 2000 levels and calculate a budget for the coming 20 years based on the 20-year target to completely remove primary materials from Aurobay's production.

$$Aurobay_{Reserve\ base\ budget} = \frac{P_{reserve\ base,\,2000}}{2} \cdot 20 \tag{3.9}$$

$$Aurobay_{Economic\ reserve\ budget} = \frac{P_{economic,\,2000}}{2} \cdot 20 \tag{3.10}$$

4

Result and Discussion

This chapter first present the main demarcations followed by the result retrieved from the midpoint and endpoint workshops. A longer version including a discussion which is the basis for the results can be found in Appendix C and Appendix D. Furthermore, this chapter covers the data collected from the OpenLCA model as well as results for each endpoint method based on different budgets and targets. In addition to the results a discussion that comments the results. Further, it reflects on the result using the question framing as well as the aim to review and reflect on what has been achieved. Lastly, a shorter discussion on further research is presented.

4.1 Demarcations

Keeping the time span in mind the thesis will investigate the impact categories of climate change and mineral resource depletion. The LCIA methods chosen for both midpoint and endpoint must be available in both openLCA and Gabi, however, the result will only be applied to the model conducted on Aurobay's engine VEP MP Gen3 which is constructed in openLCA. Furthermore, the midpoint results will all be gathered from the model. The thesis will not perform an inventory analysis but rather use the one already in place because of a former thesis.

There was no weighting approach adopted apart from the one included in the Environmental Footprint method. The reason was that the normalisation already was subjective. Lastly, when estimating budgets based on reduction targets those will be simplified and linearised.

4.2 Midpoint method selection

Based on the midpoint workshop detailed in Appendix C a pair-wise comparison was conducted for mineral resource depletion where CML, ILCD and Environmental Footprint were chosen, as can be seen in table 4.1. The comparison was enabled by using the RACER framework with custom sub-criteria for the context-specific purpose of the thesis. All methods competed against each other based on their performance in fulfilling the set criteria. In some cases, there was no need for a direct comparison and some methods won by default due to former results which also helps avoid contradictory results.

	CML	**ReCiPe**	**IW+**	**ILCD**	**EF**
CML	-	-	-	-	-
ReCiPe	CML	-	-	-	-
IW+	CML	ReCiPe	-	-	-
ILCD	ILCD	ILCD	ILCD	-	
EF	EF	EF	EF	EF	-

Table 4.1: The pair-wise comparison between midpoint methods intended for mineral resource depletion.

As described in section 3.1, a pair-wise comparison was used to derive the aforementioned outcome. A similar pair-wise comparison was done intended for climate change. As can be seen in table 4.2 IPCC, Environmental Footprint and, ILCD were chosen. The workshop is described further in Appendix C.

	CML	**ReCiPe**	**EcoFoot**	**IW+**	**ILCD**	**TRACI**	**EF**	**IPCC**
CML	-	-	-	-	-	-	-	-
ReCiPe	ReCiPe	-	-	-	-	-	-	-
EcoFoot	CML	ReCiPe	-	-	-	-	-	-
IW+	CML	ReCiPe	IW+	-	-	-	-	-
ILCD	ILCD	ILCD	ILCD	ILCD	-	-	-	-
TRACI	CML	ReCiPe	TRACI	IW+	ILCD	-	-	-
EF	EF	EF	EF	EF	EF	EF	-	-
IPCC	IPCC	IPCC	IPCC	IPCC	IPCC	IPCC	IPCC	-

Table 4.2: The pair-wise comparison between midpoint methods intended for climate change

Based on the selected midpoint methods for both mineral resource depletion and climate change, results from the OpenLCA model were retrieved and are displayed in table 4.3. These results are the total modelled cradle-to-grave emissions of the mild-hybrid VEP MP Gen3 Aurobay engine using the selected impact assessment methods from the midpoint workshop for both impact categories. The model from Aurobay has been completely untouched and only changes in the impact assessment step have been made by using different methods.

Method	**CC (kg CO_2 eq.)**	**MRD (kg Sb eq.)**	
IPCC2021	4218.1		GWP100
CML-IA Baseline		0.0402	Ultimate reserves
CML-IA Non-Baseline		0.1033	Reserve base
CML-IA Non-Baseline		0.2191	Economic Reserves
EF3.1	4218.1	(0.0392)	GWP100 and Ultimate reserves
EF3.0	4218.1	0.0406	GWP100 and Ultimate reserves
ILCD 2011 Midpoint+	4158.1	0.1095	GWP100 and Reserve base

Table 4.3: Midpoint impact results for both Climate Change (CC) and Mineral Resource Depletion (MRD) retrieved from the model in OpenLCA, based on the methods selected in the midpoint workshop

When using the selected methods on the LCA model a few observations can be made. IPCC2021 and both versions of Environmental Footprint (EF) use AR6 as a basis for their impact assessment meaning they are identical. ILCD is based on the AR5 report and that version's GWP values which results in a slightly different outcome. For the mineral resource depletion results, it can be seen that the main difference is caused by the referenced reserve estimate. Within the reserve estimates, the results are similar between the different methods. The reason as to why they differ mainly depends on the number of substances included in the assessment method. In general, the results from the different reserve estimates behave as expected. Using large reserves results in a lesser as in the ultimate reserve case, and using smaller reserves results in a larger impact as in the case of economic reserves.

The main contributor to the climate change category is the user phase where around 80% of the total impact comes from. On the mineral side, around a similarly sized share of the impact, based on ultimate reserves, comes from the metal tellurium which is not included in the final engine as it is a by-product of copper refinement.

The Environmental Footprint 3.0 is included as well even though the successor 3.1 version is already implemented in the latest Ecoinvent database. The results differ where contributions from five substances are missing in the 3.1 version including gold which has the highest ADP value of all minerals according to the ADP method. The other missing substances are colemanite, tungsten, gangue, and yttrium. The difference in the results however is low and could potentially be attributed to the present weight cut-off in the LCA model. As the original LCA model was created using Ecoinvent 3.8 and contains Environmental Footprint 3.0, the introduction of Ecoinvent 3.9.1 and Environmental Footprint 3.1 seem to have introduced issues with certain processes and will not be used further in that category. Or at the very least introduced changes that require an investigation out of the scope of this report. For climate change, there was no difference between the two versions.

As can be seen in the table above, the results within the same impact- and subcategory are of the same magnitude. The midpoint results vary at most 5.6% for each of the different reserve types within mineral resource depletion and 2.7% in the climate change category. This means that a few select results will be used to evaluate the large amount of normalisation approaches presented below.

The midpoint results that will be used are the following:
- Climate Change, IPCC 2021 AR6
- Mineral Resource Depletion, EF 3.0 Ultimate Reserves Ref. The year 2000
- Mineral Resource Depletion, CML-IA Reserve Base Ref. The year 2000
- Mineral Resource Depletion, CML-IA Economic Reserves Ref. The year 2000

The selection of midpoint impact methods using the same underlying models calculated results that for climate change were very similar while in the mineral resource depletion category, reserve type was the most defining characteristic. As the IPCC method is the global standard, all methods used for midpoint evaluation use AR5 and AR6 to calculate climate change. The same standard does not apply to the mineral resource depletion category where a variety of different sub-categories are used. As an example, ReCiPe or Impact World+ uses surplus ore potential or material scarcity index which has several differences and would generate a completely different result compared to using the abiotic depletion potential (ADP). The main reasoning behind using ADP was that it uses the static ultimate reserve estimates hence being less dependent on economic circumstances. However, dependence on production will still heavily influence the results and is directly linked to the selected reference year. The static nature of the reserve estimates only adheres to the ultimate reserves as reserve base and economic reserves tend to change over time as well.

Another important aspect when working with mineral resource depletion is to make sure that high-impact substances are included in both impact categories. These are mainly rare earth metals and metals with a generally high ratio of production versus reserves such as gold. This is also closely tied to how the engine is modelled in OpenLCA. What processes are available for use in the Ecoinvent database and how well they represent reality will also have a considerable impact on the magnitude of the results and the number of substances included in the final impact assessment. One demarcation in the LCA model is a 1-gram cut-off which could alter the result significantly. Failing to include a small amount of a high-impact metal such as gold, platinum, tellurium, and other rare earth metals could potentially result in a completely different outcome. A thorough review of the discarded or aggregated components could mitigate this uncertainty although time consuming. The included impact from tellurium is another large and uncertain variable now as it represents almost 70% of the total impact in the ADP ultimate reserve category without being included in the final engine. Looking into copper production more would be ideal to conclude whether tellurium is completely discarded as a by-product or recovered and used for other purposes. If that is the case, the inclusion of the metal should be reconsidered.

The RACER criteria that were used covered multiple perspectives and were constructed by the European Commission. The use of well-thought-out questions can favour the project in making sure that all relevant areas are covered in the decision-making process. However, it could be beneficial to modify the criteria to be better suited for the intended area. While can also lead to value choices steering the project in a certain direction. This will introduce some form of bias already in the midpoint selection process.

The time limit of the project made it more convenient to use the set criteria by RACER. No other relevant approach could be identified for this purpose which affected mainly the midpoint workshop. Having several approaches for method selection could have validated the choice of RACER since that methodology is not widespread in the literature. If there would have been more time, a larger number of methods could have been investigated as opposed to the methods mentioned in the project which are all to some extent well used and common in literature. A more in-depth study of a broader number of methods could also generate the discovery of newer methods which have not yet been used, hence the limited amount of information about them.

For the midpoint impact evaluation using the latest IPCC method along with the updated ADP values which reference ultimate reserves would be ideal. The issue that remains here is that the updated ADP values have not been incorporated into the Environmental Footprint method yet. This means that the method still uses the year 2000 as a reference year which is an important note. Using RACER with similar sub-criteria to evaluate methods not included in this report is a recommended approach. However, looking at other impact categories the sub-criteria will have to be revised.

4.3 Endpoint method selection

The second workshop aimed to decide which two endpoint methods should be used to evaluate the midpoint results. Table 4.4 shows the full pair-wise comparisons between the endpoint methods presented.

	ReCiPe	**EF**	**IW+**	**Eco Scarcity**	**Eco-Indicator**	**EPS**	**CE Delft**
ReCiPe	-	-	-	-	-	-	-
EF	EF	-	-	-	-	-	-
IW+	IW+	EF	-	-	-	-	-
Eco Scarcity	Scarcity	TIE	Scarcity	-	-	-	-
Eco-indicator	ReCiPe	EF	IW+	Scarcity	-	-	-
EPS	ReCiPe	EF	IW+	Scarcity	Eco-indicator	-	-
CE Delft	ReCiPe	EF	IW+	Scarcity	CE	CE	-

Table 4.4: The pair-wise comparison between endpoint methods intended for both mineral resource depletion and climate change.

The two methods selected for further evaluation were Environmental Footprint which uses a basic normalisation approach and Ecological Scarcity which uses a distance-to-target approach to derive single scores. See Appendix D for further details on the selection process.

The choice of midpoint methods is to some extent stable for the two impact categories, given the guidance of established organisations such as the European Commission aiding the selection process. However, for endpoint evaluation, there is much less guidance and research. In addition, the choice of method could be of even greater importance for the results. For this project, Environmental Footprint and Ecological Scarcity were used partly because of their ability to calculate comparable single-score results that were dimensionless and in the number of eco-points (UBP) respective. In addition, those methods were selected based on their ability to normalise global emissions and resource extraction in the form of budgets as well as using a distance-to-target approach. The choices are characterised by the time frame of the project as well as the collaboration with Aurobay. At this stage in the LCIA process, there was little guidance from established institutions in the field and a lack of consensus. This makes the selection of normalisation and weighting approaches generally challenging. A key criterion was that the methods should be transparent and easily reproducible meaning that cost estimations or areas of protection approaches were rejected.

4.4 Normalisation approach result

In table 4.5 below, the different normalisation values are shown. Both as budgets from the year 2020 to 2050 and from 2020 to 2040 based on Aurobay targets but also as yearly emissions for the year 2020 and 2050. The methodology used to acquire these numbers is described in more detail in section 3.3.

Normalisation reference	**Gt CO2 eq.**	**Reference year**
Total		
SSP1-1.9 Budget	810.95	2020-2050
SSP1-2.6 Budget	1198.1	2020-2050
Aurobay Budget	526.30	2020-2040
Yearly		
SSP1-1.9 Current	52.630	2020
SSP1-2.6 Current	52.421	2020
SSP1-1.9 Yearly	9.0029	2050
SSP1-2.6 Yearl	26.058	2050

Table 4.5: Overview of derived climate change normalisation references both as total budget and yearly based on current emissions and estimated emissions in 2050.

The Aurobay target aims for net zero approximately ten years earlier than that of the 1.5-degree target, corresponding to SSP1-1.9, which results in a significantly lower GHG budget. The yearly emission targets for 2050 reflect this as well where net zero has been reached for CO_2 but not for the other two contributing gases, hence the 9 Gt yearly emissions.

In table 4.6, the normalisation values for mineral resource depletion are displayed. Ultimate reserve, reserve base and economic reserves are being used as references to estimate the amount of available minerals in the crust as a total budget using 2015 as a reference year and as a basis for the yearly extraction using 2000 and 2015 as reference years.

Normalisation reference	**kg Sb eq.**	**Reference year**
Total		
Ultimate Reserve Budget	$3.35 \cdot 10^{16}$	2015
Ultimate Recoverable Reserve	$3.35 \cdot 10^{12}$	2015
Aurobay Ultimate Budget	$58.8 \cdot 10^{9}$	2015
Yearly		
Ultimate Reserve Yearly	$3.61 \cdot 10^{8} yr^{-1}$	2000
Reserve Base Yearly	$2.30 \cdot 10^{9} yr^{-1}$	2000
Economic Reserve Yearly	$2.54 \cdot 10^{9} yr^{-1}$	2000
Ultimate Reserve Current	$5.88 \cdot 10^{9} yr^{-1}$	2015

Table 4.6: Derived mineral depletion normalisation references using the three reserve estimates. Both as a total budget using 2015 as the reference year but also based on yearly resource use, using 2000 and 2015 as the reference year.

The reference year 2015 refers to the world production and estimated ultimate reserves that year. This results in total world production of $5.88 \cdot 10^9$ kg Sb eq. per year. The equivalent numbers for the reserve base were not calculated because USGS stopped reporting this category in 2011. The economic reserves were not updated either in this publication leaving only ultimate reserve-based results for the year 2015.

Using total reserve estimates as budgets in the normalisation step instead of per-year production, is another approach used in this report. Using the total ultimate reserves, the reserve estimate was $3.35 \cdot 10^{16}$ Sb eq. Re-scaling that to Ultimate Recoverable Reserves with an assumption of humanity only being able to reach down to around 3 km deep into the crust for resource extraction, the reserve estimate lands on $3.35 \cdot 10^{12}$ kg Sb eq.

As said the updated ADP values for the year 2015 did not update economic reserves meaning this had to be done manually by gathering published data on estimated economic reserves from USGS and converting them using the new values from 2015. Where reserve data was missing, 20 times the world extraction was used if available. The result is a total estimated economic reserve of $2.77 \cdot 10^{12}$ kg Sb eq. or 2.77 Gt Sb eq.

Normalising using world yearly emissions or extraction is problematic both for the sake of trying to reduce emissions also when used to compare the severity using different reference years. This can be misleading because the engine can have a constant impact, however, if the yearly world emissions increase then it will result in a decreased severity. Resulting in an indication that the performance of the engine has improved even though it is only based on a change in the relation between engine impact and emissions.

Using a distance-to-target method might be a more robust way of evaluating each category to its reference target making them comparable in some sense. Ecological Scarcity could be used for this purpose given that equivalent targets have been set. This also holds for Environmental Footprint where a reduction target could be used as a normalisation basis. For both methods, an approach where each evaluated substance has its reduction target would be ideal giving more insight into potential hot spots about the different targets.

Given the lack of established global mineral boundaries or budgets, the final normalised result will be almost exclusively determined by the chosen reference. This is an issue in several ways. Leaving the choice of reference up to the authors themselves, which the midpoint results will be evaluated and normalised with, making bias unavoidable. Basing these boundaries on something like the global normalisation factors from the Environmental Footprint could mitigate some of that bias, even though those numbers have flaws as well. The Environmental Footprint normalisation factors are conservative in comparison with yearly estimates from both IPCC and existing ADP values regardless of the chosen reserve estimate. Most likely it lacks data for the regionalised approach which they chose to use, meaning less data qualifies for inclusion in the data set.

The report only investigated normalisation based on global targets or budgets as opposed to the share of a single person or industry. The reason is the decreased risk for bias as well as aiming at a result that is somewhat robust despite the many demarcations which is the very nature of this project. By assigning a yearly share to a person or industry the choices must be justified and since resources are far from evenly distributed over the world it would be difficult to argue for anything. Perhaps such a budget could be more justified for climate change, however for mineral resource depletion there isn't an established equivalent. As seen in the planetary boundaries there are no targets for mineral resource depletion which implies the complexity. With the previous as background, it was chosen to calculate the Aurobay target by applying their target for 2040 to the whole world, i.e., still using global values as a basis but with stricter reduction targets which shows the severity of the engine comparing the Aurobay targets with SSP1-1.9 and SSP1-2.6.

For this project, climate change is compared to mineral resource depletion. Comparing a global standard such as IPCC with reserve estimates and budgets using ADP raises a few questions. Is it currently possible to match the IPCC environmental boundaries with equivalent boundaries of mineral resource depletion? They are not equivalent and the question that has to be answered then is, how close to equivalency the boundaries must be to be useful at all in a comparison.

An alternative to using aggregated total antimony and greenhouse gas budgets would be to look at specific substances in the two categories and set individual targets accordingly. This makes the normalisation for each target more specific and arguably more equal for comparison. This also makes it possible to concentrate efforts on substance-specific hotpots regardless of which impact category they belong to. For this purpose, as mentioned, the Ecological Scarcity method is well-suited and enables comparisons between substances as well as between impact categories.

Looking at table 4.6, the updated values used for the different versions of ADP are from 2000 and 2015 respectively where only the values based on ultimate reserves were updated. A part of the demarcations was to use the most recent updated method and data available which compared to resource depletion, is AR6 from 2021 for climate change. This again, shows the difficulties with estimating mineral resource use which also further proves the complexity of comparing the severity between the two impact categories.

As previously mentioned, the use of different reference years for the same product could indicate that the product has improved, when it is the relation between emissions and product that has changed. To prevent this issue when comparing generations of products and measuring their improvement over time, using an identical approach and reference is vital. Even in the case when updated numbers are available it should be used as a tool for relative improvement rather than absolute performance. This emphasises the aim of the entire project at large, to provide a framework to guide Aurobay's efforts at mitigating the most severe impacts.

4.5 EF 3.0 endpoint result

This sub-chapter presents selected results from using the Environmental Footprint normalisation approach for obtaining comparable single score results. The results shown in the figures below are dimensionless and the figures should be used as an indication of relative impact in relation to the normalisation approach rather than their calculated score.

4.5.1 Yearly world emission normalisation

This part goes through the normalised, single-score results based on yearly emissions using different scenarios and reference years for both impact categories.

4.5.1.1 Climate Change

Figure 4.1 below shows the impact of one engine using emissions in the year 2020 as normalisation according to the two predicted SSP1 scenarios compared to the Environmental Footprints own normalisation factor for the reference year 2010. In addition, the global emissions from the year 2000 have been added as well for reference. The EF 2010 result has a considerably higher impact compared to the SSP scenarios. This is directly influenced by the difference in the reference year affecting the estimated emissions. In addition, EF 2010 normalisation factors are based upon AR5 while the SSP scenarios are based on AR6. Compared to emissions in the year 2000, EF 2010 results are much closer to those emission levels compared to SSP levels, indicating uncertainty.

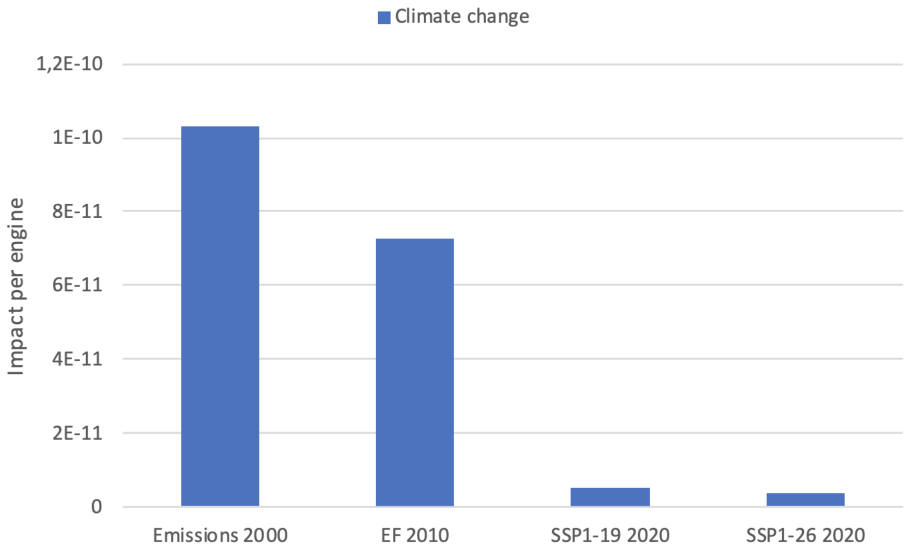


Figure 4.1: Impact of an engine based on normalised results using emissions in 2000, EF 2010's normalisation factors and, yearly budget based on SSP1-1.9 and SSP1-2.6 in 2020.

By using a standard normalisation approach based on world emissions for a specific year, the result can vary significantly depending on the reference year where the selected budget completely dictates the outcome. A higher total budget results in a lower relative impact from the engine. This indicates that using a specific year and budget will only indicate the severity compared to the budget itself and not to the severity of the product.

4.5.1.2 Mineral Resource Depletion

Figure 4.2 shows similarities to the previous figure when comparing the results from the impact of EF 2010 normalisation factors. Due to the much lower extraction estimates, the engine makes up a larger share of the total world extraction compared to the other normalisation numbers, hence the large impact. As the EF 2010 normalisation basis is based on the same ADP CFs as the ultimate reserve world extraction estimates with reference year 2000, the extraction estimate is what controls the total impact - which is much lower. This entails that either EF 2010 normalised values are conservative or that the 2000-year references gathered from CML authors have generous estimates. The difference between the three results using the reference year 2000 is mostly attributed to their inherent difference in the estimated reserves used to calculate the ADP values.

The ultimate reserve extraction estimates with the reference year 2015 is approximately 16 times higher than the same estimate for the year 2000. This is mainly because the extraction ratio has changed and is less attributed to the ultimate reserves as the concentration in the crust is not time-sensitive.

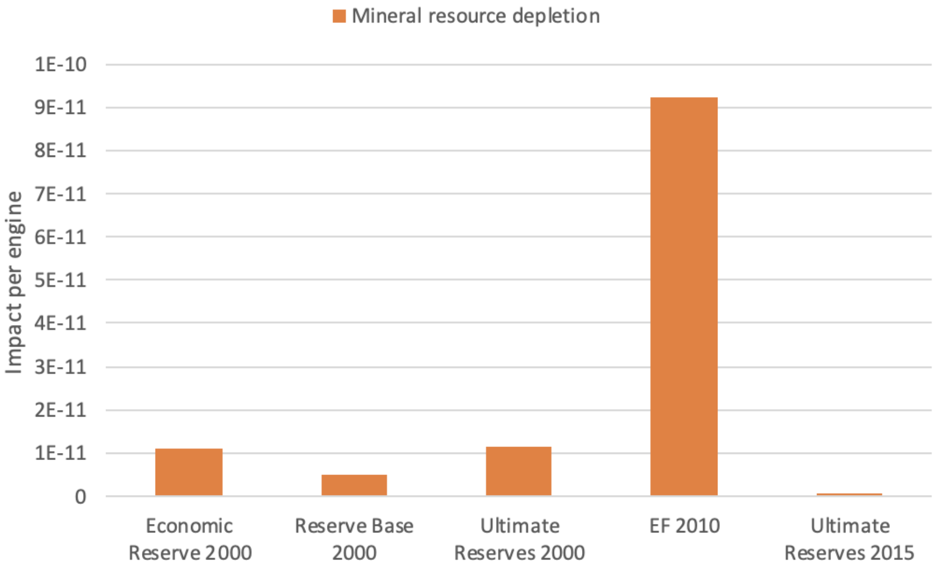


Figure 4.2: Impact per engine based on normalised results using world production for economic reserves, reserve base and, ultimate reserves in 2000, EF 2010 and, ultimate reserves using 2015 as the reference year.

Much like the climate change category, reference year makes a large difference. In the mineral resource depletion category, there is also the choice of reserve estimate that influences the results additionally.

4.5.2 Normalisation with total budgets

Figure 4.3 shows the impact of the engine normalised using the calculated total greenhouse gas (GHG) emissions and mineral resource budgets. The climate change budgets are calculated using the total per-year emission budget from 2020 to 2050 when adhering to the respective scenario. The ultimate mineral reserve budget is based on the total available minerals in the earth's crust whilst the ultimate recoverable reserves reference the top 3 km layer of the crust. The economic reserves are the total available, economically viable to mine, mineral resources in 2015.

Even though the economic reserves are much smaller than the ultimate reserves, when compared to the SSP scenarios which are indirect reduction targets, there is a significant difference. The result shows that the engine has a climate change impact several orders of magnitude greater than any of the current impacts based on these mineral reserve estimates when using this perspective.

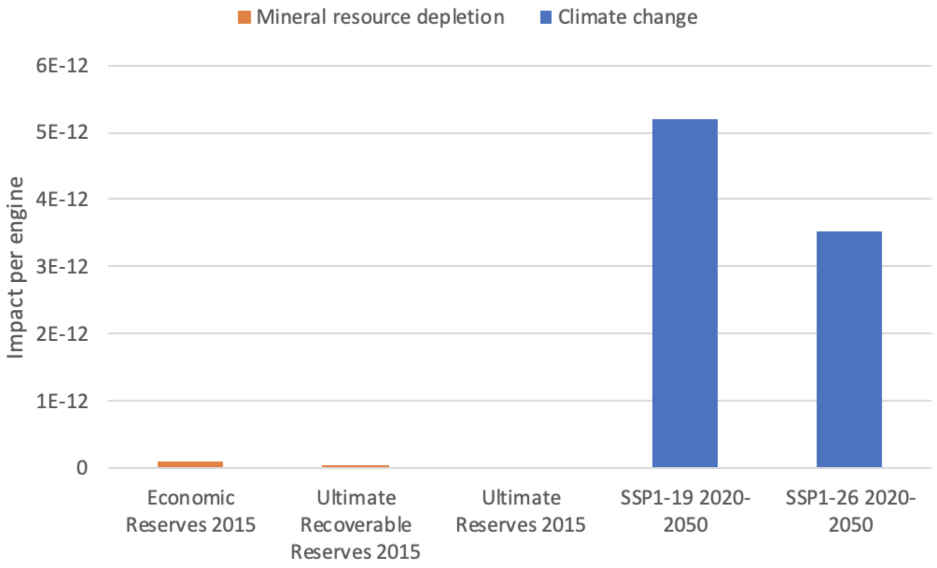


Figure 4.3: Normalised impact of the engine using the EF method for climate change 2020-2050 budget and different mineral reserve budgets from 2015.

4.6 Ecological Scarcity endpoint result

The Ecological Scarcity method heavily relies on reduction targets where the critical flow and the reduction target, are completely vital for the result to be relevant. Due to the lack of political reduction targets within the mineral resource depletion category, the method lacks purpose and makes the result more ambiguous. The method supports normalising with current emissions, but the Environmental Footprint method can be used for this purpose as well with minimal efforts with equivalent outcomes. In section 4.7.2, the Ecological Scarcity is used with internal Aurobay reduction targets and SSP scenarios to derive the single score in a number of UBP.

4.7 Aurobay result

This section contains the results of using both endpoint methods with the 2040 Aurobay targets as a normalisation basis. The approach for simplicity's sake assumes that the global targets and budgets all adhere to the Aurobay 2040 targets.

4.7.1 Aurobay Targets using Environmental Footprint

Figure 4.4 shows the engine impact based on budgets which are calculated using a net-zero approach for both impact categories by the year 2040. Although they are displayed in the same figure, it does not necessarily mean that they are directly comparable but rather based on the same approach. The starting point for climate change is essentially the same for SSP1-1.9 and SSP1-2.6 hence only the SSP1-1.9 is used to estimate a budget until 2040. For mineral resource depletion, the categories differ significantly due to different reference years used and reserve estimates. The different reference years and their production estimates to align with climate change, are all assumed to adhere to 2020 and 20 years forward when calculating the budget until 2040.

As stated prior the mineral world production in 2015 was much greater than in the year 2000 hence ultimate reserve for the latter reference year was much larger and the total impact was much lower. The world production based on ultimate reserve 2000 in Sb eq. is lower than the economic and reserve base estimates for the same reference year. Because of that the resulting budget will be lower for the ultimate reserves than for the economic reserves and reserve base. The smaller the budget the larger the resulting normalised impact will be, meaning that the approach will alter the severity of the impact category and the allowed resource use. This approach will result in a larger reserve that leads to a larger impact whereas prior results show the opposite.

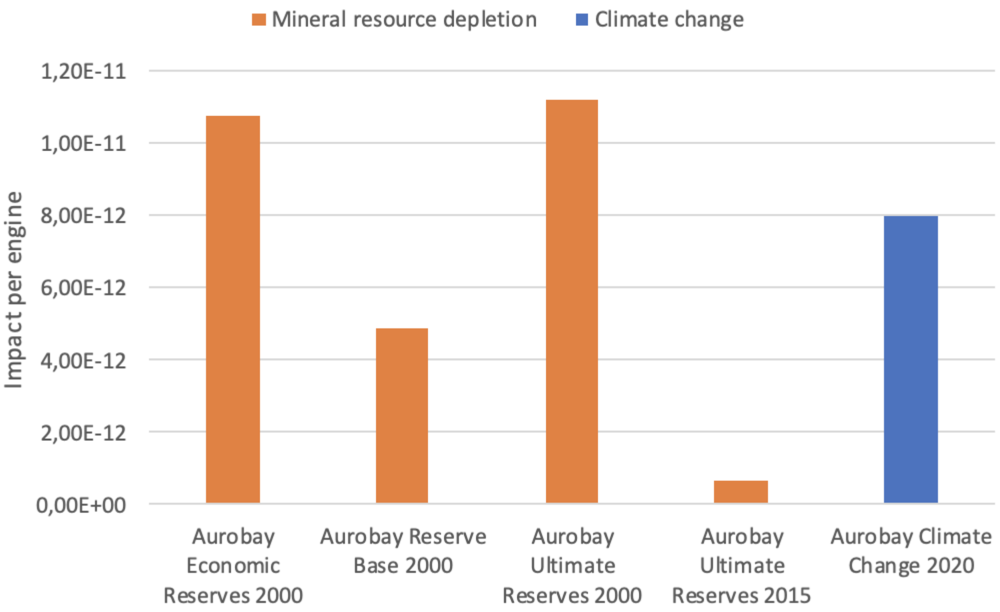


Figure 4.4: Normalised impact of the engine using EF method with Aurobay 2040 budgets.

Environmental Footprint can be a suitable choice of impact assessment method for an environmental evaluation of the engine. As mentioned, it can be done using a simple normalisation approach that is not especially time-consuming as it can use current emissions which are readily available. The method however is less robust when used for evaluation against targets.

4.7.2 Aurobay Targets using Ecological Scarcity

As seen in table 4.5, the yearly budget in 2020 used for climate change was practically the same for both SSP1-1.9 and SSP1-2.6 hence only SSP1-1.9 was shown for climate change. For Ecological Scarcity, however, the estimated yearly budget in 2030 was set as the critical flow, resulting in different yearly budgets for SSP1-1.9 and SSP1-2.6.

In addition, the halved SSP1-1.9 budget was used for the Aurobay result which is equivalent to reaching halfway to net zero emissions in 2030. The equivalent 2030 target is a product of simplifying the 2040 target and not an actual official target from Aurobay. This shows that a greater budget as used in the SSP1-2.6, will result in a lesser impact compared to the Aurobay target.

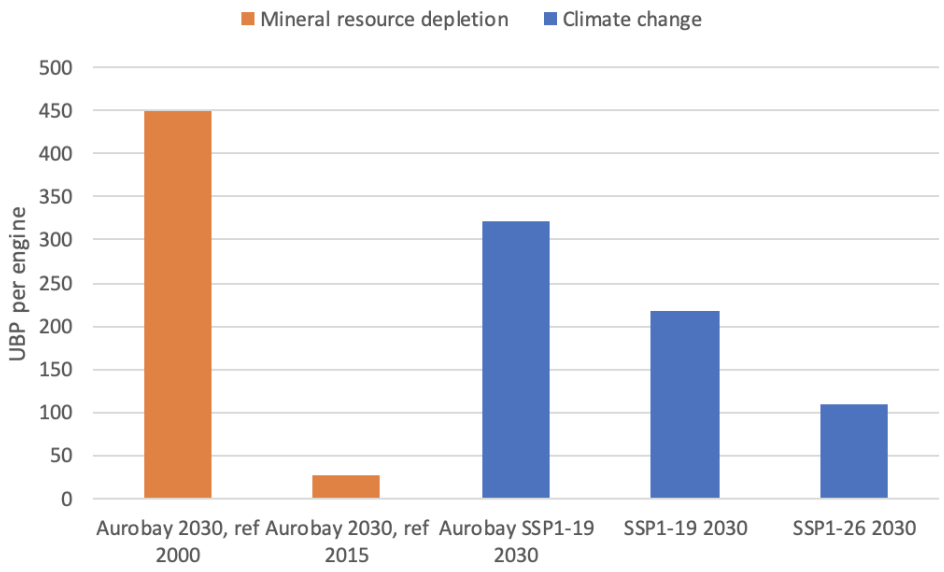


Figure 4.5: Normalised impact of the engine using the Ecological Scarcity method with SSP and Aurobay targets.

When using Ecological Scarcity to calculate the severity, 1 UBP is divided by the normalisation factor which for the year 2015 is much greater than in the year 2000, hence the severity using ultimate reserves in 2000 will be significantly larger than when using 2015. The reduction target for all five approaches is the same, meaning that the contribution from the fraction of current flow divided by critical flow will be identical. This results in that only the normalisation flow will contribute to different impacts on the results in this comparison.

Compared to the Environmental Footprint approach for the Aurobay approach, this could be an alternative way of estimating the severity of the engine. The ability to incorporate both aggregated emissions as in entire impact categories, and substance-specific emission targets, generating a comparable result in UBP is advantageous for this purpose.

Regarding normalisation, it is of utmost importance to be consistent with approach and reference years as it can heavily impact the results as we've shown above. Using the normalised results as anything else than a relative comparison between impact categories or between substances within the context of the same product is not recommended. The results say little about the absolute sustainability of the product.

4.8 Areas of Improvement

An area of improvement is that the different high-impact minerals should be investigated. As an example, tellurium which is not used in the engine means that the tellurium in the Ecoinvent process is just counted as waste when refining the copper needed for the engine. If tellurium is not wasted and used for other purposes, it should not be attributed to the engine. More research is needed here.

The linearised approach used to calculate the different normalisation budgets is a large uncertainty that could be modelled much more closely to a real-life scenario. No reduction of this sort is linear in reality and instead of using 10-year increments, a yearly resolution such as is available for the SSP scenarios could be used and would better reflect a future reduction scenario. More research is needed on the mineral side where specific minerals could be individually mapped and evaluated instead of using an aggregated indicator.

Given the lack of targets for mineral resource depletion in general and among most methods evaluating this category, a more extensive comparison of methods and available normalisation approaches would be a good approach moving forward. A workshop could be one approach including many more relevant stakeholders and experts to decide upon a framework to measure and evaluate the severity of the mineral resource depletion category - ideally not for a specific industry or sector. But for the LCA community as a whole.

5

Conclusion

When choosing relevant midpoint LCIA methods the RACER framework is recommended. Since the IPCC is the global standard, it should be selected to calculate climate change impacts. For mineral resource depletion, the choice of method will alter the results because different methods use different sub-methods. To compare impact categories within an Aurobay context, ADP is recommended as it provides a good basis for further normalisation.

Choosing an endpoint evaluation method is even more context-specific. Depending on the goal of the evaluation the selection will vary. For this report, simplicity and transparency were prioritised along with the possibility to incorporate reduction targets. For these purposes, the Environmental Footprint and Ecological Scarcity endpoint methods were chosen.

The Environmental Footprint method as an endpoint method is useful when a baseline normalisation reference is needed. This baseline can be comprised of current world production or relevant budgets and can be used for comparison with the next-generation products to measure relative environmental impacts. Even reduction targets if available can be used with the method to gain insight into which impact category performs the worst.

The Ecological Scarcity method is less flexible but under certain circumstances it can prove useful. Its distance-to-target approach emphasises the set reduction targets when available and magnifies the differences between targets within and between impact categories.

Given the above, for Aurobay, both methods can be used where Environmental Footprint is more flexible but Ecological Scarcity has its uses when proper targets have been set. A single final approach cannot be recommended as it solely depends on the circumstances and what comparison is desired.

Bibliography

[1] IPCC, “Ar6 synthesis report - headline statements,” Available at https://www.ipcc.ch/report/ar6/syr/resources/spm-headline-statements (2023/04/11).

[2] S. R. Center, “The nine planetary boundaries,” Available at https://www.stockholmresilience.org/research/planetary-boundaries/the-nine-planetary-boundaries.html (2023/04/11).

[3] H. Ritchie, M. Roser, and P. Rosado, “co_2 and greenhouse gas emissions,” *Our World in Data*, 2020, https://ourworldindata.org/co2-and-greenhouse-gas-emissions.

[4] E. Parliament, “Eu ban on the sale of new petrol and diesel cars from 2035 explained,” 2022, https://www.europarl.europa.eu/news/en/headlines/economy/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained.

[5] International Energy Agency, “Comparative life-cycle greenhouse gas emissions of a mid-size bev and ice vehicle,” 2022, https://www.iea.org/data-and-statistics/charts/comparative-life-cycle-greenhouse-gas-emissions-of-a-mid-size-bev-and-ice-vehicle.

[6] M. Schmid, “Challenges to the european automotive industry in securing critical raw materials for electric mobility: the case of rare earths,” 2020, available at https://www.cambridge.org/core/journals/mineralogical-magazine/article/challenges-to-the-european-automotive-industry-in-securing-critical-raw-materials-for-electric-mobility-the-case-of-rare-earths/BCFFE02B053E190F08C0A014D0BCA652# (2023/04/11).

[7] C. Thuve and H. P. Yuvaraj, “Life cycle assessment of a combustion engine - mapping the environmental impacts and exploring circular economy,” Ph.D. dissertation, Chalmers university of technology, Gothenburg, Sweden, 2022.

[8] M. A. Curran, *Life Cycle Assessment Handbook : a guide for environmentally sustainable product*, 1st ed. John Wiley & Sons, Incorporated, 2012.

[9] Koch D., Friedl A., Mihalyi, B., “Influence of different lcia methods on an exemplary scenario analysis from a process development lca case study,” 2022, https://doi.org/10.1007/s10668-022-02302-w.

[10] Ecoinvent, “Impact assessment,” Available at https://ecoinvent.org/the-ecoinvent-database/impact-assessment/#1598279979877-ae9113c5-17e11611227980159166141833340316614291937081661429832917 (2023/04/11).

[11] SS-EN ISO 14040, “Environmental management - Life cycle assessment - Principles and framework,” (ISO 14040:2006).

[12] SS-EN ISO 14044, “Environmental management - Life cycle assessment - Requirements and guidelines,” (ISO 14044:2006/Amd 1:2017).

[13] European Commission, “Life Cycle Assessment (LCA),” Available at https://eplca.jrc.ec.europa.eu/lifecycleassessment.html (2023/05/30).

[14] European Comission, “Life cycle assessment (lca),” Available at https://eplca.jrc.ec.europa.eu/lifecycleassessment.html (2023/09/05).

[15] Aurobay, “Introducing aurobay,” Available at https://www.aurobay.com/about/introducing-aurobay/ (2023/04/11).

[16] F. B. de Oliveira, A. Nordelöf, B. A. Sandén, A. Widerberg, and A.-M. Tillman, “Exploring automotive supplier data in life cycle assessment – precision versus workload,” *Transportation Research Part D: Transport and Environment*, vol. 105, p. 103247, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1361920922000773

[17] E. Commission, “Toolbox better regulation,” Available at https://commission.europa.eu/system/files/2023-02/br_toolbox-nov_-2021_en.pdf (2023/06/04), 2021.

[18] A López, L Mabe, B Sanchez, C Tapia, A Alonso, Tecnalia Research and Innovation, “Best practice solutions: Methods for sustainability assessment within the process industries,” Available at https://www.aspire2050.eu/sites/default/files/users/user355/SAMT_D2.1_final.pdf (2023/06/05), Podunk IN, 2015.

[19] T. Wiedmann, H. Wilting, S. Lutter, Viveka Palm, S. Giljum, A. Wadeskog, D. Nijdam, “Development of a methodology for the assessment of global environmental impacts of traded goods and services,” Available at https://www.rivm.nl/bibliotheek/digitaaldepot/SCHO1009BRAM_e_e.pdf (2023/04/24).

[20] European Commission, “Improving monitoring indicators system to support dg competition’s future policy assessments, final report,” Available at https://ec.europa.eu/competition/publications/reports/kd0117397enn.pdf (2023/04/24).

[21] IPCC, “Climate change 2021: The physical science basis,” Available at https://report.ipcc.ch/ar6/wg1/IPCC_AR6_WGI_FullReport.pdf (2023/06/05).

[22] J. B. G. . R. Heijungs, “A proposal for the definition of resource equivalency factors for use in product life-cycle assessment,” *Environmental Toxicology and Chemistry*, vol. 14, no. 5, pp. 917–925, 1995.

[23] L. van Oers et al, “Abiotic resource depletion in lca,” Available at https://www.universiteitleiden.nl/en/research/research-projects/science/cml-abiotic-depletion-in-lcia (2023/06/05), 2002.

[24] T. Henckens, “Scarce mineral resources: Extraction, consumption and limits of sustainability,” *Resources, Conservation and Recycling*, vol. 169, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S092134492100118X(2023/09/13)

[25] L. van Oers et al, “Abiotic resource depletion potentials (adps) for elements revisited—updating ultimate reserve estimates and introducing time series for

production data," *The International Journal of Life Cycle Assessment*, vol. 25, no. 2, pp. 294–308, 2020.

[26] V. P. et al, "Interpretation of comparative lcas: external normalization and a method of mutual differences," *The International Journal of Life Cycle Assessment*, vol. 22, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S092134492100118X(2023/09/13)

[27] Sala, S. et al., "Development of a weighting approach for environmental footprint. european commission," *Publication Office of the European Union*, 2017.

[28] United Nations Climate Change, "The paris agreement," Available at https://unfccc.int/process-and-meetings/the-paris-agreement (2023/06/29).

[29] IPCC, "Climate change 2023: Synthesis report. a report of the intergovernmental panel on climate change," Available at https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_LongerReport.pdf (2023/06/29), Geneva, Switzerland, 2023.

[30] Our World in Data, "Data explorer: Ipcc scenarios," Available at https://ourworldindata.org/explorers/ipcc-scenarios (2023/06/20).

[31] Riahi, K. et al., "The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview," *Global Environmental Change*, vol. 42, pp. 153–168, 2017.

[32] Stockholm Resilience Center, "Planetary boundaries," Available at https://www.stockholmresilience.org/research/planetary-boundaries.html (2023/05/23).

[33] J. Rockström, W. Steffen, K. Noone, Åsa Persson, F. S. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. A. Foley, "A safe operating space for humanity," *Nature*, vol. 461, 2009.

[34] M. W. Ryberg, M. Owsianiak, K. Richardson, and M. Z. Hauschild, "Development of a life-cycle impact assessment methodology linked to the planetary boundaries framework," *Ecological Indicators*, vol. 88, pp. 250–262, 2018.

[35] K. R. et al, "The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview," *Global Environmental Change*, vol. 42, pp. 153–168, jan 2017.

[36] G. J. et al, *Handbook on life cycle assessment. Operational guide to the ISO standards.* Dordrecht: Kluwer Academic Publishers, 2002.

[37] USGS, "Mineral commodity summaries 2016," Available at https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/mcs/mcs2016.pdf (2023/09/17).

[38] European Commission, *Recommendations for Life Cycle Impact Assessment in the European context - based on existing environmental impact assessment models and factors*, 1st ed. EUR 24571 EN. Luxemburg. Publications Office of the European Union: European Commission-Joint Research Centre - Institute for Environment and Sustainability, 2011.

[39] E. Commission, "Understanding product environmental footprint and organisation environmental footprint meth-

ods," Available at https://circabc.europa.eu/ui/group/6e9b7f79-da96-4a53-956f-e8f62c9d7fed/library/537534a4-9c76-40a1-b488-e9127db2befd/details?download=true (2023/06/05), 2021.

[40] D. Su, *Sustainable Product Development Tools, Methods and Examples.* Nottingham Trent University, Nottingham, UK: Springer Nature Switzerland AG, 2020.

[41] Ministry of Housing, Spatial Planning and the Environment, "Eco-indicator 99 manual for designers, a damage oriented method for life cycle impact assessment," Available at https://pre-sustainability.com/wp-content/uploads/2013/10/EI99_-Manual.pdf (2023-06-15), 2000.

[42] H. et al, "Ecological footprint accounting in the life cycle assessment of products," *Ecological Economics*, vol. 64, no. 4, pp. 798–807, 2008.

[43] J. Venetoulis, J. & Talberth, "Refining the ecological footprint," *Environment, Development and Sustainability*, vol. 10, no. 4, pp. 441–469, 2008.

[44] F. R. et al, "Swiss eco-factors 2021 according to the ecological scarcity method," Available at www.bafu.admin.ch/uw-2121-e, 2021.

[45] European Commission, "Environmental footprint methods," https://environment.ec.europa.eu/news/environmental-footprint-methods-2021-12-16_en (2023-06-01).

[46] B. Steen, "A systematic approach to environmental priority strategies in product development (eps). version 2000–general system characteristics," *Gothenburg Centre Environ Assess Prod Material Syst*, 1999.

[47] I. S. E. R. Institute, "Environmental priority strategies (eps)," https://www.ivl.se/english/ivl/our-offer/our-focus-areas/consumption-and-production/environmental-priority-strategies-eps.html (2023-06-03).

[48] B. Steen, "The eps 2015d impact assessment method – an overview," *Swedish Life Cycle Center, Report number 2015:5*, 2015.

[49] C. e. a. Bulle, "Impact world+: a globally regionalized life cycle impact assessment method," *International Journal of Life Cycle Assessment*, vol. 24, pp. 1653–1674, 2019.

[50] T. B. et al, "Ipcc 2021 ar6 impact assessment method," Available at https://nexus.openlca.org/ws/files/22956 (2023-06-03), 2022.

[51] IPCC, "Mitigation pathways compatible with 1.5°c in the context of sustainable development," Available at https://www.ipcc.ch/sr15/chapter/chapter-2/ (2023/06/03).

[52] M. a. J. Huijbregts et al, "Recipe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level," *International Journal of Life Cycle Assessment*, vol. 22, no. 2, pp. 138–147, 2017.

[53] M. D. M. V. et al, "Ore grade decrease as life cycle impact indicator for metal scarcity: The case of copper," *Environmental Science & Technology*, vol. 25, no. 2, pp. 294–308, 2012.

[54] ——, "Surplus ore potential as a scarcity indicator for resource extraction," *Industrial Ecology*, vol. 46, no. 23, pp. 12 772–12 778, 2016.

[55] United States Environmental Protection Agency, "Tool for the reduction and assessment of chemical and other environmental impacts (traci)," August 2012, user's manual.

A

RACER

A table showing the RACER criteria together with a number of the sub-criteria. Some of the sub-criteria are marked in bold; this highlights the criteria that Aurobay finds most interesting and relevant from a business standpoint for the mild-hybrid VEP MP Gen3.

RACER (MID)	**Climate Change**	**Mineral Resource Depletion**
Relevant	• **How well it covers the life cycle of the product** • **Sectoral and geographical coverage** • **How well it utilises IPCC model with regards to the automotive industry** • **Number of considered substances** • Midpoint indicators available for endpoint use	• How well it covers the life cycle of the product • **Sectoral and geographical coverage** • **Coverage of vital engine materials** • **Utilises a suitable method for the automotive industry (ADP, SOP, etc)** • Midpoint indicators available for endpoint use
Acceptability	• **Widely accepted by relevant stakeholders (Industry, public administration, scientific community etc)**	• **Widely accepted by relevant stakeholders**
Credibility	• Applicable on state-of-the-art technologies, i.e. the engine (age/updates) • **Clearly defined methodology** • **Transparency (documentation of assumptions and limitations)** • Unambiguous	• Applicable on state-of-the-art technologies, i.e. the engine (age/updates) • **Clearly defined methodology** • **Transparency (documentation of assumptions and limitations)** • Unambiguous
Easiness	• **Data should be accessible and easy to implement with regards to formatting and automation** • Cost	• **Data should be accessible and easy to implement with regards to formatting and automation** • Cost
Robustness	• **Responsiveness to input changes** • Consistency and accuracy • Against manipulation (bias, selection of boundaries etc)	• **Responsiveness to input changes** • Consistency and accuracy • Against manipulation (bias, selection of boundaries etc) • Comparability against targets (can the results be normalised or evaluated towards any existing targets, SDGs, PBS)

Table A.1: RACER-criteria with sub-criteria conducted for midpoint evaluation.

B

LCIA methods

The LCIA of the Life Cycle Assessment can be conducted using different methods, as described in 2.1. The selected methods for the purpose of this thesis are described in more detail below.

B.1 CML

The CML impact assessment method is a part of the Handbook on Life Cycle Assessment - Operational Guide to the ISO Standards released in 2002 by the Institute of Environmental Sciences (CML) at Leiden University in the Netherlands. They include nine impact categories for their baseline approach with recommended evaluation methods for each category. Apart from the baseline methodology, the authors describe alternative methods for impact assessment for all nine categories although the baseline methods have been selected based on current best practices. A non-exhaustive list of criteria includes linearity of models for ease of use, indicator should have minimal uncertainty while maintaining relevance and data both with and without spatial information should be applicable [36].

For the impact category of abiotic resource depletion the method proposed as a baseline is the ADP as described by Guinée & Heijungs (1995) [22] where ultimate reserves, extraction rate and antimony as reference substance are used. At the time of adopting the ADP method it was not authorised by any international body but recently the proposed depletion method has been recommended by both ILCD 2011 [38] and for use in recent EF [39] updates. The authors also state that the problem definition itself is a value-choice which should be noted as well as the lack of competitive aspect of resources. The other alternatives proposed for impact assessment and mainly sensitivity analysis are the use of economic reserves instead of ultimate reserves, only based on ultimate or economic reserves disregarding extraction rates and lastly, an approach based on exergy content as described by Finnveden 1996b and Ayres et al 1996 [36].

For climate change, the indicator proposed in the baseline method is GWP100 by the IPCC with alternatives of using a 20 or 500-year-long time horizon. The authors also state that the upper and lower limit of net GWP could be used as a third and fourth alternative to the baseline approach (based on the discussions of that time regarding ozone-depleting gases which may not be of interest today). Value choices of the method are acknowledged but deemed acceptable due to the acceptance by the authoritative body IPCC. Using the latest estimates for GWP is recommended and no further research was explicitly stated because of the already ongoing work by the IPCC [36] which holds today with the release of AR6 with updated GWP values [21].

B.2 Eco-indicator 99

Eco-indicator 99 is an LCIA method that can be applied at both midpoint and endpoint. It is a follow-up on the Eco-indicator 95 but is also the method together with CML 2002 that both ReCiPe and IMPACT 2002+ are based on [40].

The method itself is available in Ecoinvent 3.8 and is based on three steps, the collection of relevant data, calculations of the damages to human health, ecosystem quality and mineral and fossil resources, and lastly the weighting of the damages [41]. Regarding the impact categories of climate change and mineral resource depletion, climate change can be linked to the endpoint of human health and ecosystem quality, whilst mineral resource depletion is only connected to mineral resources.

In many other LCIA methods panel weighting is used to rank different impact categories. However, for Eco-indicator 99 the weighting is used to compare the different endpoint categories, i.e. human health, ecosystem quality and mineral resources [41].

B.3 Ecological Footprint

The ecological footprint impact assessment method is based on the biologically productive land along with water resources a population needs for its production and waste absorption [40] [42]. The impact of a product would be calculated in the following way:

$$EF = EF_{direct} + EF_{CO_2} + EF_{nuclear} \tag{B.1}$$

Where EF is the total time-integrated land use related to direct and indirect land use, CO2 emissions from fossil energy use and related to nuclear energy use. To convert CO2 emissions to land use the method uses the additional biologically productive land needed to sequester the additional atmospheric CO2 released [42].

The method can be used to conduct a so-called ecological footprint analysis which compares the derived footprint of a country or product with the available biocapacity that is renewable. This analysis makes it possible to distinguish what is sustainable on a basic level and to estimate the global ecological overshoot which has been estimated to be around 23 % according to Loh & Wackernagel in 2004 [43].

B.4 Ecological Scarcity

This distance-to-target endpoint impact assessment method derives its magnitude of severity based on political targets or policies specific either to countries or larger entities such as the EU. The baseline method uses Swiss environmental targets as the reference for calculating so-called Eco-factors or points, UBPs. These are calculated by using the following equation:

$$Eco - factor = K \cdot \frac{1\,UBP}{F_n} \cdot (\frac{F}{F_k})^2 \cdot c \tag{B.2}$$

where K is an optional characterisation factor of the pollutant e.g. CO2 eq per kg pollutant, F_n is the normalisation flow, F is the current flow, F_k is the critical flow and c is a constant. By flow the authors refer to any type of load of a pollutant or quantity of any type of resource released or used up within a set period, often annually.

The authors mention the use of planetary boundaries to approach global targets and refer to articles such as Doka 2016, Sala 2016 and Frischknecht & Büsser Knöpfel (2015). There are a few considerations when comparing the current Swiss targets and that global approach. The Swiss targets include the planetary boundaries directly or indirectly but also feature many other impacts not covered by the PBs. Uniformity across regions is not considered in the PBs and no way to do so has been adopted as of this report. The formality of the targets differs as some of the PBs have been internationally agreed upon such as climate change and stratospheric ozone depletion while all Swiss targets have been legislated into official law [44].

B.5 Environmental Footprint

The Environmental Footprint (EF) methods adopted by the European Commission aim to assist actors that want or need to calculate their environmental performance. This is achieved by proposing a harmonised methodology that is comparable and reliable enabling actors to make better informed decisions in the quest for sustainability. The EF methods include both the Product Environmental Footprint (PEF) and the Organisation Environmental Footprint (OEF) which has an additional set of rules and guidelines available [45].

EF follows the classical LCA approach but has standardised all parts of the process, from inventory modelling to single indicator impact assessment for use in decision-making. The approach is generally in line with the UNEP Life Cycle Initiative although some differences might exist due to the European context targeted by the Commission. For some product categories, there are specific rules, PEFCRs, that have been developed to further harmonise footprint calculations and ensure that especially harmful or impactful products are highly comparable to assist better decisions and trigger development towards sustainability [39].

The method has a set of criteria that decides what data is deemed appropriate and of high enough quality to be used for assessment and must comply with specific data formats as well. The requirements of the data used are evaluated based on, completeness, methodology, and representativeness in areas of technology, geography, precision, and time. Apart from having to also fulfil proper documentation and nomenclature a review by a qualified expert is needed to verify the data along with a report on that subject. All these criteria will result in an overall data quality score of 1-5 to indicate to users who have free access to the EF database for PEF/OEF evaluations [39].

The impact assessment included in EF covers 16 different impact categories where the EU Commission recommends what impact method should be used for the respective category. For climate change contribution to the global warming potential, GWP100 (CO2 eq.) is recommended as a measure of increased global radiative forcing. For mineral and metal use the abiotic depletion potential, ADP (kg Sb eq.) is recommended. Additionally, EF provides a normalisation and weighting step based on impact assessment to derive a single score indicator for hotspot identification and decision-making. To be able to compare single score indicators of products within the same product category, e.g. between two companies, only products that are applicable for PEFCRs should be compared to ensure consistency [39]. The normalisation numbers can be found below [27]:

Impact category	**Model**	**Unit**	**global NF**
Climate change	IPCC (2013)	kg CO2 eq	5.79E+13
Resource use, minerals and metals	ADP ultimate reserve (2002)	kg Sb eq	4.39E+08

Table B.1: Proposed global normalisation values for climate change and mineral resource depletion in the environmental footprint method using regionalised CFs, reference year 2010.

B.6 EPS

Environmental Priority Strategies, EPS is an endpoint method and started its development during the 90s as a collaboration between Volvo who requested the project, IVL and the Swedish Federation of Industries [46] [47]. EPS had a goal of being a versatile tool during the product development stages as it should be able to quickly in the early stages of a product point towards more sustainable options while being able to analyse impacts more thoroughly in the later stages of development. EPS is in line with the ISO-14000 series and is aimed towards companies' internal product development process as a guide rather than conforming to emission or quality standards [46].

The default indices of the original EPS were the 'WTP to avoid changes' from the reference present environment which did not include the cost of direct impacts as the economic system was not included in the reference safeguard objects [46].

An updated version released in 2015 instead uses monetary values derived from an estimated market value of resources and functions of impacted safeguard areas. These areas are ecosystem services, access to water, abiotic resources, biodiversity, and human health. Emissions and resource use will impact some or all these categories resulting in estimated monetary damage. This is expressed in Environmental Loading Units, ELU which corresponds to 1 Euro under certain conditions per unit of emission or resource used. A 0% percent discount rate was used when calculating impacts with longer time horizons [48].

B.7 ILCD

The International Reference Life Cycle Data System (ILCD) is a paper conducted by the European Commission in 2011 [8]. It can be used to assess impact categories at the midpoint using openLCA, however, it is mainly conducted to be used as a guidance for choosing methods for different impact categories at midpoint and to some extent, the endpoint. It is developed based on the international standards of LCA as well as ISO 14040/44 which covers both emissions to air, water and soil, as well as impact categories which have an effect on human health, environment, and natural resources [40]. Furthermore, it does not cover recommendations for weighting or normalisation within an impact category.

For the impact category climate change, ILCD presents methods that all use GWP100 according to IPCC AR4 2007 [38]. The following methods all refer to different IPCC reports, however, newer reports could be applied to each method, such as AR6, which is the latest report.

• Eco-indicator 99	*Mid- and Endpoint*
• EPS2000	*Mid- and Endpoint*
• ReCiPe	*Mid- and Endpoint*
• LIME	*Mid- and Endpoint*
• IPCC	*Midpoint*

All methods above could be applied to evaluate climate change at midpoint, however, at endpoint, no method was recommended. Despite ILCD not recommending any method for endpoint evaluation, the document still emphasises the benefits of evaluating climate change at both mid- and endpoint [38]. If it is necessary to express the impact in terms of DALY or species loss, they recommended ReCiPe, however, that method is not recommended.

For mineral resource depletion, ILCD argues that there is a lack of consensus on what the issue is [38]. The ILCD recommends CML for calculating mineral resource depletion which uses ADP, given in *kg Sb eq.* The reason is that it includes extraction as well as reserves of a given resource. Furthermore, CML covers most substances and materials identified as critical by the European Commission. Again, ILCD argues that no method could be recommended for endpoint evaluation, however, if one had to be recommended they viewed ReCiPe as a solution.

B.8 IMPACT World+

The Impact World+ impact assessment method combines and updates three former methods, IMPACT 2002+, EDIP and LUCAS to achieve a globally regionalised method [49]. It utilises 18 different impact categories, both global and regional which then translates to 21 damage level indicators. Furthermore, these damage level indicators contribute to the three main areas of protection (AoP), human health, ecosystem quality resources & ecosystem services. In addition to the three AoPs two areas of concern are defined as water and carbon-related concerns with a total of six subcategories which overlap with the AoPs but give other indications deemed relevant by the authors.

At the midpoint level, GWP100 is used as a climate change contribution measure while the GTP100 is used in addition to measure long-term impacts. For mineral resource depletion, the material scarcity index is applied [49].

B.9 IPCC

The results from the latest assessment report from the IPCC, AR6 have been implemented into software such as OpenLCA meaning it is now widely available for midpoint impact assessment [50].

The IPCC 2021 method for climate change brings updates to the GWP and GPT values over several different time horizons which is the basis for many other impact methods of climate change calculations. Updated carbon budgets, better accuracy across many different impact areas and the effects of COVID-19 are a few of the many updates brought to the public [21].

To be able to meet the 1.5 degree target the estimated yearly maximum GHG emissions in 2030 would have to be reduced to 25-30 GtCO2 eq. per year. This is approximately half of the projected median emissions of 52-58 GtCO2 eq. per year based on the current unconditional NDCs (nationally determined contributions). The total carbon budget for keeping below 1.5 degrees (66% chance) is approximately 420 GtCO2 without including non-CO2 forcers. A high cost of emissions reflected in policies is needed to cope with the 1.5-degree target, especially since the marginal abatement cost (with discounting) compared to the 2-degree target is approximately 3-4 times higher modelled over the century [51].

B.10 LC-impact

Not included in any software. Potential to be an updated "version" of ReCiPe 2016 as they use the same methods of assessing damage for climate change and minerals (roughly the same AoPs and uses SCP for minerals). One of the final deliverables of the project "D1.9 Abiotic resource use impacts" is still being worked on according to their website with a status 'coming soon'.

B.11 ReCiPe 2016

A method, first developed in 2008 by RIVM, Radboud University Nijmegen, Leiden University and PRé Sustainability [52]. Since the release in 2008, an updated version was developed in 2016 and it now covers 18 indicators at midpoint and three at endpoint.

To calculate the impact category climate change, ReCiPe 2016 uses IPCC, AR5 from 2014 [52]. ReCiPe uses global warming potential (GWP) to calculate the characterisation factor and this could be applied to three different time periods; individualist which is 20 years, hierarchist which equals 100 years and egalitarian which stands for 1,000 years. The GWP for each time period is calculated by dividing the absolute global warming potential (AGWP), meaning the amount of radiative forcing caused by 1 kg of GHG, with the AGWP for CO_2 as follows;

$$GWP_{x,TP} = \frac{AGWP_{x,TP}}{AGWP_{CO_2,TP}} \tag{B.3}$$

Where x represents the GHG and TP the time period. By using the equation endpoint results can be retrieved in $DALY/kgCO_2eq$ and $Species.year/kgCO_2eq$ [52].

When calculating the characterisation factors for mineral resource depletion two different approaches can be used. These are reserves, and ultimate recoverable resources [52]. ReCiPe uses Surplus Ore Potential (SOP) which can be retrieved by dividing the Absolute Surplus Ore Potential (ASOP), meaning the potential concerning 1 kg of mineral resource extracted (x) and reserve type (R), and dividing it with the potential concerning 1 kg of copper extracted (Cu) and reserve type.

$$SOP_{x,R} = \frac{ASOP_{x,R}}{ASOP_{Cu,R}} \tag{B.4}$$

Surplus Ore Potential (SOP) is a method based on future efforts of extraction rather than the current extraction of natural stocks as seen in ADP. It refers to the surplus ore mined in the future and how that is affected by the ore degradation as it diminishes over time [53] [54].

B.12 TRACI 2.1

TRACI short for Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts version 2.1 is an inherent impact assessment method that aims to be a manageable approach that should be easy to use, cover perceived important impact categories as well as be consistent with current legislation. The tool aims to apply to LCIAs, process design and emission minimisation in the effort to become more sustainable [55].

For the impact category Global Climate Change, the GWP100 published by the IPCC is used and at the time of the report in 2012, the most updated values at the time were used. The impact category of resource depletion had no recommended impact assessment approach in this version of the tool. It is stated that it is an "...extremely important issue for the use and development of sustainability metrics and LCA methodologies." However, because of the lack of international agreement or policies and difficulty in minimising value choices, it was deemed too difficult to concretise in this version. Efforts to address subcategories of land use and water use will be focused on within TRACI coming years [55].

C

Midpoint workshop

Workshop together with Aurobay to decide on three midpoint methods suitable for mineral resource depletion and climate change. The decisions are based on the RACER method including sub-criteria. Due to the time constraints of the thesis, the workshop was intended as a rough screening to decide which three midpoint methods were suitable to use in the next stage of the thesis. A summary of the workshop can be found below.

C.1 Mineral resource depletion

For mineral resource depletion, all methods were weighed against CML. ReCiPe was weighed against IMPACT World+ and ILCD against PEF/EF. Product Environmental Footprint (PEF) and Environmental Footprint (EF) have been investigated separately; however, PEF is based on EF and will therefore be weighted as one.

	CML	**ReCiPe**	**IW+**	**ILCD**	**EF**
CML	-	-	-	-	-
ReCiPe	CML	-	-	-	-
IW+	CML	ReCiPe	-	-	-
ILCD	ILCD	ILCD	ILCD	-	
EF	EF	EF	EF	EF	-

Table C.1: Pair-wise comparison used to choose midpoint evaluation methods for mineral resource depletion.

CML vs. ReCiPe 2016

CML and ReCiPe both have global coverage, but CML can also be applied in Europe specifically on a regional scale, however, it was agreed that the decision was not going to be based on that. CML and ReCiPe are both widely used and one of the largest differences between them in calculating mineral resource depletion is the sub-method they are using, CML uses ADP ultimate reserve and ReCiPe SOP. It was discovered that most of all methods investigated were using ADP ultimate reserves, and discussions about whether that is the best option for Aurobay took place. SOP on the other hand investigates materials and how there might have to be an increased number of ore to obtain the number of materials. The decision however landed on CML, much because of ADP's ability to estimate the total amount of metals on earth which all agreed on to be a suitable choice for this topic.

CML vs. IMPACT World+

As contrary to CML, IMPACT World+ is still new and it was therefore discussed if that was an argument not to choose it. IMPACT World+ might be interesting when wanting to understand waste but that is not the purpose of this thesis. Lastly, instead of using a method such as ADP or SOP, IMPACT World+ uses dollars/kg dissipated, which was seen as a more complex method to use, hence, CML was chosen.

CML vs. ILCD

ILCD was created by the European Commission and uses CML. One difference, however, is that ILCD includes 20 extra substances and the impact of that was discussed. ILCD was later chosen but not with regards to the substances, rather to the fact that it is developed by the European Commission but also because it incorporates CML as well. Thus, making the choice less relevant when only looking at the impact part of the LCA.

CML vs. PEF/EF

Much like with ILCD, PEF/EF is developed by the European Commission and is more recently published compared to ILCD which led to the workshop agreeing on PEF/EF.

ReCiPe 2016 vs. IMPACT World+

Using the same argument as for CML vs. IMPACT World+, IMPACT World+ is a newly developed method and ReCiPe is a more established, updated, and well-known method, hence ReCiPe was chosen.

ILCD vs. PEF/EF

As mentioned above, both methods were developed by the European Commission. Both use CML to some extent, however, there is a difference in sub-method, where ILCD uses ADP reserve base and PEF/EF ADP ultimate reserves. It was discussed that by using the ADP reserve base the numbers will differ more depending on how much is available at the time compared to the ultimate reserves where the numbers will stay more consistent. ILCD was published in 2010 and the latest updates for PEF in 2019. PEF/EF was therefore considered the better choice.

C.2 Climate change

The procedure when comparing methods suitable to calculate climate change was done on the basis that all methods use IPCC as a standard, which led to IPCC being chosen above all other methods. In addition, TRACI 2.1 was not considered in any other case than with Ecological Footprint, the reason being that TRACI 2.1 was developed to fit the U.S. and Canada. Lastly, as mentioned in the section about resource depletion IMPACT World+ is considered a new immature method and was not considered other than with Ecological Footprint.

	CML	**ReCiPe**	**Fprint**	**IW+**	**ILCD**	**TRACI**	**EF**	**IPCC**
CML	-	-	-	-	-	-	-	-
ReCiPe	ReCiPe	-	-	-	-	-	-	-
Fprint	CML	ReCiPe	-	-	-	-	-	-
IW+	CML	ReCiPe	IW+	-	-	-	-	-
ILCD	ILCD	ILCD	ILCD	ILCD	-	-	-	-
TRACI	CML	ReCiPe	TRACI	IW+	ILCD	-	-	-
EF	EF	EF	EF	EF	EF	EF	-	-
IPCC	IPCC	IPCC	IPCC	IPCC	IPCC	IPCC	IPCC	-

CML vs. ReCiPe 2016

When comparing CML and ReCiPe 2016 it can be noticed that they differ in the number of substances. CML contain 42-188 whilst ReCiPe 2016 has 217 which is also close to IPCCs 219 substances. Apart from that, ReCiPe 2008 was also recommended by ILCD (2010) alongside IPCC2007. Lastly, ReCiPe 2008 was the most used method in 2018, hence, ReCiPe 2016 which is the updated version was chosen.

ILCD vs. ReCiPe 2016

Similar to how ILCD refers to CML when calculating the impact category mineral resource depletion, it refers to ReCiPe for calculating climate change. ILCD was developed by an institution, leading to ILCD being chosen over ReCiPe 2016. This is further strengthened by the fact that ReCiPe uses SOP to evaluate mineral resource depletion which during this workshop was not preferred because of the uncertainties it brings compared to ADP.

PEF/EF vs. ILCD

Much like the discussion between these methods about mineral resource depletion, they are much alike. When calculating climate change, they both use IPCC (2013)

AR5, GWP100, and since PEF/EF is more recently published it was chosen over ILCD. EF 3.1 implements the latest AR6 report which furthers its lead over ILCD.

IMPACT World+ vs. Ecological Footprint

As mentioned, IMPACT World+ was cut for most of the cases because it is still new, and many improvements will happen this year. However, when it comes to the comparison with Ecological Footprint, IMPACT World+ could still be seen as more robust since Ecological Footprint only looks at CO2 eq. and therefore needs another method to first get CO2 eq. unlike IMPACT World+ which is a full mid-to-endpoint method.

D

Endpoint workshop

	ReCiPe	**EF**	**IW+**	**Eco Scarcity**	**Eco-Indicator**	**EPS**	**CE Delft**
ReCiPe	-	-	-	-	-	-	-
EF	EF	-	-	-	-	-	-
IW+	IW+	EF	-	-	-	-	-
Eco Scarcity	Scarcity	TIE	Scarcity	-	-	-	-
Eco-indicator	ReCiPe	EF	IW+	Scarcity	-	-	-
EPS	ReCiPe	EF	IW+	Scarcity	Eco-indicator	-	-
CE Delft	ReCiPe	EF	IW+	Scarcity	CE	CE	-

Table D.1: Pair-wise comparison used for evaluation of endpoint methods

Survey-based monetary methods such as EPS and CE delft have two issues: The estimation based on surveys (or partly on surveys) is uncertain and subjective by nature and dependent upon the asked participants and their views. The measuring unit itself can be a bit of a hindrance for use within a business as it can be misinterpreted as an actual cost for the company and not a total societal/ecosystem cost that is paid by society and the coming generations. Therefore, other single indicators were preferred in a business use case such as Environmental Footprint and Ecological Scarcity.

Environmental Footprint is scientifically robust as it stops at midpoint and normalises based on emissions meaning that the main uncertainty is applied at weighting based on panel and/or targets. The use of damage pathways and estimates incorporates further uncertainties that must be accounted for. However, it normalises based on current emissions since the goal is to lower them considerably.

ReCiPe is like Impact World+ in many ways although the impact category mineral resource depletion comes out a bit below the MACSI index used by Impact World+.

The SCP used by ReCiPe is based on current economic prices which will fluctuate a lot over time and are hard to predict. MACSI index is interesting because of the substitution part which Aurobay found interesting. Especially when choosing between materials during development.

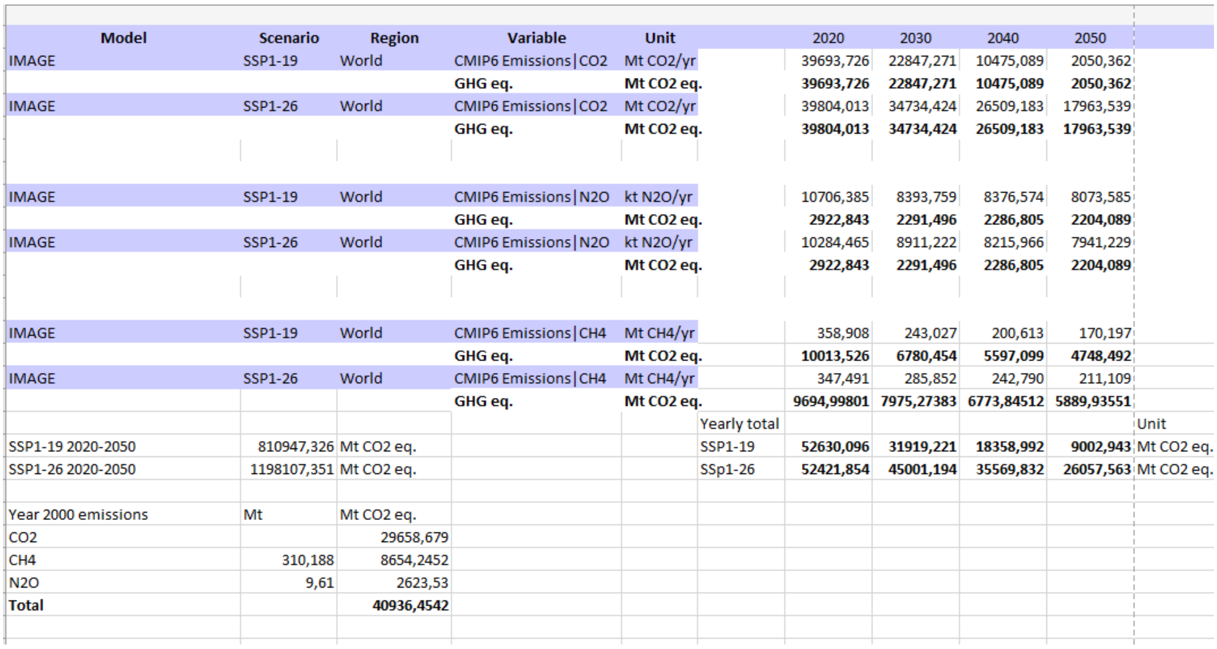
Eco-indicator is in part superseded by Impact World+ and in addition, their approach, much like EPS, is over 20 years old. Within a field that is 30 years old, incredible progress and understanding have been gathered which they lack even though their characterisation factors have been updated.

Ecological Scarcity uses a quite simple approach where the user selects a target and that will change the points allocated to the emission. The method can be adopted for the EU or perhaps a company depending on how the allocation is selected.

Another argument for Environmental Footprint and Ecological Scarcity is the fact that the implementation of different mineral reserves and estimates and climate change targets or budgets could be done straightforwardly as this would have to be at least in part manual work.

E

CIMP AR6 data



Model	Scenario	Region	Variable	Unit		2020	2030	2040	2050	
IMAGE	SSP1-19	World	CMIP6 Emissions|CO2	Mt CO2/yr		39693,726	22847,271	10475,089	2050,362	
			GHG eq.	**Mt CO2 eq.**		**39693,726**	**22847,271**	**10475,089**	**2050,362**	
IMAGE	SSP1-26	World	CMIP6 Emissions|CO2	Mt CO2/yr		39804,013	34734,424	26509,183	17963,539	
			GHG eq.	**Mt CO2 eq.**		**39804,013**	**34734,424**	**26509,183**	**17963,539**	
IMAGE	SSP1-19	World	CMIP6 Emissions|N2O	kt N2O/yr		10706,385	8393,759	8376,574	8073,585	
			GHG eq.	**Mt CO2 eq.**		**2922,843**	**2291,496**	**2286,805**	**2204,089**	
IMAGE	SSP1-26	World	CMIP6 Emissions|N2O	kt N2O/yr		10284,465	8911,222	8215,966	7941,229	
			GHG eq.	**Mt CO2 eq.**		**2922,843**	**2291,496**	**2286,805**	**2204,089**	
IMAGE	SSP1-19	World	CMIP6 Emissions|CH4	Mt CH4/yr		358,908	243,027	200,613	170,197	
			GHG eq.	**Mt CO2 eq.**		**10013,526**	**6780,454**	**5597,099**	**4748,492**	
IMAGE	SSP1-26	World	CMIP6 Emissions|CH4	Mt CH4/yr		347,491	285,852	242,790	211,109	
			GHG eq.	**Mt CO2 eq.**		**9694,99801**	**7975,27383**	**6773,84512**	**5889,93551**	
					Yearly total					Unit
SSP1-19 2020-2050	810947,326	Mt CO2 eq.			SSP1-19	**52630,096**	**31919,221**	**18358,992**	**9002,943**	Mt CO2 eq.
SSP1-26 2020-2050	1198107,351	Mt CO2 eq.			SSp1-26	**52421,854**	**45001,194**	**35569,832**	**26057,563**	Mt CO2 eq.
Year 2000 emissions	Mt	Mt CO2 eq.								
CO2		29658,679								
CH4	310,188	8654,2452								
N2O	9,61	2623,53								
Total		**40936,4542**								

Figure E.1: Data gathered from the CIMP6 model via the SSP Database 2.0 and used for normalisation.

Data available at the SSP Database (Shared Socioeconomic Pathways) - Version 2.0 based on [35].

F

ADP Characterisation factors

ADP characterisation factors based on ultimate reserve in 1999 [23] and updated values in 2015 [25].

Element	**ADP 1999**	**ADP 2015**
Aluminum	1.1E-09	4.2E-08
Antimony	1.0E+00	1.0E+00
Arsenic	3.0E-03	1.3E-03
Barium	6.0E-06	1.2E-05
Beryllium	1.3E-05	6.0E-05
Bismuth	4.1E-02	5.9E-01
Boron	4.3E-03	9.8E-03
Bromine	4.4E-03	1.5E-03
Cadmium	1.6E-01	3.2E+00
Calcium		5.4E-07
Carbon		3.8E-05
Cerium		1.5E-05
Cesium		2.8E-03
Chlorine	2.7E-05	5.3E-06
Chromium	4.4E-04	1.2E-03
Cobalt	1.6E-05	4.7E-04
Copper	1.4E-03	2.7E-02
Dysprosium		7.0E-05
Erbium		1.1E-04
Europium		4.2E-04
Fluorine		1.3E-05

Element	**ADP 1999**	**ADP 2015**
Gadolinium		9.2E-05
Gallium	1.5E-07	1.7E-06
Germanium	6.5E-07	9.2E-05
Gold	5.2E+01	1.5E+03
Hafnium		2.9E-06
Holmium		1.9E-04
Hydrogen		8.5E-09
Indium	6.9E-03	2.3E-01
Iodine	2.5E-02	1.7E-02
Iridium		1.4E+02
Iron	5.2E-08	1.1E-06
Lanthanum		3.7E-05
Lead	6.3E-03	1.9E-02
Lithium	1.1E-05	5.2E-05
Lutetium		1.0E-03
Magnesium	2.0E-09	2.8E-07
Manganese	2.5E-06	3.3E-05
Mercury	9.2E-02	1.5E+00
Molybdenum	1.8E-02	2.2E-01
Neodymium		3.1E-05
Nickel	6.5E-05	1.2E-03
Niobium	1.9E-05	5.0E-04
Nitrogen		5.0E-05
Osmium		5.4E+01
Oxygen		3.2E-09
Palladium	5.7E-01	9.8E+02
Phosphorus	5.5E-06	8.6E-05
Platinum	2.2E+00	1.0E+03
Potassium	1.6E-08	1.9E-07

Element	**ADP 1999**	**ADP 2015**
Praseodymium		1.4E-04
Rhenium	6.0E-01	1.4E+03
Rhodium		2.1E-03
Ruthenium		2.7E+02
Samarium		1.1E-04
Scandium		5.6E-08
Selenium	1.9E-01	3.1E-01
Silicon	1.4E-11	1.3E-09
Silver	1.2E+00	1.0E+01
Sodium	5.5E-08	1.9E-07
Strontium	7.1E-07	1.7E-06
Sulfur	1.9E-04	1.8E-04
Tantalum	4.1E-05	1.6E-03
Tellurium	4.1E+01	1.1E+02
Terbium		3.8E-04
Thallium	2.4E-05	1.4E-05
Thulium		7.2E-04
Tin	1.6E-02	7.4E-02
Titanium	2.8E-08	4.0E-07
Tungsten	4.5E-03	2.8E-02
Uranium1		9.4E-03
Vanadium	7.7E-07	9.3E-06
Ytterbium		1.5E-04
Yttrium	5.7E-07	1.6E-05
Zinc	5.4E-04	3.2E-03
Zirconium	5.4E-06	3.4E-05

G

Economic Reserve 2015 Data

An estimate of the economic reserves with reference year 2015 based on the Mineral Commodities Summary report by the USGS. For some substances an estimate of the reserves is missing which depends on two things; the estimate is missing and would need to be filled in by another data set or, they are not part of the substance list used in the updated 2015 version of the ADP ultimate reserve [37].

Element	**Reserves [t]**	**Sb eq.**	**Comment**	**kg Sb eq.**
Abrasives				0
Actinium				
Aluminium	65000000000	2,54E-08		1,65E+03
Americium				0
Antimony	2,00E+06	1,00E+00		2,00E+06
Argon				0
Arsenic	720000	0,002361424	world production x 20	1,70E+03
Asbestos				0
Astatine				0,00E+00
Barium				0
Barite				0,00E+00
Berkelium				0
Beryllium				0,00E+00
Bismuth	370000	0,295759095		109430,8651
Bohrium				0,00E+00
Boron	380000	4,98E-03		1892,184663
Bromine				0,00E+00
Cadmium				0
Calcium				0,00E+00

Element	**Reserves [t]**	**Sb eq.**	**Comment**	**kg Sb eq.**
Californium				0
Carbon				0,00E+00
Cerium				0
Cement				0,00E+00
Cesium	210000	1,93E-03		405,7576975
Chlorine				0,00E+00
Chromium	480000	7,92E-04	"shipping grade"	380,382182
Clays				0,00E+00
Cobalt	7100000	2,51E-04		1780,335922
Copper	720000	2,13E-02		1,54E+04
Curium				0
Diamond	700			0,00E+00
Diatomite			"large"	0
Dubnium				0,00E+00
Dysprosium				0
Einsteinium				0,00E+00
Erbium				0
Europium				0,00E+00
Fermium				0
Fluorine				0,00E+00
Francium				0
Feldspar			"large"	0,00E+00
Flourspar	250000			0
Gadolinium				0,00E+00
Gallium	23200	8,42E-06	World production x 20	0,195398024
Garnet				0,00E+00
Gemstones				0
Germanium	3 300 000	1,40E-03	World production x 20	4,62E+03
Gold	56000	1,37E+03		76761496,31

Element	**Reserves [t]**	**Sb eq.**	**Comment**	**kg Sb eq.**
Graphite				0,00E+00
Gypsum				0
Hafnium				0,00E+00
Hassium				0
Helium				0,00E+00
Holmium				0
Hydrogen				0,00E+00
Indium	15100	2,18E+00	World production x 20	32848,99322
Iodine	7500000	1,33E-02		1,00E+05
Iridium				0
Iron				0,00E+00
Iron and Steel				0
Iron Ore				0,00E+00
Iron Oxide Pigments				0
Kyanite				0,00E+00
Krypton				0
Lanthanum				0,00E+00
Lawrencium				0
Lead	89000	1,87E-02		1,66E+03
Lime				0
Lithium	14000000	2,57E-05		3,60E+02
Lutetium				0
Magnesium	2400000	1,75E-07	compounds	4,20E-01
Manganese	620000	2,51E-05		15,5312716
Meitnerium				0,00E+00
Mendelevium				0
Mercury	46800	5,41E+01	world production x 20	2,53E+06
Mica				0

Element	**Reserves [t]**	**Sb eq.**	**Comment**	**kg Sb eq.**
Molybdenum	11000000	1,73E-01		1,91E+06
Neodymium				0
Neon				0,00E+00
Neptunium				0
Nickel	79000000	8,15E-04		6,44E+04
Niobium	4300000	2,87E-04	"larger than"	1232,753778
Nitrogen				0,00E+00
Nobelium				0
Osmium				0,00E+00
Oxygen				0
Palladium				0,00E+00
Peat				0
Perlite				0,00E+00
Phosphate Rock				0
Phosphorus				0,00E+00
PGMs (Platinum, Palladium)	66000	9,66E+02		63735579,13
Potash				0,00E+00
Plutonium				0
Polonium				0,00E+00
Potassium				0
Praseodymium				0,00E+00
Promethium				0
Protactinium				0,00E+00
Pumice				0
Quartz Crystal				0,00E+00
Rare Earths				0

Element	**Reserves [t]**	**Sb eq.**	**Comment**	**kg Sb eq.**
Radium				0,00E+00
Radon				0
Rhenium	2500000	1,05E+03		2,61E+09
Rhodium				0
Rubidium	80000	0,00E+00		0,00E+00
Ruthenium				0
Rutherfordium				0,00E+00
Samarium				0
Salt				0,00E+00
Sand and Gravel				0
Scandium				0,00E+00
Seaborgium				0
Selenium	120000	3,12E-01		3,75E+04
Silicon	162000	1,64E-08	world production x 20	0,002655439
Silver	570000	8,64E+00		4,93E+06
Soda Ash				0
Stone				0,00E+00
Sodium				0
Strontium	6800000	1,66E-06		1,13E+01
Sulfur	1402000	3,14E-03	world production x 20	4403,600547
Talc			large	0,00E+00
Tantalum	100000	1,26E-03	"larger than"	125,785415
Technetium				0,00E+00
Tellurium	25000	1,70E+02		4257894,072
Terbium				0,00E+00
Thallium	200	3,85E-04	world production x 20	0,077083065
Thorium				0,00E+00
Thulium				0

Element	**Reserves [t]**	**Sb eq.**	**Comment**	**kg Sb eq.**
Tin	4800000	8,15E-02		3,91E+05
Titanium	790000	3,79E-07		0,299406963
Tungsten	3300000	2,10E-02		6,94E+04
Uranium				0
Vanadium	15000	6,58E-06		9,87E-02
Vermiculite				0
Wollastonite				0,00E+00
Xenon				0
Ytterbium				0,00E+00
Yttrium	500000	1,11E-05		5,559299732
Zeolites				0,00E+00
Zinc	200000	2,76E-03		552,4084327
Zirconium	78000	2,63E-05		2,05E+00
Total				**2,77E+12**

DEPARTMENT OF SOME SUBJECT OR TECHNOLOGY
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY