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Comparative Life Cycle Assessment of Electric Hydrofoil Boats and Fossil Driven Alternatives

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ABSTRACT

The pressure on the planet from Global Warming mainly originates from human activity since the Industrial Revolution. If the average temperature would increase by 1.5 degrees compared to pre-industrial level, this could highly affect areas such as biodiversity, food availability and water levels, to just name a few. In 2020, the transportation sector was responsible for 24 % of the emissions on a global scale. To mitigate climate impacts from transportation, the electrification of cars has already come a long way, but in the boating sector, more needs to be done. There is a lack of studies of comparative life cycle assessments about electric and fossil driven boats.

Two studies are conducted in this thesis. The first study focuses on the difference in environmental impact between an electric hydrofoil leisure boat and two petrol driven alternatives. In the second study, the ferry Candela P-12 is compared to the current diesel driven ferries used on Ekerölinjen in Stockholm. The method that is used to determine the environmental impact of the different boats, is a comparative Life Cycle Assessment (LCA). Three impact categories are assessed in the analysis of the environmental impacts. Global Warming Potential (GWP) to calculate the CO_2-eq. emissions, Mineral Resource Scarcity (MRS) to account for scarce minerals that are commonly used in electric vehicles and therefore lead to a high impact in this category, and Cumulative Energy Demand (CED) to evaluate the total energy consumption by the vehicles.

The result from the leisure boat comparison shows that the C-8 is highly favorable in two out of three impact categories, namely GWP and CED. Only in relation to MRS, the C-8 has the highest impact, mainly due to manufacturing in general, and specifically the batteries. The total life cycle impact of the Candela C-8 concerning GWP is affected by different grid mixes. However, compared to the emissions from the combustion engines, the differences in the grid mixes become small.

In the second study, the result showed that utilizing three Candela P-12´s to fulfill the function of Ekerölinjen will mitigate the environmental impact in GWP by 1670 tons for CO_2-eq per year. It can be concluded that the P-12 is more environmentally friendly in all three impact categories in comparison to the current ferries on Ekerölinjen if the occupancy rate is considered.

SAMMANFATTNING

Trycket på planeten från den globala uppvärmningen kommer främst från mänsklig aktivitet sedan den industriella revolutionen. Om medeltemperaturen skulle öka med 1,5 grader jämfört med den förindustriella temperaturen kommer det att i hög grad påverka områden så som biologisk mångfald, livsmedelstillgång och vattennivåer, för att bara nämna några. År 2020 stod transportsektorn för 24 % av utsläppen på global nivå. Elektrifieringen av bilar har redan kommit långt, men inom båtsektorn behöver det göras mer.

Två studier genomförs i denna avhandling. Den första studien fokuserar på skillnaden i miljöpåverkan mellan en elektriskbärplansbåt och två fossildrivna fritidsbåtar. I den andra studien jämförs färjan Candela P-12 med de nuvarande färjorna som används på Ekerölinjen i Stockholm. Metoden som användes för att fastställa de olika båtarnas miljöpåverkan var en jämförande livscykelanalys (LCA). Tre konsekvenskategorier bedömdes i analysen av miljökonsekvenserna. Klimatpåverkan användes för att beräkna CO2-ekv. utsläpp, mineralresursbrist för att ta hänsyn till knappa mineraler som vanligtvis används i elfordon och därför leder till en hög påverkan i denna kategori, och Kumulativ energiförbrukning för att utvärdera fordonens totala energiförbrukning.

Resultatet från fritidsbåtsjämförelsen visar att i jämförelse med de fossildrivna alternativen är C-8 gynnsam i två av tre påverkanskategorier, nämligen inom klimatpåverkan och Kumulativ energiförbrukning. Endast i förhållande till mineralresursbrist har Candela C-8 störst effekt, främst på grund av tillverkningfasen, men i synnerhet på grund av batterierna. Vidare så visare resultatet att Candela C-8:s totala livscykelpåverkan på klimatet influeras av vilket lands elnät som används. Jämfört med utsläppen från de fossildrivna båtarna, så blir dock denna påverkan väldigt liten.

I den andra studien visade resultatet att en tillämpning av tre Candela P-12:or på Ekerölinjen skulle minska klimatpåverkan med 1670 ton för CO2-ekv per år, i förhållande till det nuvarande scenariot. Sammanfattningsvis är Candela P-12 mer miljövänlig i alla tre påverkanskategorier jämfört med nuvarande färjor på Ekerölinjen om beläggningsgraden beaktas.

Acknowledgement

First of all, we want to thank all members of the Candela Technology AB for the opportunity to conduct this project in collaboration and for the support on the way. A special thanks to Mikael Mahlberg and Erik Eklund.

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Preface

The daily work on the thesis was highly influenced by collaboration. Every part in the report was done in union and solutions to problems that arose throuhout the process have been mutualy discussed and agreed on.

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List of Abbreviations

Alu	Aluminium
CED	Cumulative Energy Demand
CFRP	Carbon Fiber Reinforced Polymers
CO_2-eq	Carbon Dioxide equivalents
FRP	Fiber Reinforced Polymers
GFRP	Glass Fiber Reinforced Polymers
GWP	Global Warming Potential
ISO	International Organization for Standardization
LCI	Life Cycle Inventory
LCA	Life Cycle Assessment
MRS	Mineral Resource Scarcity

1 Introduction

The pressure on the planet from Global Warming mainly originates from human activity since the Industrial Revolution. If the average temperature would rise by 1.5 degrees compared to the pre-industrial level, this could highly affect areas such as biodiversity, food availability and water levels, for just naming a few (IPCC, 2021). In 2020, the transportation sector was responsible for 24% of the emissions on a global scale (World Resources Institute, 2019). The electrification of cars has already come a long way, representing 9 % of the cars sold on the market in 2021 (IEA, 2022b). To mitigate climate impacts in the boating sector, a transition on the from fossil fuels to electric alternatives can be a solution. In the leisure boat market, there are electrified alternatives coming up, such as the Candela C-8 and the Candela P-12. However, the environmental impact of these boats was unknown.

The use of a life cycle perspective when mapping the environmental impacts of a product is important, since it includes all the burdens from material extraction to the disposal of the product. Furthermore, Life Cycle Assessment has the advantage of quantitatively display how choices of materials and processes affect the environmental impact of a product (UNEP, 2004).

Several studies have been conducted on the topic of leisure boats. Some of the studies focus on a certain phase of the life cycle. Johansson *et al.* (2020) and Bonus Change Project (2017) investigate the emissions related to the use phase, such as maintenance or emissions from the combustion process, whereas Önal and Neşer (2018) investigate the impact from different end of life treatments of hull materials. There are also studies that include all life cycle phases, such as the IVL report by Zhang *et al.* 2021), where the aim is to explore the circular possibilities for a diesel driven leisure boat. Comparative LCA studies have been conducted on the topic of electric versus fossil driven marine vehicles. A study from Hemez *et al.* 2020) investigates the environmental impact for different propulsion systems for pump boats and where mixes between virgin and recycled aluminum hulls are included in the scope. However, there is a lack of comparative LCA´s between electric and fossil driven leisure boats, where all life cycle phases are included.

There are policies for leisure boats, such as The European Directive 2003/44/EC, which sets legal efficiency values for leisure boats between 2.5m and 24m. This directive sets efficiency limits of emissions in relation to the power of the engine and covers the exhaust emissions Carbon Monoxide, Hydrocarbons, Nitrogen oxides, and Particulates (European Commission, 2005). But according to the European Boating Industry (EBI), more needs to be done. In order to reduce the climate impact, a shift in prioritization needs to be implemented, regarding low and zero emission recreational boating engines (EBI, 2020).

To mitigate the impact from recreational boating, a holistic approach is needed, which not only involves the boating industry, but also policy makers. The coastal waters tend to be overseen, which could be due to the lack of awareness from policy makers regarding boat emissions (Carreño and Lloret, 2021). As such, there is an urgency of empowering policy makers with environmental data regarding impacts from boating within the coastal areas.

The goal of this study is to evaluate the environmental impact of Candela´s electrified boats compared to fossil driven alternatives based on three impact categories: Global Warming Potential, Mineral Resource Scarcity and Cumulative Energy Demand.

1.1 Introduction of Candela Technology AB

Candela Technology AB is manufacturer of electric boats and ferries. The company is located at Lidingö in Stockholm. Candela has recently released a new leisure boat called Candela C-8 and is about to release a ferry called P-12. The main characteristics of Candela´s boats are the combination of the electric propulsion system and the use of hydrofoils, which will be further explained later in the study. Candela Technology AB identifies themselves as an environmentally conscious company with products that have a lower environmental impact than comparable conventional fossil-driven alternatives.

1.2 The structure of the report

Two studies are conducted in this thesis. The first study focuses on the difference in environmental impact between Candela C-8 and two fossil driven leisure boats. In the second study, Candela P-12 is compared to the current ferries in use on Ekerölinjen in Stockholm. The background and method section are shared between the two studies, whereas individual scope, results and discussions are separate for each study. The first study presented in the report is the leisure boat comparison, which is introduced with its aim under chapter 1.3. The report then has a shared part of general background information about electric boats and the different boat components of the comparison boats. Later, the Methodology for both studies is explained under chapter 3. Chapter 4 to 8 contains the leisure boat comparison where Candelas C-8 is compared to two conventional petrol alternatives. As some information regarding the boat construction is displayed in more detail than in the ferry comparison, it’s recommended to read this part first. Chapter 9 to 12 contains the ferry comparison where the Candela P-12 is compared to the ferries currently in use on Ekerölinjen in Stockholm.

1.3 Aim of the leisure boat comparison

Overall aim of this comparative LCA is to evaluate the environmental impact of Candela´s electrified leisure boat compared to petrol-driven alternatives. The environmental impact of the products is assessed in three impact categories, which are Global Warming Potential, Mineral Resource Scarcity (MRS), and Cumulative Energy Demand (CED).

The defined goals of this study are to investigate the following:

- Identify environmental hotspots throughout the life cycle of the C-8
- Determine the difference in environmental impact between the C-8 and a conventional petrol boat, based on the selected impact categories.
- Determine the break-even point in relation to hours driven, after which the electric boat will be environmentally beneficial over the conventional petrol-boat, from a global warming perspective.

A general conclusion about an overall environmental superiority of one boat over the other cannot be drawn from the results as only three environmental impact categories are accessed. Environmental impacts occur in many different forms and emissions. To explore three common categories for LCAs in connection with electric vehicles, GWP, MRS, and CED were chosen. However, the results can be used to determine which boat is more environmentally beneficial in the specific categories applied in this report. The intended audience is first of all Candela Technology AB, which is the producer of the C-8 and P-12. Due to the lack of research on the topic of electric hydrofoil boats, there is an interest to find out about the environmental impact of their boats, in relation to fossil driven alternatives, and to communicate the results with different stakeholders. This study can also be used by policy makers, to provide information regarding electric vehicles on coastal waters. Regional public transport providers can use the result of the study for their future fleet planning. Additionally, private consumers can use the results to make a more sustainable boat choice.

2 Background and literature review

In the following section insights in the development of electric boats, the previous research in the field, as well as an introduction to the objects of comparison in this study are presented.

2.1 Electrification in the boating industry

Electric boats are no new invention. First boats with electric propulsion system were developed in 1830 by Moritz Hermann von Jacobi. Back then, the achieved range was 1.8 hours at a speed of 4km/h. In the following decades until around 1920, improvements in range and speed were made, however issues concerning the limited energy amount that could be stored, as well as high maintenance costs of the batteries, slowly led to a shrinking of the electric boat market. Boats with combustion engines gained higher market shares due to increasing efficiency, presence of fuel stations, as well as the possibility to store much fuel on board to achieve long ranges (Porru *et al.*, 2020). To tackle today's challenges of Global Warming, the electrification of transportation is considered one of the mitigation measures. In the boating industry, electrification is not yet widely present today (Campillo, Domínguez-Jimenez and Cabrera, 2019).

2.2 Previous research

Before conducting the study on the leisure boats and the ferries, a literature review was done to assess the research in the field, compare existing reports with the planned methodology approach for this report, and to understand the emission relation between conventional fossil driven and electric vehicles. Zhang *et al.* (2021) conducted a life cycle assessment over the whole lifetime of a leisure boat with a size almost similar to the Candela C-8. Other than conducting a comparative LCA, they focused on the analysis of their case boat to identify hotspots over its lifetime (Zhang *et al.*, 2021). The expected lifetime of 30 years for the boats, as well as methodological suggestions were drawn from this report. The emissions related to the combustion process of the leisure boats and the leisure boat usage of 50 hours per year, was retrieved from (Jun, Gillenwater and Barbour, 2021).

Beside studies on boats, LCAs' that compare electric and conventional fossil driven vehicles in general were considered. Girardi and Brambilla (2019) e.g., found that an electric car has a higher manufacturing impact of CO_2-eq. than a conventional petrol or diesel driven one. Due to the high environmental impact of the use phase from the combustion of fossil fuels, the electric vehicle becomes more sustainable, considering the whole lifetime. Higher impacts in manufacturing combined with a lower use phase impact for the electric vehicle caused a break-even point after a certain use time (Girardi and Brambilla, 2019). Similar trends were found by Scania (2021) in their comparison of a electricity driven truck with a conventional diesel driven one. An electric boat compared to a conventional fossil driven one should show a comparable relation as all studied literature concerning the comparison of electric and fossil driven vehicles, had similar results concerning GWP. In relation to MRS, previous studies have shown that the battery has a high contribution. According to Koroma *et al.*, (2022), the batteries of electric vehicles take a share of more than 90% of the total impact.

To see how different boat materials affect environmental impacts, studies that compared different hull materials were assessed too. Schmidt and Watson (2013) compared two small, diesel driven, car ferries, one CFRP and one steel based. Earlier research about fossil driven boats has been conducted. The result from Schmidt and Watson (2013) shows that the use phase of fossil based boats is the main contributor to GWP.

In a comparison of a conventional diesel driven ferry, with an electric alternative, Wang *et al.* (2021) found that for the Global Warming related emissions the electric ferry is beneficial over the lifetime and results in around 30% emissions saved.

2.3 The objects of comparison

Two comparisons are conducted in this study. The first object of comparison is the Candela C-8, which is a leisure boat. The C-8 provides features that could be expected from other boats in the same size, including range and speed, but also cabin, shower, and toilet. It is aimed at buyers that would otherwise purchase a powerboat in the premium (290 000€) segment (Candela Technology AB, 2022). The comparison petrol boats will have the same functions as described for the C-8. There will be two types of petrol bots compared to the C-8, one in which structural components are aluminium based and the other one which is CFRP based. Figure 1 displays the Candela C-8.

Figure 1: Candela C-8
(Candela Technology AB, 2022)

The second comparison is conducted between two kinds of ferries. The Candela P-12, with a capacity of 30 passengers is compared to existing aluminium diesel ferries that are used today on Ekerölinjen. Figure 2 shows the preliminary picture of the Candela P-12.

Figure 2: Preliminary picture of the Candela P-12
(Candela Technology AB, 2022)

In the leisure boat comparisons, the fossil driven alternatives do not reflect one specific boat model, but rather a generalized version of boats in the same category. Whereas the ferry comparison is based on existing ferries.

2.3.1 Drivetrain

The drivetrain includes all the parts that are needed for the boats to move. The assessed leisure boats differ highly in their propulsion systems. While Candelas’ boats have an electric drivetrain combined with hydrofoils, the petrol and diesel boats use the common technology of a combustion engine. In the Candela C-8 and the P-12, the electric engine is fueled by electricity from a lithium-ion battery.

2.3.2 Batteries

Even though the drivetrain of the fossil driven boats is not powered by electricity it still needs batteries to maintain the functions of the boat. Lithium-ion batteries could serve as both a starting battery and a deep-cycle battery. For the electric boats, the battery functions as the energy storage for the engine and all the other energy dependent devices on the boat.

2.3.3 Electric engine (C-Pod)

Candela uses a self-designed and constructed electric engine on their boats, named C-Pod. By making the volume of the engine smaller, it can be fitted in a torpedo-shaped casing. Due to its position next to the propellers, the transition efficiency is very high, as little losses occur from gears, compared to conventional constructions. The reduction in gears and moving parts benefits the noise emissions and the C-Pod is almost silent. With the submerged design of the C-Pod, no additional cooling is needed, as the constant water flow around it provides sufficient temperature reduction inside the engine. The lifetime of the engine is expected to be over 3000 hours of operation time without any maintenance, as stated by Candela Technology AB (2022). The power of 50 kW from the C-pod, allows the C-8 to have a top speed of 30 knots. At 22 knots, the energy consumption is 1 kwh/nautical mile, which results in a range more than 50 nautical miles (Candela Technology AB, 2022).

Hydrofoils

The idea of wing supported watercrafts dates back to the nineteenth century. The first successful hydrofoil flight was achieved around the year 1900 and by the end of World War I hydrofoil speeds of 60 knots were reached. The main driver of the development was the hope to reduce the drag of a watercraft to achieve higher operating speeds (Acosta, 1973).

Hydrofoils are used to lift and control a foil or strut in water. Arranging the hydrofoils vertically can be utilized to generate a control force. If the hydrofoils are placed horizontally, the created force can be used to lift a boat's hull out of the water, leaving only the hydrofoils submerged. Today, hydrofoils can be found in many commercial and non-commercial applications like yachts, stabilizer fins, rudders, and kite surfing boards. By lifting a boat’s hull out of the water, the drag reduces, which therefore results in a reduced energy consumption to maintain the cruise speed. To achieve the momentum to lift a boat out of the water, a certain speed needs to be achieved (Molland and Turnock, 2022).

In the Candela C-8 horizontal, fully submerged foils are used which can lift the boat out of the water at speeds above 16 knots. Caused by the low resistance of the hydrofoils, the creation of wake is reduced, which protects marine environments, harbors, and other boats (Candela, 2022).

Combustion engines

The comparison leisure boat is a conventional boat using a combustion engine run on petrol, which uses a 4-stroke engine within the range of 200-300 horse powers. The fuel consumption varies a lot between different petrol boats. According to (Johansson *et al.*, 2020) there is a range between 25-75 liters of petrol consumed per hour driven for leisure boats. The wide range of fuel consumption for this category of boats implies that there is a big uncertainty in regards of determining the fuel consumption for a specific boat. In the other boat comparison, the ferries use combustion engines which run on diesel. Several factors affect the fuel consumption of a specific boat, such as weight of the boat, hull construction and cruise speed (Johnson, 2011). Furthermore, there are multiple factors influencing the emissions emitted during the combustion process, such as the engine type, the composition of the fuel and the amount of horse powers (Burke *et al.*, 2021).

2.3.4 Structural materials

The main material for the different components in Candelas' boats is carbon fiber reinforced polyester (CFRP), which is a composite material. The overall most used material for leisure boats used in Sweden is another composite material, namely glass fiber reinforced plastic (GFRP), which represents 80% of all leisure boats. Other materials used for constructing leisure boats are wood (7%) and aluminum (6%) (U.S. Department of Commerce, 2018).

There are several reasons for GFRP being the most frequently used material for leisure boats, such as the high strength to weight ratio and the ability to resist environmental influences over time (Önal and Neşer, 2018). Moreover, the price of GFRP is also relatively low, compared to other materials, such as CFRP. Advantages of CFRP could instead be seen in a higher strength to weight ratio compared to GFRP. Thus, using CFRP enables boat builders to reduce the weight but still maintain the durability and strength over time (Shakir Abbood *et al.*, 2021).

The manufacturing process for CFRP and GFRP is similar. Beside the Carbon fiber or Fiberglass, the material used in the manufacturing phase is resin. The resin is the polymer additive in the reinforced fiber mix which provides functions such as high resistance to moisture absorption and high tolerance against corrosive liquids (Fiore and Valenza, 2013). There are different methods for assemble the fiber reinforced polymers and resin. One of the more common methods to produce CFRP and GFRP is to use Vacuum Infusion. The different layers of materials are put on top of each other in a sealed bag which is compressed to form a vacuum to create pressure on the different layers (Abdurohman *et al.*, 2018; Candela Technology AB, 2022).

Aluminium is another common hull material for boats, due to its characteristics of being strong despite having a light weight. The method of manufacturing aluminium is linked to three steps, namely: Sheet rolling, cutting, and welding (Poulikidou *et al.*, 2015). There are several aluminium alloys to choose between. According to (Hentinen, 2021), a common aluminium type for marine applications is AlMg3, which is used in this study for the aluminium based petrol boat and ferry.

2.3.5 Waste treatment and disposal

For boats reaching the end of life, there is mainly two common scenarios of how boats are disposed in Europe. Either the boats are brought to dismantling facilities, or they are abandoned. It is estimated that 6,000 to 10,000 boats each year boats are abandoned in the European Union (European Commission, 2017). However, there are initiatives in Sweden that retrieve boats that have reached their end of life. Båtretur is a company which is located in 25 different places in Sweden. Boat owners can dispose their boat to this company for disassembling and to ensure further treatment of different materials according to current standards (*Båtretur*, 2022). As such, the waste treatment processes for the materials described below is not specifically linked to leisure boats, but rather the most common material treatment methods in the European Union.

Lithium-ion batteries

There are two common processes for handling lithium-ion batteries at the end of their lifetime, which are Hydrometallurgy and Pyrometallurgy (Gaines, 2018). The hydrometallurgical treatment process consists of several steps: pretreatment, the leaching and partition of valuable metals, as well as the recovery of the metals from the leaching solution (Yonglin *et al.*, 2018). Whereas Pyrometallurgy applies smelting in order to retrieve metals in a high temperature environment. Lately, advancements have been made into the recycling process, where a combination of Pyrometallurgy and Hydrometallurgy are applied. (Gaines, 2018).

Metals

The boats in this study contain several types of metals. In the European Union the recycling rate of metals is high. Scrap steel has a recycling rate of over 90%, and aluminum reaches 69%. Copper is recycled to about 61% (EuRIC AISBL, 2020).

Fiber reinforced plastics (CFRP and GFRP)

There are currently two end of life treatment options available for fiber reinforced polymers (FRP), namely incineration and landfill (Ribeiro *et al.*, 2016), with landfill being the dominating option for treatment of FRP used for boat construction (IMO, 2019). There are actions taken against landfilling of FRP, such as implementations of directions, in order to enforce development of more circular options such as recycling and reuse (Dr. Halliwell, (2006) and Ribeiro *et al.*, (2016)).

Engines

In Sweden, used engines from boats are treated in the same way as car engines. As such, the boat engines will be disassembled, and the materials recycled (Stena Recycling, 2022).

3 Methodology

Two different comparisons were conducted in this study. One study was conducted on the Candela C-8 compared to two petrol boats and another one compared the Candela P-12 ferry to diesel driven alternatives. The comparison between the leisure boats was a boat-to-boat comparison, whereas for the ferry comparison, a case scenario was applied which is further described in section *9 Candela P-12 compared to a conventional diesel ferry*. The petrol driven boats in the leisure boat comparison weren't actual boats on the market, but rather a representative image of boats with the same function and size as the C-8, based on literature research. Since it is the difference in environmental impact between the boats that was in focus, parts and assemblies that were deemed as equal weren't included.

To determine the difference in environmental impact between Candelas boats and their comparisons, all life cycle phases from cradle to grave were modelled in SimaPro. Assemblies and components with their respective materials and manufacturing processes were defined for each boat. In order to determine if there is a break-even point, after which the electric boats will be more environmentally beneficial, the emissions retrieved from the different boat models in SimaPro were put in relation to time or distance. Lastly, to identify the different hotspots for the C-8, the boats individual lifecycle was assessed.

3.1 Life-Cycle-Assessment Methodology

The method used to determine the environmental impact of the different boats, was a comparative Life-Cycle-Assessment (LCA). In its methodology, the LCA was conducted according to the international standard ISO 14040 by the International Organization for Standardization (ISO). Key features of the LCA methodology are to assess environmental impacts and characteristics of products. By including the whole life cycle from raw material extraction to the product's disposal. This systematic approach aims to draw a holistic picture of the total emissions of a product system (ISO, 2006).

Key phases of LCA studies are goal and *scope definition, inventory analysis, impact assessment, and interpretation* (ISO, 2006). Direct measures of an LCA's results can be drawn, such as further development and improvement of the product system, decision making in strategic planning and public policy, as well as marketing or other purposes (Hauschild *et al.*, 2018).

The basic LCA framework is pictured in Figure 3 below, for better comprehension.

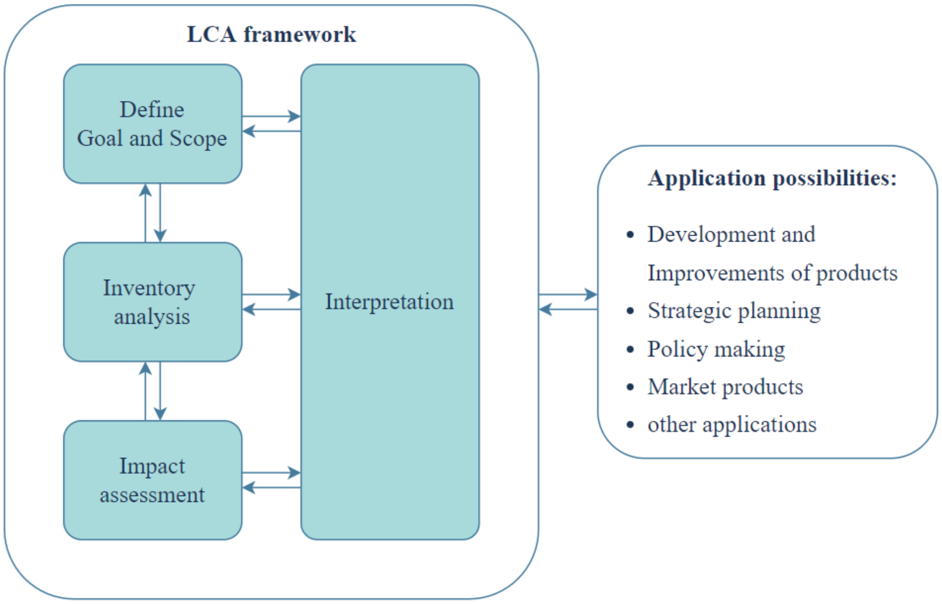


Figure 3: LCA Framework modified from ISO 14040

To create models of the life cycles, the LCA software SimaPro in version 9.2.0.2 was used. SimaPro is one of the leading LCA software solutions and is used by many academies, businesses, and consultancies. SimaPro enables the user to model complex lifecycles, assess environmental impacts and distinguish hotspots in the product life from cradle to grave of products or services (PRé Sustainability, 2022). Furthermore, Ecoinvent was used, which is connected to SimaPro and serves as a database that provides a diverse range of processes data on a global and regional level. These "activities", or else called datasets, entail information about natural resource use, emissions released to the environment, energy used in the activity, as well as products, co-products and waste produced (ecoinvent, 2022a). Therefore, the environmental data comes from ecoinvent in version 3.7, while the software used to create the model and connect the processes is SimaPro.

3.1.1 Definitions of system boundaries

This section provides an explanation of the subtopics related to the system boundary. System boundaries are defined as the unit processes which are included in the system to be analyzed. Focus should be put on the elementary flows, which contribute the most to the environmental impacts. Smaller material or energy flows, which don't contribute significantly to the overall impact, and will therefore not change the overall outcome of the study, can be excluded (ISO, 2006). The system boundaries define what is analyzed in the LCA, which can be defined by the boundaries between nature and the system or system processes, geographical locations, temporal boundaries, and by distinguishing between life cycles of the assessed product and other related side products (Tillman *et al.*, 1994). In the following paragraphs, the different subtopics to define the system are explained.

Functional unit

The purpose of a functional unit is to provide the quantitative basis to define the function of a product or a service on which the assessment is performed. This basis defines the way a LCA is executed, the results, and interpretation, particularly in comparative LCAs (Hauschild *et al.*, 2018).

System processes

The conducted LCA follows a cradle to grave approach, which means the whole life cycle of the products is included: Raw-material production, manufacturing, use-phase, and disposal at the end of the product life (Muralikrishna and Manickam, 2017).

Foreground background system

By using a foreground and background system, an overview of processes is provided that are either directly or indirectly influenced by the intended audience of this report (Hauschild *et al.*, 2018).

Geographical boundaries

Setting the geographical boundaries in LCAs is an important step to assess a product or service. Depending on where parts are produced or services are provided, the infrastructure may differ, such as the electricity mix for production, transportation, or how waste is handled at the end-of-life of a product. Additionally, to this direct variation in emissions, environmental effects of pollutants in different regions and environments, can vary (Tillman *et al.*, 1994).

Temporal boundaries

The temporal boundaries define the time related matters within an LCA, which for example includes the collected data and the impact of emissions (Beloin-Saint-Pierre *et al.*, 2020).

Cut-off criteria

The application of Cut-off criteria serves to provide an overview of the excluded processes and products (Hauschild *et al.*, 2018).

Allocation procedure

Allocation procedures are used to avoid multi-output problems (Hauschild *et al.*, 2018). For example, the allocation procedure can be used to define the material flows in the end-of-life treatment.

3.1.2 Impact categories

The impact categories are used to interpret the output from the SimaPro model. Furthermore, the result of an LCA is highly dependent on the choice of impact categories, since they provide the perspective of how the observed system should be evaluated and which emissions are compared.

3.1.3 Normalization and weighting

Normalization uses a reference value for each impact category to provide a context to compare the result with, for example the average annual impact of a European citizen within a year (Goedkoop *et al.*, 2016). Normalization was not used in this study, since the main purpose was to identify the relative difference in impact between the boats.

Weighting is a subjective method, where the modeler gives different impact categories different importance. The weighting is executed by multiplying each impact category with a chosen number and then summarizing the result into a single score (Hauschild *et al.*, 2018). Weighting was also excluded in this study, due to its subjective nature.

Normalization and weighting are not mandatory according to (ISO, 2006) but could be used with the aim to simplify the interpretation of the results (Goedkoop *et al.*, 2016).

4 Candela C-8 compared with a petrol leisure boat

The different subtopics included in the LCA methodology are defined in this section. An attributional LCA was conducted and the details about the scope can be found in the subchapters below.

4.1 Functional Unit

The functional unit applied in the leisure boat comparison was the use of an 8-person leisure boat, for 50 hours a year over a 30-year period with an average cruise speed of around 22 knots.

The size and speed used in the functional unit was based on the functions of the C-8, since the comparison was aimed towards petrol driven boats with similar sizes and functions as the C-8. As such, the functional unit ensured that the boats were compared in the same way. The hours used per year provided a base scenario for how much the boats were to be used. Furthermore, the time span of 30 years was related to the total impact over the whole life cycle.

4.2 System boundaries

The system boundaries define the objects that were compared. Furthermore, details regarding time and geographical information are also provided in this section.

4.2.1 System processes

The system boundaries of the boat comparisons were from a cradle to grave perspective. As such, all the life cycle phases from extraction of raw materials to end of life was included in the study. Since there was no specific boat model that was compared to the C-8, the same measurements and included parts were applied for the structural components for all three boats, based on the ones of the C-8. To achieve this, a material transformation was applied, which took the strength and density of the materials into consideration. This resulted in different weights for the GFRP and aluminum boat hulls, based on the material's relative strength and density in relation to CFRP.

4.2.2 Foreground and background system

Since Candela was the focus of this report, the foreground and background systems were created to provide an overview of their areas of direct influence as a boat manufacturer. As could be seen in Figure 4, the background covers most of the different processes throughout the life cycle, which implied that most of the processes are indirectly influenced by Candela. In other words, they do not control the processes. As such, material changes from Candelas side, for any component in the boat, would only affect the demand from the supplier rather than changing the process of how the materials are produced. The use phase was influenced by the energy consumption of the boat. However, Candela can't control how often and when the boat will be used.

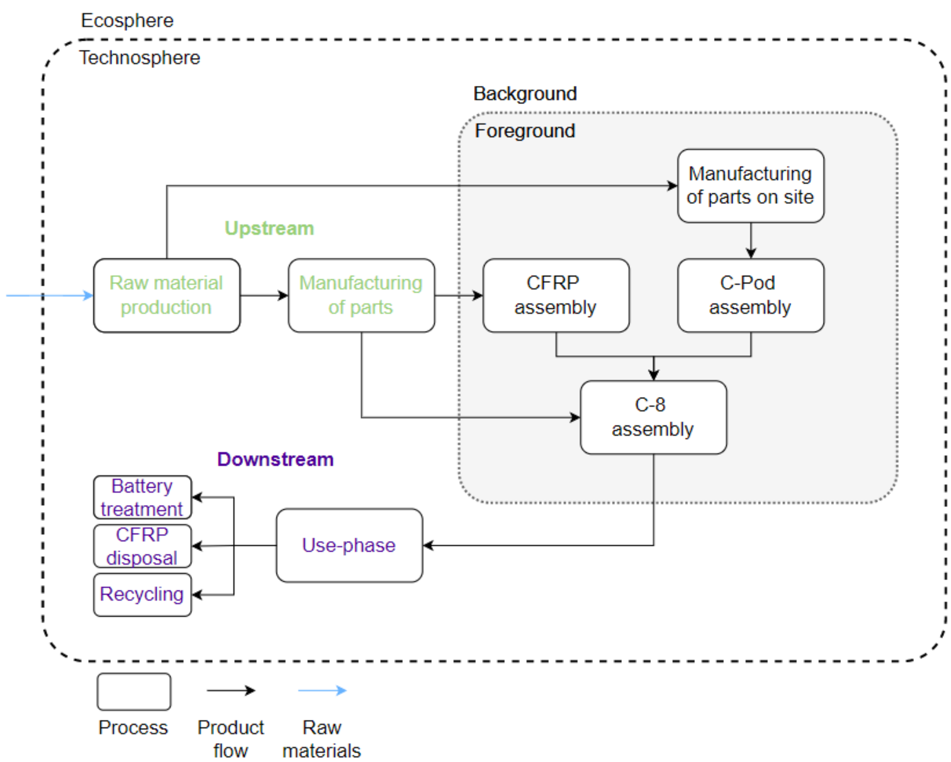


Figure 4: Foreground and Background system

The foreground on the other hand is where the intended audience has a direct influence (Hauschild *et al.*, 2018). For Candela as a boat manufacturer, it's mainly the processes linked in the assembling of the boat, with parts that are directly provided from suppliers. However, the engine in the boat, the C-Pod, is manufactured on site. The process of creating the engine is therefore in direct control of Candela.

4.2.3 Geographical boundaries

Transportation was included in different phases of the life cycle as can be seen in Table 1, below. For materials retrieved from Ecoinvent, a global average was used for all the materials and components. A global average was chosen instead of a European average, since not enough data of the supply chain could be identified. Thus, minimizing the risk of inaccurately mitigating impact from transportation.

Table 1: Geographical boundaries of life-cycle steps

Life-cycle step	**Geographical boundary**	**Transport**
Extraction of materials e.g., Steel, aluminum, bronze	Global	From extraction site to the producer of structural and technical components Distance: Global average
Production process for Structural components Carbon fiber, Fiberglass, global average	Global	Distance: Global average
Production of technical components Battery, engine	Global	From producer to boat manufacturer Distance: Global average
Assembling of the boats CFRP, GFRP, Engines, batteries	In Sweden	No transport to costumers included
Waste treatment disassembly and treatment	In Sweden	To: Battery recycling facility Distance: Global average

4.2.4 Temporal boundaries

Present and past data was used in the report. Data on the Candela C-8, e.g., material weights and compositions were provided by Candela Technology AB and was seen as recent, in a temporal perspective. The secondary data provided by Ecoinvent via SimaPro, and scientific reports may vary in age. Long term-emissions were included in the result, by using the ReCiPe Midpoint (Hierarchist) method. Since the scope of this study included a framework of 30 years, some components of the boats were affected. One of those was the lithium-ion batteries, which was assumed to have a lifetime of 10 years. As such, two replacements were needed, resulting in the manufacturing of three batteries in total. The rest of the structural and technical components included in the comparison were assumed to last for the whole period.

4.2.5 Cut-off criteria

There were uncertainties regarding different parts for a generic petrol boat in terms of mass and the range of materials available. Some parts were deemed as equal and therefore excluded since the environmental impact was assumed to be the same. Excluded parts contain glass windows, as well as smaller structural parts such as screws and bolts. Furthermore, electronics and navigation instruments were assumed to be the same and therefore excluded. The same goes for seats, cushions, and other equipment on the boat since the range of plausible options makes it hard to model a general comparison to the C-8 and would be assumed to be the same for the petrol boats to achieve a fair comparison. Those materials can therefore be excluded, as they would not influence the relative result between the boats. Maintenance during the whole life cycle is assumed to be unnecessary for the Candela C-8 as the electric engine has low maintenance need. For the petrol boats, regular oil changes are assumed. Other maintenance work, e.g. hull painting is assumed to be equal between the boats and therefore excluded. Charging devices for the electric driven boats were excluded from the study, since the system boundaries of the boat comparisons are defined for the actual boats, rather than the infrastructure needed to use the boats. Equally, the infrastructure needed for fuel provision of the petrol boats was excluded as well.

4.2.6 Allocation procedure

The allocation procedure used in this report was cut-off by classification. By using the cut-off approach, the share of recycled materials going into the production of different assemblies are deemed burden free (ecoinvent, 2022b). However, in the end-of-life treatment, the recycling processes for the different materials are applied, without adding the benefit of creating reusable materials (ecoinvent, 2022b). To account for the energy used in material recycling, those processes were added manually in SimaPro. The cut-off criteria in SimaPro, would otherwise not account for the energy use and result in emissions from recycling activities. Furthermore, by using cut-off criteria, the problem of identifying or assuming how the material will be refined and used in the next lifecycle is not relevant.

4.3 Assumptions

Key assumptions:

- Lifetime of both carbon and fiberglass is assumed to be equal (30 years)
- Use phase: 50 hours per year in cruise average speed of around 22 knots
- The fuel consumption for the petrol boat is 50 liters per hour in cruise speed
- The lifetime for the batteries is assumed to be 10 years.

Production and manufacturing

- The different structural components in the boats are assumed to be homogeneously built, with only one material type (CFRP, GFRP or aluminium)
- The surface area of the structural components of the comparison boats is the same as the C-8.
- The engines for both Candela and the petrol boat are assumed to function for the whole lifetime.

Use phase

- Fuel use is only limited to driving at cruise speed. As such the energy or petrol use of the boats is assumed to be zero when the boats are not moving/ just sitting somewhere (e.g., if someone is out in the archipelago and listening to music this would drain battery/fuel. Such energy use is not included).
- Except for oil changes in the petrol engine, maintenance is excluded for all components of the boats.

End-of-life treatment

- Due to the high recycling rates within the European Union a recycling rate of 100% for metals was assumed. As such, no other waste treatment processes are allocated for the metals.
- To limit the data gathering, only energy consumption was assumed as input for the recycling processes.

4.4 Impact categories and impact assessment method

In this report, three impact categories were applied:

- Global Warming Potential (GWP)
- Mineral Resource Scarcity (MRS)
- Cumulative Energy Demand (CED)

GWP was included as one of the impact categories, since it is frequently linked to the transport sector and potential mitigations are discussed on a global scale (Sims *et al.*, 2014). MRS considers how the use of minerals will affect the future availability (Berger *et al.*, 2020). Moreover, electric vehicles in general need more minerals in the production phase, compared to fossil driven alternatives (EIA, 2022). Thus, Mineral resource scarcity was an important impact category to consider in this boat comparison. The last impact category called CED, focuses on the direct and indirect energy usage linked to the different processes throughout the life cycle (Huijbregts *et al.*, 2006). CED also maps the primary sources used throughout the lifecycle, in the categories: renewable and nonrenewable sources (Frischknecht *et al.*, 2015). Primary energy sources are directly retrieved from natural resources, such as coal, renewables, and natural gas. The impact assessment method used for GWP and MRS is called ReCiPe2016 Midpoint (Hierarchist) methodology. The ReCiPe method provides a result which is representable on a global scale (Huijbregts *et al.*, 2016). The method used for the CED was called single issues, which created a combined score of the subcategories: Nonrenewable fossil, nuclear and biomass, along with renewable biomass, wind, solar, geothermal and water.

5 Life cycle inventory analysis

This section provides an overview of the collected data used to create the leisure boats and is divided into the three subchapters: Material composition, Use phase, and End of Life. The data was retrieved from Candela, scientific literature, and manufacturer information. In order to create an overview of the collected data, a simplistic approach was applied, by providing the main categories and components and the related materials. As mentioned earlier in the report, the surface area for the comparison boats is assumed to be the same, which affects the structural components of the petrol boats. The measurements from the Candela C-8 were applied to the petrol boats, by transforming the CFRP into aluminum and GFRP in order to create comparison boats that reflected the C-8, in terms of length and width. This was done by multiplying the amount of CFRP used for the C-8, with a factor based on the difference in strength and density to the other hull materials. As such, the thickness and weight of the structural components was different for the boats. Furthermore, the weight of components such as engines and batteries were also different for the boats. The components for the C-8 were retrieved from Candela whereas for the petrol boat, generic data was used. More detailed information regarding calculations and where data was retrieved can be found in section 15.1.1 in the appendix.

In the next paragraphs, material composition and end of life treatment of the C-8 respectively the petrol boat is described, followed by the use phase.

5.1 Material composition and end of life for the Candela C-8

The flow diagram in Figure 5 below represents the different assemblies used to create the Candela C-8. Assemblies represent the composition of different components and materials.

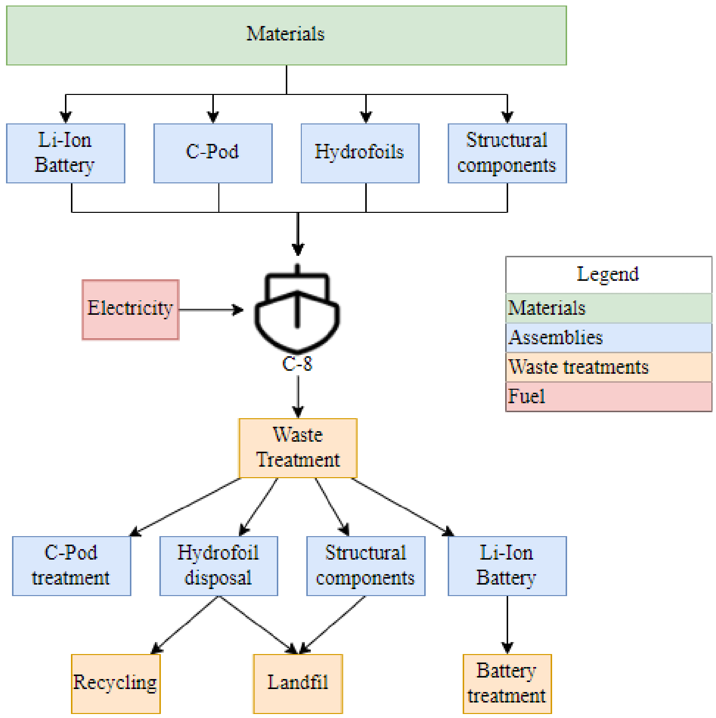


Figure 5: Material composition and end of life for the Candela C-8

The assemblies along with the specific components and materials used to create the Candela C-8 is described in Table 2, below. The raw material composition in materials and technical components such as the CFRP, C-POD and batteries are excluded in the table. The data provided for the different assemblies was retrieved both from Candela and through conducting a literature review.

Table 2: Composition of the Candela C-8 in the model

Assemblies	**Components**	**Materials**
Structural components	Hull	CFRP
	Deck	
	Consoles	
	Stringer system	
	Liners	
Hydrofoils	Foils	CFRP
	Rudder	
	Strut	
	Pitch spring	Steel
	Sliders	Teflon
	Actuators	Electric engines
	Rudder headbox	Aluminum
	Rake box	
Battery	Battery	Lithium-ion battery
Engine	Propeller	Steel
	Housing	Bronze
	Shaft	Steel
	Electric engine	

In the following Figure 6, the mass composition for the different materials used in the Candela C-8 is displayed.

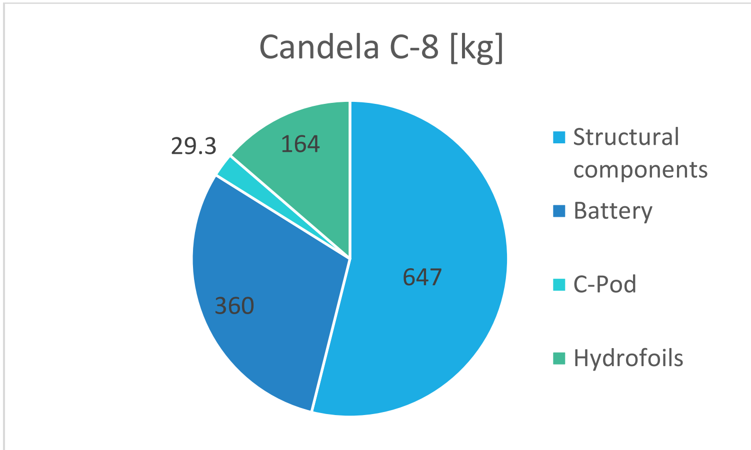


Figure 6: Mass composition of the Candela C-8

Table 3 displays the end-of-life treatment of the C-8, Along with the different assemblies, related materials, and the specific treatment method. Based on the literature review, the C-8 is assumed to be sent to a treatment facility, where the different assemblies are disassembled, sorted, and distributed to the standard treatment process. More details regarding the end of life treatment can be found in section 15.1.3 in the appendix.

Table 3: End-of-life treatment for the Candela C-8

End of life		
Assemblies	**Material**	**Treatment**
Structural components	CFRP	Landfill
Battery	Lithium-ion battery	50% Hydrometallurgy 50% Pyrometallurgy
Engine	Electric engine	Recycling
Hydrofoils	Electric engine	Recycling
	CFRP	Landfill
	Steel	Recycling

5.2 Material composition and end-of-life for the Petrol boats

The flow diagram in Figure 7 below represents the different assemblies used to create the petrol boats and information regarding the different life cycle phases.

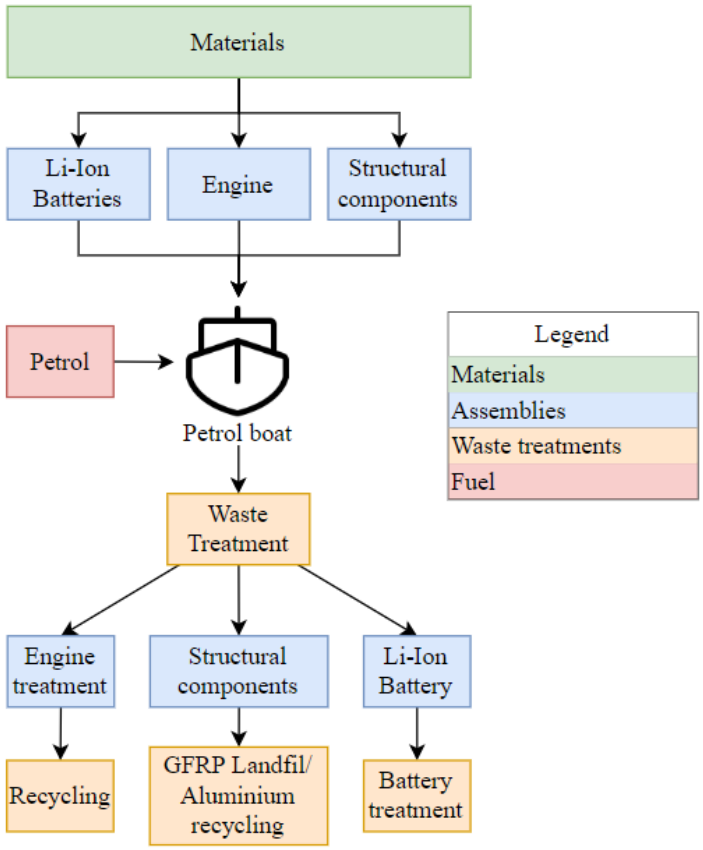


Figure 7: Material composition and end of life for the Petrol boats

Both petrol boats are similar, except for the waste treatment of the structural component, where GFRP is landfilled, while aluminium is recycled. In the following Table 4, the different assemblies and their related components and materials are provided. The data that was provided is solely based on the literature review. As for the C-8, the raw material composition for the materials and technical components such as the GFRP, engine and battery are excluded in this section.

Table 4: Composition of the GFRP Petrol Boat in the model

Assembly	**Components**	**Materials**
Structural components	Hull	GFRP
	Deck	
	Consoles	
	Stringer system	
	Liners	
Battery	Starting battery	Lithium-ion battery
	Deep cycle battery	Lithium-ion battery
Engine	Propeller	Stainless Steel
	Shaft	Steel
	Petrol combustion engine	

Further information about the compositions of the boats can be found in section 15.2.1 Manufacturing in the appendix.

Mass composition for the different materials

In Figure 8 the mass composition of the GFRP Petrol boat is displayed, to provide an overview of the components in the model.

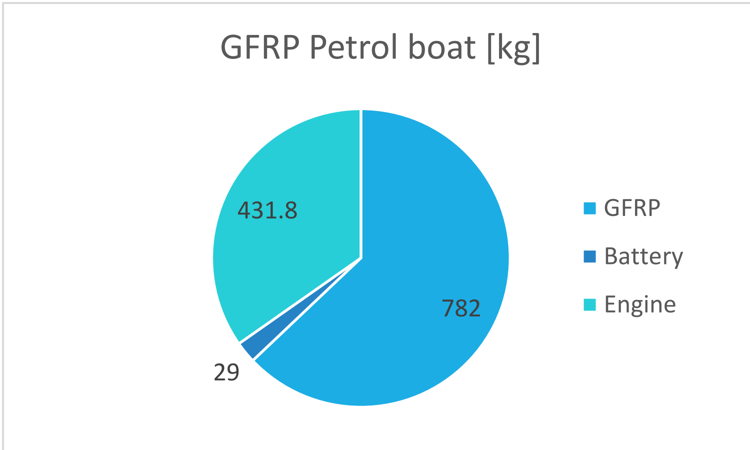


Figure 8: Mass composition of the GFRP Petrol Boat

The different components for the petrol boats are disassembled, sorted, and distributed to the standard treatment process. The components and the related treatment method can be found in Table 5 for the GFRP Petrol Boat.

Table 5: End-of-life treatment GFRP Petrol Boat

End of life treatment		
Assembly	**Material**	**Treatment**
Structural components	GFRP	Landfill
Batteries	Lithium-ion battery	50% hydrometallurgy 50% Pyrometallurgy
Engine	Petrol engine	Recycling

The aluminium boat has the same features as the GFRP boat for all different assemblies except for the material of the structural components. As such, the only two columns introduced for the boat will be for structural components and the end-of-life treatment of structural components, which is displayed in Table 6. Additionally, more details regarding the end-of-life treatment can be found in section 15.1.3 in the appendix.

Table 6: Composition of the Aluminium Petrol Boat in the model

Assembly	**Components**	**Materials**
Structural components	Hull	Aluminium
	Deck	
	Consoles	
	Stringer system	
	Liners	
End of life treatment		
Structural components	Aluminium	Recycling

The mass composition of the aluminum petrol boat differs to the GFRP alternative. Since the GFRP has a lower density along with higher strength properties, the mass of aluminum used is higher relative the other components. The distribution of different materials is displayed in the following Figure 9.

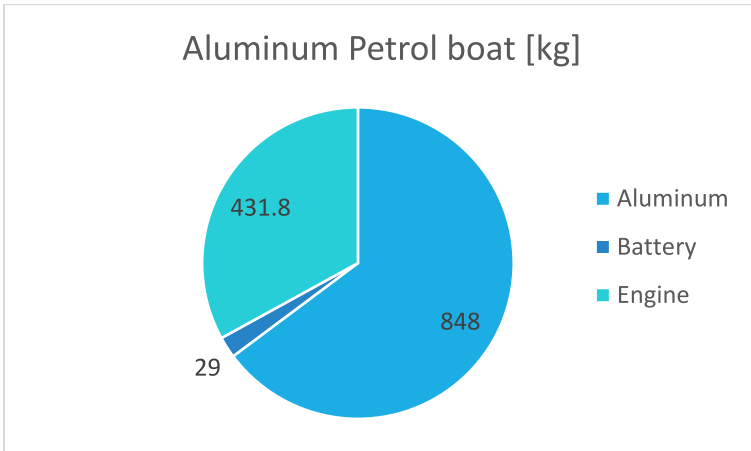


Figure 9: Mass composition of the Aluminium Petrol Boat

5.2.2 Use phase

The number of hours driven for a year and throughout the lifetime of the two boats is displayed in Table 7 below. The numbers are based on assumptions and will be assessed in a sensitivity analysis later the report

Table 7: Use-phase scenario

Category	**Amount**	**Unit**
Lifetime	30	Years
Hours driven per year	50	Hours
Total hours over lifetime	1500	Hours

Table 8 below describes the petrol and electricity consumption at cruise speed for the different boats. The amount of electricity needed to drive the C-8 at cruise speed is retrieved from Candela, whereas the fuel consumption for the petrol boat was retrieved from scientific literature. The total consumption throughout the lifetime is based on the 1500 hours which the boats are assumed to be driven. More details regarding the use phase treatment can be found in section 0 in the appendix.

Table 8: Fuel consumption for the different boat types

C-8			
Category	**Amount**	**Unit**	**Comment**
Fuel	Electricity	kWh	Swedish grid mix
Fuel consumption	22	kWh/h	Per hour driven at 22 knots
Hours driven per year	50	hours/year	
Total electricity consumption	33 000	kWh	Over 30 years
Petrol boats			
Category	**Amount**	**Unit**	**Comment**
Fuel consumption Petrol	50	Liters per hour [l/h]	Per hour driven at 22 knots
Total Fuel consumption	75000	Liters [l]	Over 30 years
Oil change	7	Liters [l]	Size of the tank
Oil change intervals	1 /100	Changes per driven hours	Every 100-hour driven
Total amount of oil	105	Liters [l]	Over 30 years

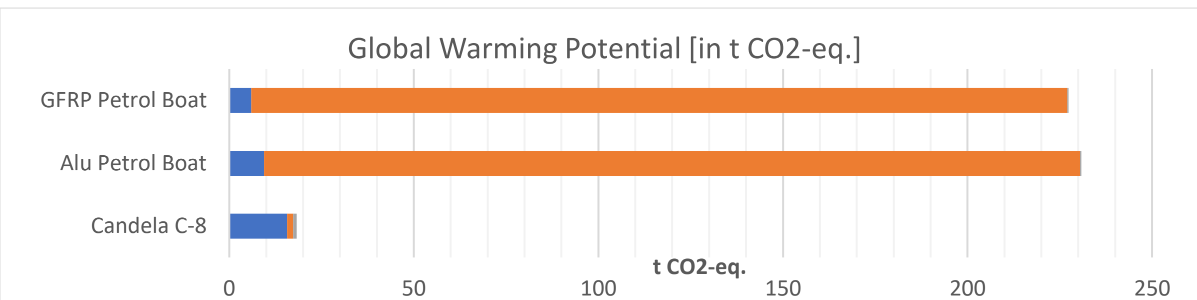
6 Life cycle interpretation

In this section, the result of the Life Cycle Assessment is presented. The result is interpreted via the chosen impact categories: GWP, MRS and CED. Furthermore, the section is divided into the subcategories: Total life cycle, Comparison of assemblies, Use phase and Break-even point.

6.1 Results total life cycle

The environmental impact from the total life cycle, consisting of 30 years use-phase with 50 hours driven per year. The results of the different boats are presented in this section for all three impact categories. The life cycle phases include manufacturing, use phase and waste treatment of each boat.

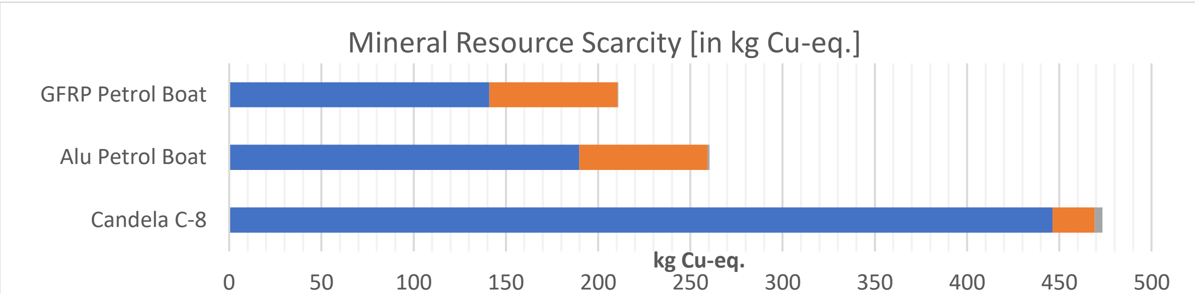
In Figure 10, the boats are compared from a GWP perspective. The aluminum boat has the highest overall impact, followed by the GFRP petrol boat. The petrol boats have the highest impact due to the emissions related to the use phase. The C-8 has the highest manufacturing impact compared to the other boats. However, the total impact of the C-8 over a 30-year life span is 8.1 % compared to the aluminum petrol boat and 8.2% compared to the GFRP petrol alternative. For the waste treatment, the higher impact for the C-8 mainly originates from the battery recycling.



	Candela C-8	Alu Petrol Boat	GFRP Petrol Boat
Manufacturing	15641	9412	5982
Use-phase	1630	221049	221049
Waste treatment	1010	354	305

Figure 10: Total life cycle comparison for GWP

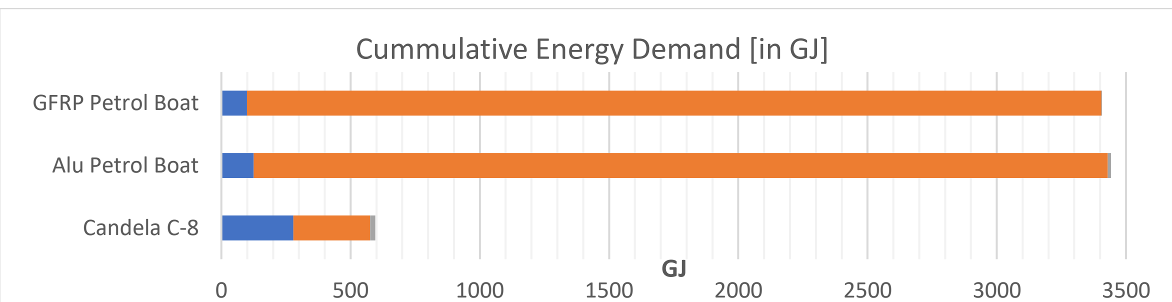
For the MRS impact category, the manufacturing of the boats has the highest share of impact, rather than the use phase. As could be seen in Figure 11, the C-8 results in the highest impact, followed by the aluminium petrol boat. The waste treatment impact in this category for the C-8 comes mainly from the battery waste treatment, and specifically from the use of sodium hydroxide in the recycling process.



	Candela C-8	Alu Petrol Boat	GFRP Petrol Boat
Manufacturing	446.3	189.8	141.0
Use-phase	22.9	69.5	69.5
Waste treatment	4.2	0.96	0.4

Figure 11: Total life cycle comparison for MRS

The Cumulative Energy Demand maps the direct and indirect energy use. When implemented throughout the lifecycle of the different boats, the petrol alternatives end up having the highest impact, mostly due to the use phase, as could be seen in Figure 12. The higher impact for the C-8s' waste treatment compared to the other boats mainly originates from the battery treatment and more specifically from the sodium hydroxide use.



	Candela C-8	Alu Petrol Boat	GFRP Petrol Boat
Manufacturing	278890	124500	99500
Use-phase	297000	3304700	3304700
Waste treatment	19300	12300	2340

Figure 12: Total life-cycle comparison for CED

The results from the previously three diagrams show that in a total life cycle perspective, the end of life treatment of the boats only contributes a to a small share of the overall emissions. In the following section, the manufacturing is assessed in more detail. Due to the relatively low impact of the waste treatment itself, it is not displayed.

6.2 Results comparison of assemblies

When overviewing the result of the three impact categories, the aluminum petrol boat has the lowest impact in two out of the three categories, whereas the C-8 has the highest impact in all the categories. The CFRP has the highest impact in all categories for the structural components except MRS, where aluminium has the highest impact.

When focusing on GWP, the C-8 has the highest impact, as can be seen in Figure 13. The battery is the hotspot of the manufacturing phase for the C-8. For the petrol boats on the other hand, the structural components contribute to the largest share of impact.

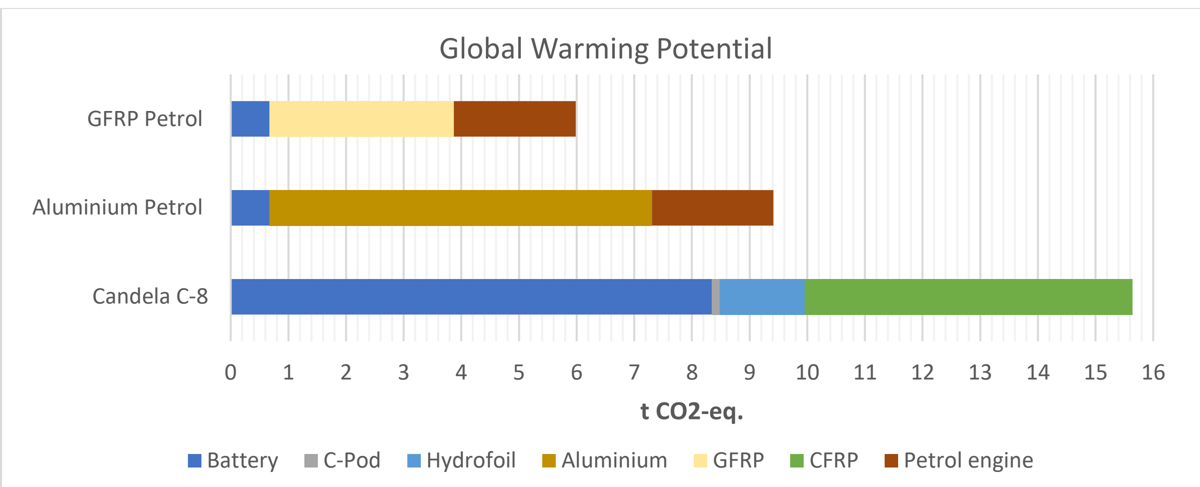


Figure 13: Comparison of assemblies GWP

Concerning MRS, the C-8 has the largest impact, as can be seen in Figure 14. The technical components are the main contributors for all boats. For the petrol boats, the engines have the highest share of the impact, whereas for the C-8, it is the lithium-ion batteries. The main contributor to the high impact from the lithium batteries is the extraction of graphite used to create the battery.

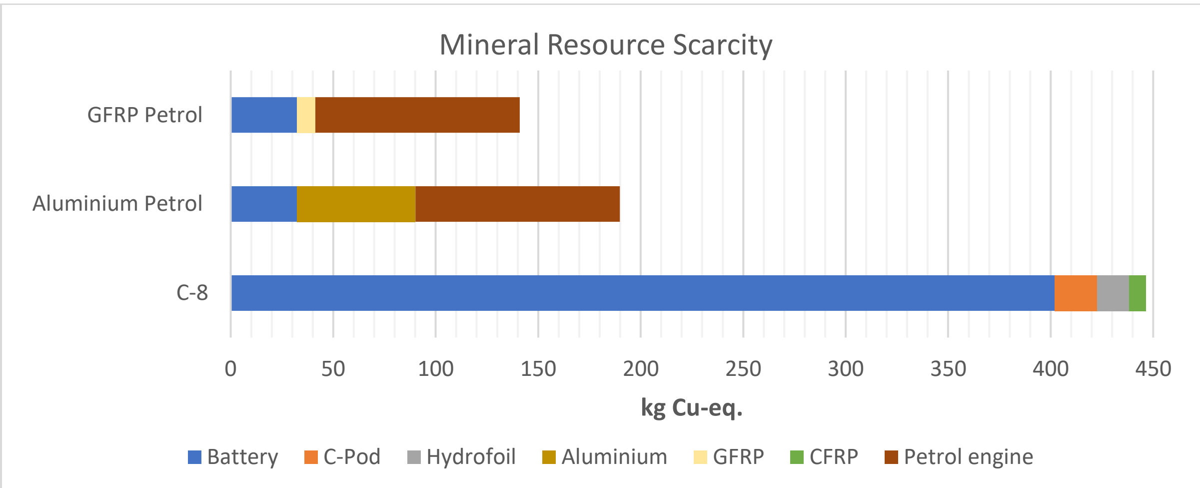


Figure 14: Comparison of assemblies MRS

When it comes to the CED, the C-8 has the highest impact, as can be seen in Figure 15.

The battery and CFRP from the C-8 has a bigger contribution than the corresponding components of the petrol alternatives.

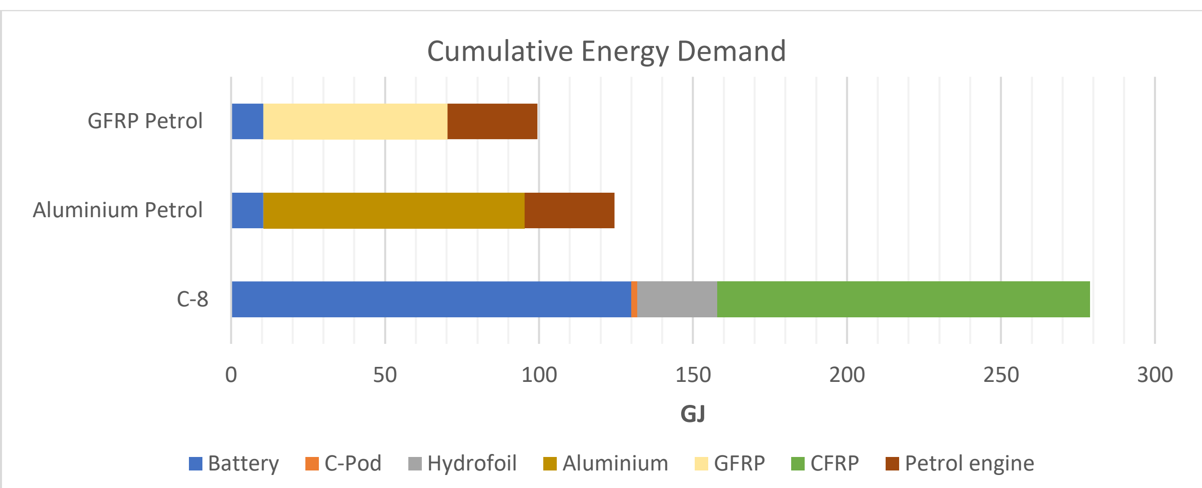


Figure 15: Comparison of assemblies CED

6.3 Results use phase

In this section, the impact of the use phase for all three impact categories are presented.

For GWP the relative impact from the C-8 is almost negligible, with an hourly impact of 1.08 kg CO_2-equivaltents per hour driven, compared to 147 kg CO_2-equivalents for the petrol boats. These hourly emissions add up to the displayed emissions over the whole lifetime that can be seen in Figure 16.

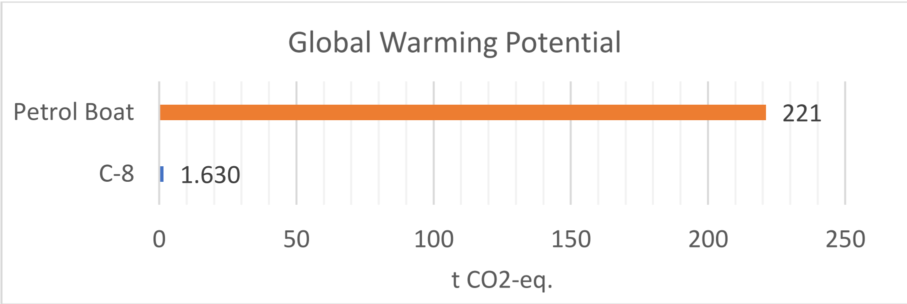


Figure 16: GWP results of the use phase

When it comes to MRS, the difference between the C-8 and petrol boats is not as significant as for the GWP, which can be seen in Figure 17. The impact from the C-8 can be linked to Swedish electricity mix, where the uranium used in nuclear power plants is main contributor. For the petrol boats, the reason is the extraction of oil.

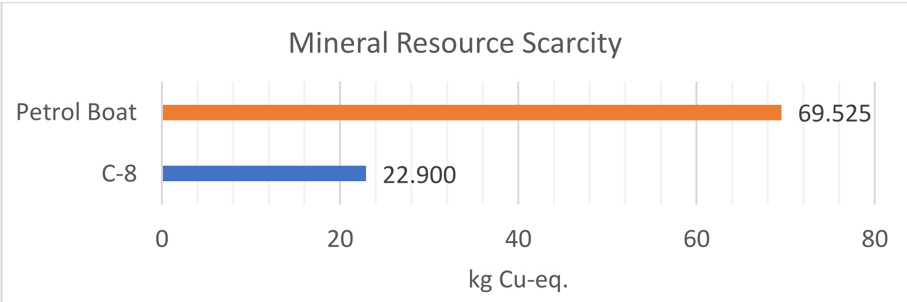


Figure 17: MRS results of the use phase

The use phase impact for the emission category CED can be seen in Figure 18. Also in this category, the petrol boat has a higher impact regarding the whole lifetime compared to the C-8.

The impact related to the C-8 is linked to the Swedish electricity mix, where the energy intensive production of uranium for the nuclear power plants is the main reason. For the petrol boats, the main contribution is related to refining process of crude oil.

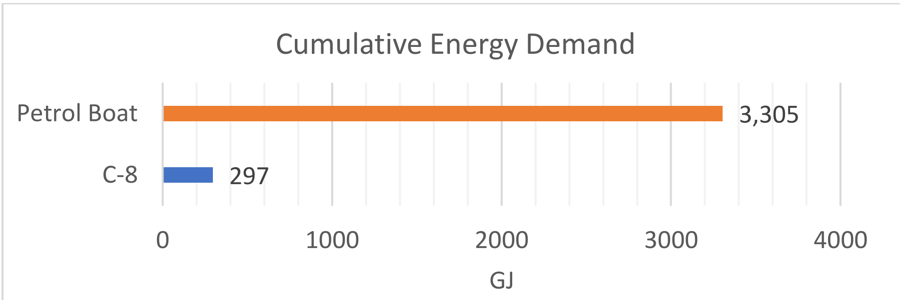


Figure 18: CED results of the use phase

6.4 Results break-even point

By analyzing the Global Warming related emissions in CO_2-equivalents from the production and the use phase of the boats, over time, a break-even point is assessable. The starting value in the graph represents the combined emissions of the manufacturing and end of life of the different boats, whereas the linear growth represents the use phase. As could be seen in Figure 19 below, the petrol boat has a higher Global Warming related emission in the use phase, due to the petrol combustion of the engine. These emissions surpass the higher production emissions of the Candela C-8 and continue to grow.

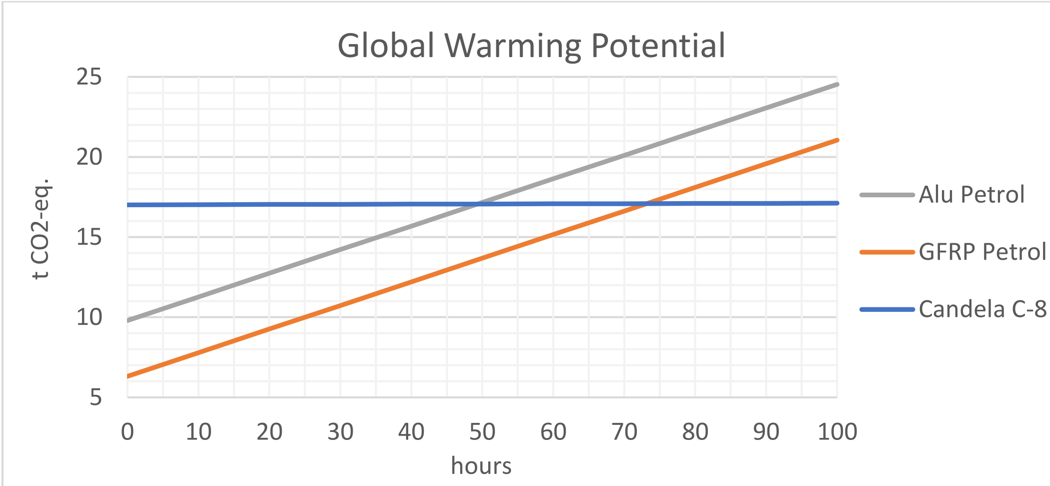


Figure 19: Break-even point GWP

From a Global Warming perspective, the specific break-even point for when Candela breaks even with the GFRP petrol boat is 48 hours, whereas for the aluminum petrol boat, the break-even point occurs after 73.1 hours. Converted to years, the C-8 is more sustainable than the GFRP petrol boat after almost one year and the Aluminium petrol boat after one and a half years.

7 Sensitivity Analysis

In this section, assumptions used to achieve the result will be assessed. By implementing a sensitivity analysis, it is possible to create different scenarios for the assumptions used in the result. As such, the uncertainty of the assumptions can be assessed. The assumptions that will be investigated in this section are the numbers of hours driven per year, fuel consumption for the petrol boats, number of batteries needed, and the environmental impact of using electricity mixes from other countries than Sweden.

7.1 Break-even point for different use hours per year

The break-even point in years is highly dependent in the number of hours that the boats are driven. As such, three scenarios were added: 20 hours per year, 60 hours per year, and 100 hours per year. As can be seen in Figure 20, the more frequent the petrol boats are driven, the faster the C-8 reaches the break-even point. Only the base scenario of 50 hours was added to the C-8 since the relative difference of the other scenarios was negligible in relation to the fossil alternatives.

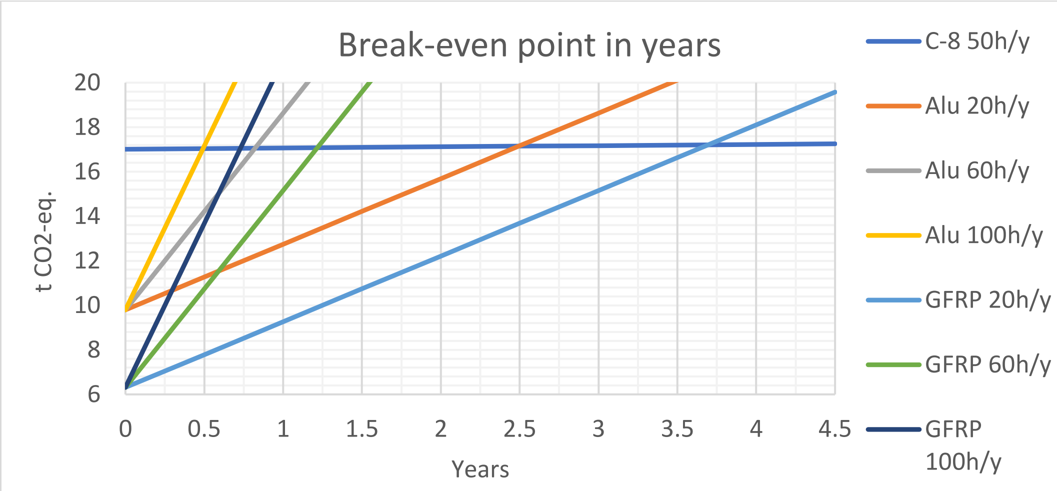


Figure 20: Break-even point for different use hours

The range of different-break even points depending on boat type and hours driven per year ranges from 0.5 years to 3.7 years. The break-even points for the different scenarios can be found in Table 9 below.

Table 9: Break-even points of boat types and use scenarios

Scenario	**Break-even point [years]**
Aluminium boat 20 hours per year	2.47
Aluminium boat 60 hours per year	0.82
Aluminium boat 100 hours per year	0.49
GFRP boat 20 hours per year	3.66
GFRP boat 60 hours per year	1.22
GFRP boat 100 hours per year	0.73

7.2 Break-even point based on use hours per year and fuel consumption

In this section, the highest and lowest use scenario in terms of hours driven per year and liters per hour driven is assessed, for the petrol boats. The assumptions used in the result was based on a 50-hour usage per year, with a fuel consumption of 50 liters per hour. For this analysis, two scenarios are implemented. For the low scenario, the fuel consumption is 25 liters per hour in combination with 20 hour of usage per year. The high scenario on the other hand, consists of a fuel consumption of 75 liters per hour driven, in combination with a usage of 100 hours per year. By implementing these scenarios to the break-even point, a wider range of use scenarios is presented, which can be seen in Figure 21.

Figure 21: High and low use hours and fuel consumption comparison

The exact break-even points for the high and low scenario for the different boat types can be found in Table 10.

Table 10: Break-even points of high and low scenario

Scenario	**Break-even point [years]**
Aluminium high	0.33
Aluminium low	4.93
GFRP high	0.49
GFRP low	7.31

7.2.1 Sensitivity analysis of different grid mixes

In this section, the fossil heavier grid mixes from India and Germany are applied to the C-8, in order to assess the impact on the break-even point. The impact of the electric grid mix in relation to the break-even point does have an impact in relation to GWP, as could be seen in Figure 22. However, the difference in numbers of hours needed for the C-8 to become more sustainable is only a few hours of driving.

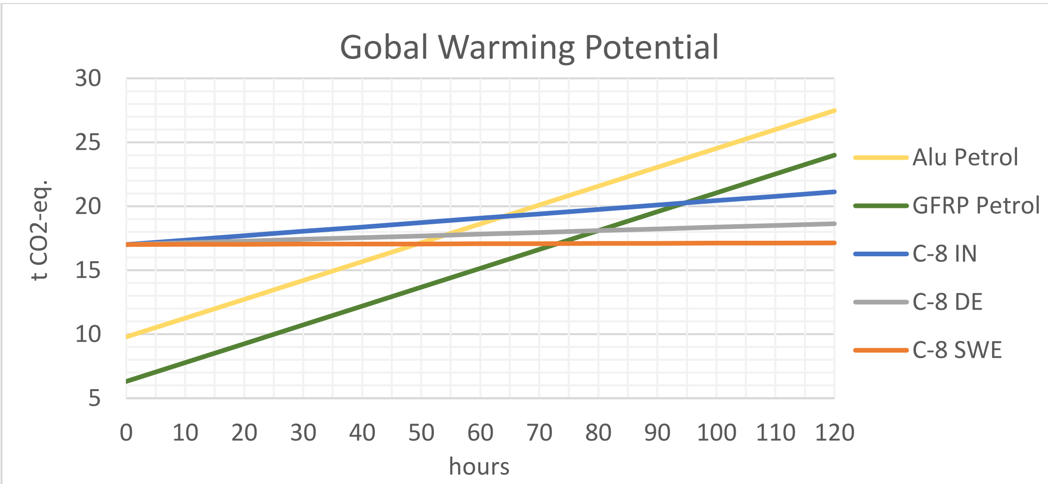


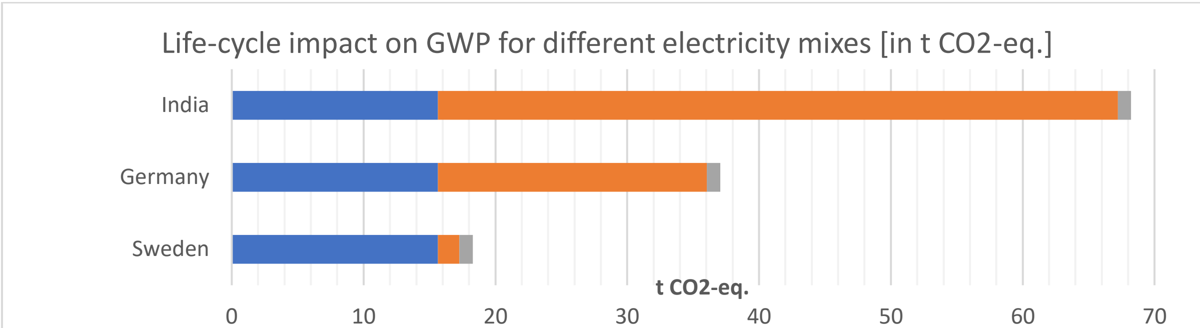
Figure 22: Sensitivity analysis on different electrical grids

The specific break-even points for the different boats and electricity mixes can be found in Table 11 for 50 hours use per year.

Table 11: Break-even point for different electricity grids

Scenario	Comparison boat	Break-even point [years]
C-8 India	Aluminum petrol	1.27
	GFRP petrol	1.89
C-8 Germany	Aluminium petrol	1.08
	GFRP petrol	1.60

When comparing the different grid mixes in relation to the total life cycle of the C-8, the relative impact becomes relevant. As can be seen in Figure 23 below, both the Indian and German grid mix makes the use phase surpass the manufacturing phase. The reason for the large impact is due to the electricity mix in both countries are more dependent on fossil fuels. From a Global Warming perspective, Germany has 12.5 times and India 31.6 times the impact, relative to the Swedish grid.



	Sweden	Germany	India
Manufacturing	15641	15641	15641
Use-phase	1630	20400	51578
Waste treatment	1010	1010	1010

Figure 23: Use phase difference electricity grid over life cycle GWP

7.3 Battery sensitivity analysis

The lithium-ion batteries were assumed to last for 10 years for all the boats, which is equal to three batteries throughout the lifetime. In order to assess the impact of different lifetimes of the batteries, two scenarios are implemented. The first scenario is based on the batteries lasting 15 years, which would be equal to two batteries. Whereas the second scenario is based on a lifetime of 7.5 years which is equal to 4 batteries throughout the life cycle. As could be seen in the figures below for the different impact categories, the number of batteries is central regarding impact in relation to the manufacturing of the C-8. The impact on the manufacturing phase for the petrol boats is not of the same magnitude, due to the relatively low battery weight compared to the C-8. From a Global Warming perspective, the relative difference in having four batteries instead of two, results in an approximately 43% increase for the manufacturing phase of the C-8, as can be seen in Figure 24.

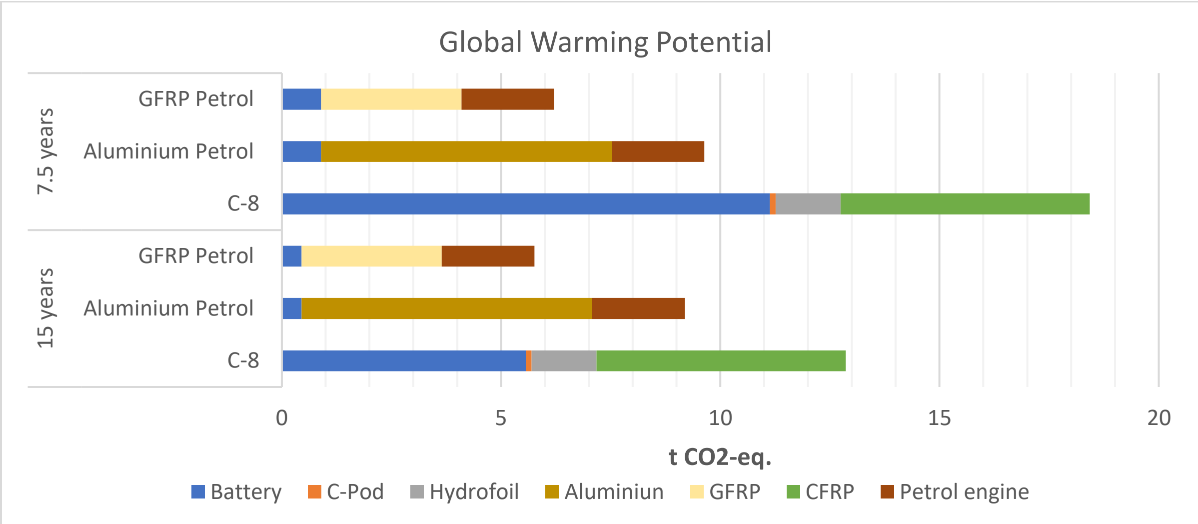


Figure 24: Influence of different battery lifetimes on the GWP emissions of manufacturing

From a Mineral Resource Scarcity perspective, regardless of the scenario, C-8 has the highest impact, as can be seen in Figure 25.

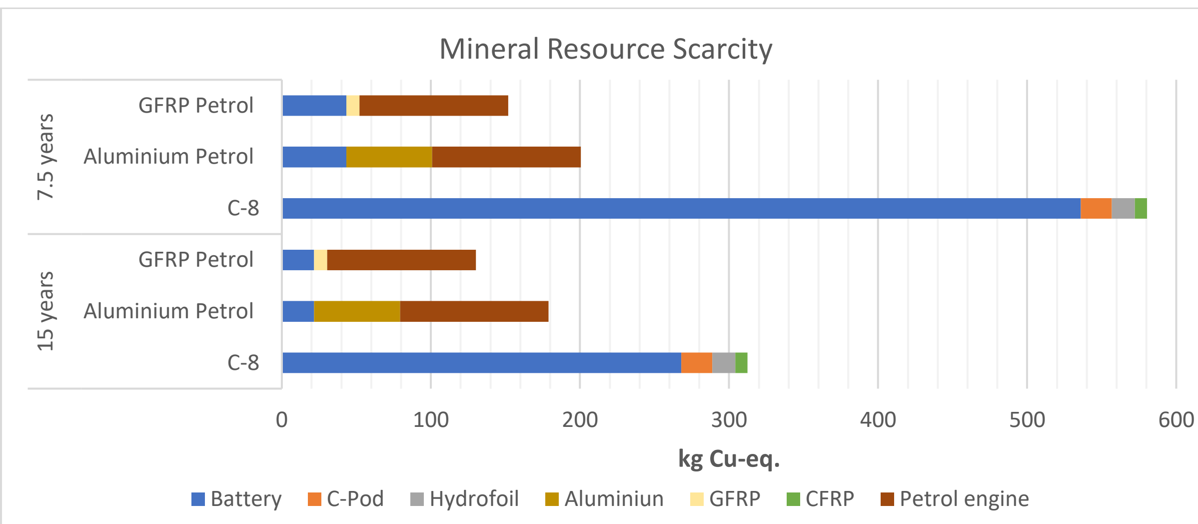


Figure 25: Influence of different battery lifetimes on the MRS emissions of manufacturing

As for the other two impact categories, the difference in number of batteries used throughout the lifetime has a big impact, as can be seen in Figure 26.

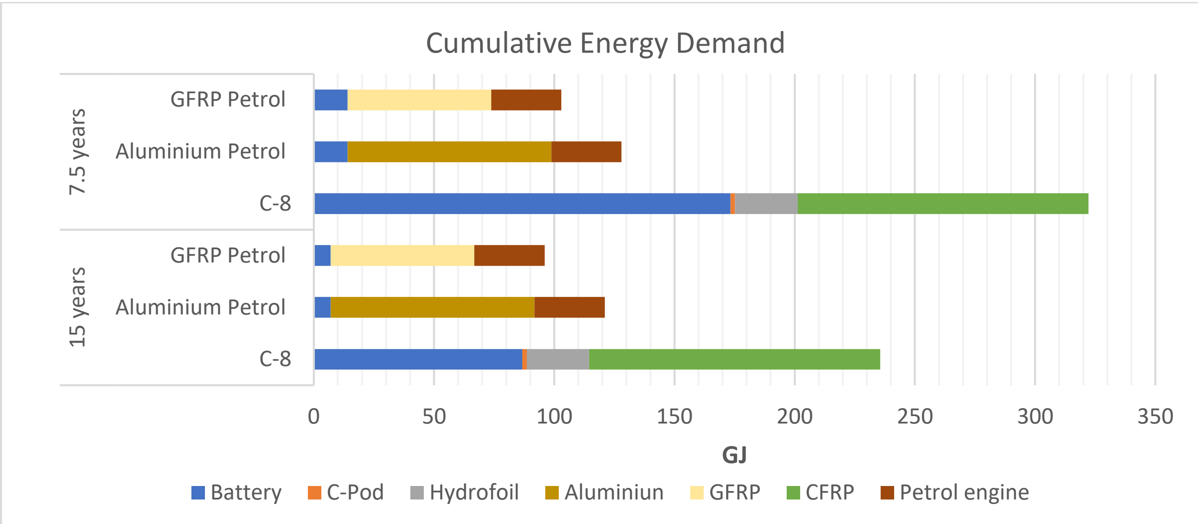


Figure 26: Influence of different battery lifetimes on the CED emissions of manufacturing

8 Discussion and conclusion C-8

The result shows that in comparison to the fossil driven alternatives, the C-8 is highly favorable in two out of three impact categories, namely GWP and CED. Only in relation to MRS, the C-8 has the highest impact, mainly due to manufacturing in general, and specifically the batteries. As can be seen in the result, the lithium-ion battery has a share of 90% of the total manufacturing impact in that impact category. A result which goes in line with other life cycle assessments of electric vehicles, such as (Koroma *et al.*, 2022).

When it comes to the use phase contribution of the C-8 in relation to the total life cycle impact, the share is relatively small in all categories except CED, where the share between manufacturing and use phase is almost even. However, considering GWP, the use phase only contributes around 8.7% of the total impact, which can be directly linked to the low CO_2- footprint of the Swedish electricity grid. The C-8 had the highest impact on GWP from manufacturing, but also the lowest from the use phase. This result is also concluded in other studies where electric and fossil driven vehicles are compared, such as Girardi and Brambilla, (2019) and Scania, (2021).

Additionally, the total life cycle impact of the C-8 concerning GWP is affected by different grid mixes. As can be seen in the sensitivity analysis, using a boat that is charged with an Indian grid mix instead of the Swedish one, results in an increased life cycle impact of 268% from a Global Warming perspective. As such, the electricity mix has a big influence on the environmental impact of the C-8. However, compared to the emissions from the combustion engines, the differences in the grid mixes become small.

When comparing the C-8 to the petrol alternatives, except for MRS, the main difference in impact is linked to the use phase. For all three impact categories, the C-8 results in lower emissions in the use phase. The main factor for being more environmentally friendly in the use phase in relation to GWP and MRS is because of the lower emissions from using electricity instead of fossil-based fuel. Furthermore, the Candela C-8 has a high efficiency, by using hydrofoil technology. The biggest difference in impact can be linked to the GWP, where the impact from the C-8 was 0.75% in relation of the fossil alternatives for the base scenario. Even if the Indian grid mix is applied, the reduced impact of C-8 compared to the fossil alternatives is

76.7%. As such, the impact from the C-8 relative to the fossil-driven alternatives is clearly reduced, even with grid mixes that have higher fossil shares.

The main environmental impacts throughout the life cycle of the Candela C-8 are the components of the boat, where the dominant component in all impact categories are the batteries. Especially in relation to MRS, where the batteries have a contribution of 90% of the total manufacturing impact. When comparing the structural materials between the boats, aluminium has the highest impact in two out of three categories. Only for CED, CFRP has the highest impact. For the engines, the C-pod has a minor contribution in all impact categories, compared to the petrol engines.

The use hours and the fuel use of the petrol boats were found to be the main influence on the break-even point concerning GWP.

The result, which was based on a use of the boat of 50 hours per year and a fuel consumption of 50 liters per hour for the petrol boats, provided break-even points of 1.46 years for the GFRP and 0.96 for the aluminum boat. However, depending on the different scenarios for fuel consumption and use hours, the break-even point is ranging between ~0.3 to ~7.5 years. The wide range shows that hours used per year and fuel consumption, have a big impact on how fast the C-8 becomes environmentally beneficial.

Life Cycle Assessments on the topic of leisure boats have been done before. These studies focused on different aspects, such as hull materials, propulsion systems, or the circularity of boats. Compared to previous research, this study contributes to the knowledge regarding the difference in environmental impact between petrol driven and electric driven leisure boats, from a life cycle perspective. Information regarding the hotspots of the manufacturing were found, which could be beneficial for Candela Technology AB, in order to mitigate impact, since they have direct influence over that part of the C-8´s life cycle. The result showed that the C-8 is more sustainable in two out of three impact categories, with GWP being the category where the highest mitigation occurs. Private consumers who want to make a more sustainable choice could therefore use this result if they seek an option how to mitigate their impact in that category when purchasing a leisure boat. The result could also be useful for policy makers who aim to mitigate the Global Warming impact from the leisure boat sector.

8.1 Uncertainties

The emission factor for the combustion engines were taken from literature for a generic 4-stroke boat petrol engine. Since the impacts related to combustion of fuel has a high contribution over the life cycle, a comparison in environmental impact from the own created combustion process to an existing one in in Ecoinvent was conducted. The result, which can be found in appendix at section 0, showed that the emissions of the own created combustion process had the same relative size of order as the process in Ecoinvent. Thus, choosing the own created process, based on data that reflects emissions from a 4-stroke petrol engine was deemed as the best option. Furthermore, the emissions related to the combustion of petrol is not linked to emissions at sea by SimaPro, as that option is not available. Emissions from fuels that is emitted directly into water highly affects ocean acidification, which changes the pH of the water (European Science Foundation, 2008). As such, the resilience of the ocean that works like a carbon sink is disturbed, which could affect the Global Warming Potential. To be able to include this factor to the result could therefore be beneficial and influence the result.

How much the boats are used influences the environmental impact and especially the break-even points. As an approximation of 50 use hours per year was applied as use case, the yearly use hours were estimated and verified by literature research and in dialog with Candela Technology AB. Furthermore, this uncertainty was addressed in the sensitivity analysis to test the influence of this estimation.

Generic engines and batteries from Ecoinvent were used, due to lack of data. As such, the electric engines used for the C-Pod does not accurately reflect the exact composition of the C-Pod. A global average transport from an engine manufacturer to boat assembly is automatically added by Ecoinvent, which in this case is inaccurate, since the C-Pod is manufactured on site. However, the impact caused by the transportation is negligible in relation to the total manufacturing phase of the C-8.

A material conversion in relation to strength and density of CFRP was applied to the structural parts of the GFRP and aluminium boats to assess their weights. However, the conversion rates were taken from applications on helicopters and cars. Even though all objects are automotives, there is an uncertainty in how well the applications are transferable to boat hulls.

The lifetime of the engines for both the C-8 and the petrol boats were assumed to 30 years. If an extra petrol engine would be needed throughout the lifetime of the petrol boat, the additional impact from a GWP perspective would be less than 2%. As such, the overall result would not be significantly affected.

There are uncertainties regarding the lifetime of lithium-ion batteries. This issue was addressed in the sensitivity analysis.

There are uncertainties in the battery waste treatment, which is one of the main contributors of emissions over all categories in the end of life of the C-8. To model the battery waste treatment, a process based on the global average was used. In this process, the main emissions came from the electricity use. To make the waste treatment of the batteries more applicable to Sweden, the electricity used in the generic Ecoinvent process was replaced with the Swedish electricity mix.

In all recycling processes, except for the engines and batteries, the recycling rate was assumed to be 100% for the different metals, which impacts the energy consumption in the end of life treatment. However, the end of life treatment for the different boats has a small contribution in all impact categories, in relation to total life cycle impacts. Furthermore, the input for these processes were solely based on electricity, which comes with uncertainties, since e.g., solvent and additives used in the recycling processes could increase the environmental impact.

9 Candela P-12 compared to a conventional diesel ferry

A second comparison was conducted in this report, based on Ekerölinjen in Stockholm, Sweden, with the application of different compositions of ferries. The current scenario was defined by the two existing ferries Lux and Sunnan, which are used during the ice-free months between April and December. In the winter months, Rex is replacing one of the ferries, due to its capability of breaking the ice. The new scenario is based on the usage of three Candela P-12´s in the period between April and December, whereas in the winter months, they are also replaced due to their inability to break the ice. In contrast to the leisure boat comparison, where boats of similar sizes were compared, the comparison objects in this study differ in characteristics such as weight, passenger capacity, and cruise speed. The P-12 is applied as a scaled-up version of the C-8. Thus, CFRP is used for the structural components, hydrofoils are included, and it is also battery powered. The carrying capacity of the P-12 is 30 passengers and the cruise speed is around 20 knots. Stockholm stad plans to use the P-12´s instead of the ferries which are currently fulfilling the service of Ekerölinjen. A visualization of the P-12 can be seen in Figure 27.

Figure 27: Candela P-12 ferry

(Candela Technology AB, 2022)

Ekerölinjen

Ekerölinjen is one of Stockholm’s commuter ferry lines, which connects the stops *Klara Mälarstrand* with *Tappström* on the island of Ekerö. Today, this line has a passenger load of about 130 000 people per year, which are transported by two boats going back and forth. Ekerölinjen and the stops on the route are displayed in the following Figure 28.

Figure 28: Ekerölinjen route map
(SL, 2022)

The current ferry service on Ekerölinjen is provided by two ferries in the summer months. Their passenger capacity is almost the same with 200 passengers for the M/S Sunnan and 190 passengers for the M/S Lux. The average speed of the two ferries is about 10.5kn on this route.

9.1 Aim and objective

The aim of this ferry comparison is to evaluate the difference in environmental impact for fulfilling the service of Ekerölinjen, by using Candela P-12 instead of the current ferries.

Furthermore, this comparison will evaluate the environmental impact of three impact categories, which are Global Warming Potential, Mineral Resource Scarcity, and Cumulative Energy Demand. The defined goals of this study are:

- Determine the environmental impact of the ferries in relation to their carrying capacity
- Investigate the environmental impact by applying the passenger load of Ekerölinjen
- Determine the difference in impact per passenger-kilometer of the ferries

9.2 Scope of the study

The methodological structure for the ferry comparison is mostly the same as in the leisure boat comparison. The only methodological topics that differ are the functional unit and assumptions and limitations, which will be further explained below. The rest of the methodological foundation can be found in section 3 Methodology, in the leisure boat comparison.

9.2.1 Functional Unit

There are two functional units used for the ferry comparison since the composition of ferries changes during the period between December and April. The first functional unit focusses on the period between April and December, where Sunnan and Lux are defined as the current ferries, and three P-12´s are defined as the new ferries. The second functional unit takes the whole year into consideration.

Functional unit 1

To fulfill the service of operating Ekerölinjen except for the winter months, with its current passenger load and travel pattern over 30 years.

Functional unit 2

To fulfill the service of operating Ekerölinjen, with its current passenger load and travel pattern over 30 years.

9.2.2 Assumptions and limitations

Key assumptions:

- The average passenger amount per month is assumed to be evenly distributed per year.

Production and manufacturing

- Lifetime of both CFRP and aluminium is assumed to be equal (30 years)
- The different structural components in the boats are assumed to be homogeneously built, with only one material type
- The engines for both Candela and the petrol boat are assumed to function for the whole lifetime.
- The lifetime for the batteries is assumed to be 10 years.

Use phase

- Fuel use is only limited to driving at cruise speed. As such the energy or petrol use of the boats is assumed to be zero when the boats are not moving
- Except for oil changes in the petrol engine, maintenance is excluded for all components of the boats.

End-of-life treatment

- Due to the high recycling rates within the European Union a recycling rate of 100% for metals is applied in the energy need for the recycling processes.

10 Life cycle inventory analysis

This section provides an overview of the collected data used to create the ferries and is divided into the three subchapters: Material composition, End of life, and Use phase. The recycling of different components is already defined in the LCI for the leisure boats and applies for the ferries too. The subchapters mainly provide an overview of the data used in the comparison. More detailed information regarding calculations and where data was retrieved can be found in section 15.2 in the appendix.

10.1 Material composition

The Candela P-12 is not constructed yet, which is why specific weights and the exact composition are not available. In order to retrieve the weight of the different assemblies for the P-12, the assemblies of the C-8 were scaled according to already existing weight estimates provided by Candela. As such, the components included in the P-12 are the same as for the C-8, which can be found in Table 2, in section 5.1. Furthermore, since the different assemblies are scaled, the mass fraction of each assembly differs between the Candela P-12 and the C-8. The mass composition of the different assemblies used for the P-12 can be found in Figure 29, below.

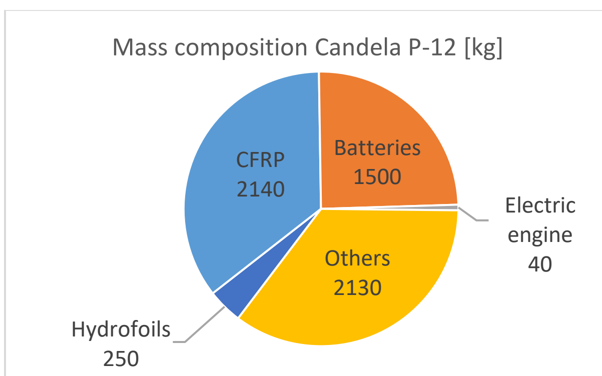


Figure 29: Mass composition Candela P-12

The assemblies of Sunnan and Lux also include the same components as the comparison boat, which can be found on Table 4 in section.0 However, in order to retrieve the weight share of each component, a ferry from (Schmidt and Watson, 2013) was used in order to get a share between the structural components, batteries, and the engine weights. More details how the weight distribution was conducted can be found in section 15.2.1. Even though the structural components and engines are the same for Sunnan and Lux, the total weight differs, which affects the share of different materials, as could be seen in the figures below. The share named “Others” in Figure 29 and Figure 30 are the cumulated weight of the excluded parts, that are assumed to be equal and therefore excluded in this comparison.

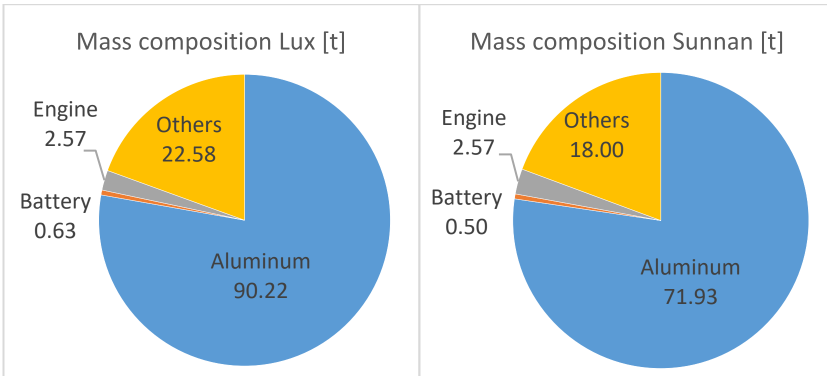


Figure 30: Mass composition Lux and Sunnan ferry

10.2 End of life

The waste management of the ferries is the same as for the leisure boat comparison. As such, more details about the end of life can be found in section 15.2.2 for0 the current ferries and in section 5.1 for the P-12.

10.3 Use phase

In this section, the data used to define the emissions per hour driven in the use phase is described. The amount of electricity needed for the P-12 to drive in cruise speed is retrieved from Candela. For the Sunnan and Lux, an average of diesel consumed per hour driven was taken from the product specifications of the engines that is used on the ferries.

Table 12: Use phase data for the ferries

Candela P-12			
Category	**Amount**	**Unit**	**Comment**
Fuel	Electricity	kWh	Swedish grid mix
Fuel consumption	60	kWh	Per hour driven at 20 knots
Sunnan and Lux			
Category	**Amount**	**Unit**	**Comment**
Fuel consumption Diesel	180	Liters [l]	Per hour driven at 10.5 knots
Oil change	31	Liters [l]	Size of the tank
Oil change intervals	1 /600	Changes per driven hours	Every 600-hour driven

11 Life cycle interpretation

The life cycle interpretation is divided into two sections, due to the use of two functional units. In section 11.1 the result linked to functional unit 1 is displayed. Whereas in section 0 the result associated with the functional unit 2 is displayed.

11.1 Results based on functional unit 1

In the following paragraphs, results based on the functional unit to fulfill the service of operating Ekerölinjen except for the winter months, with its current passenger load and travel pattern over 30 years, is provided.

11.1.1 Impact per seat

The impact per seat relates the environmental impact of the ferries to their passenger capacity, in order to compare the different sized ferries. As can be seen in Figure 31, the current ferries have a higher impact in two out of three impact categories. However, in relation to MRS, the P-12 is the one that has a higher impact per seat.

In relation to GWP, the use phase of the current ferries has an impact per seat of 2.5 kg CO_2-eq per hour driven, in relation to 0.1 kg CO_2-eq for the P-12´s. As such, the trend in Figure 31 shows, that the more frequently the P-12 is used, the more the absolute impact is reduced.

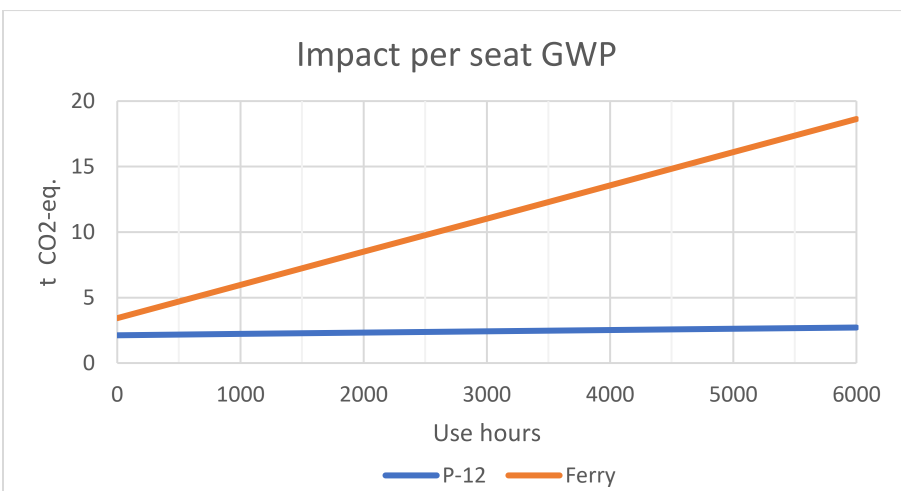


Figure 31: Ferry comparison Impact per seat GWP

Regarding MRS, the impact from the P-12´s are higher, both when it comes to manufacturing and use phase. From a manufacturing perspective, the main reason for the higher impact can be linked to the contribution of the batteries in the P-12.

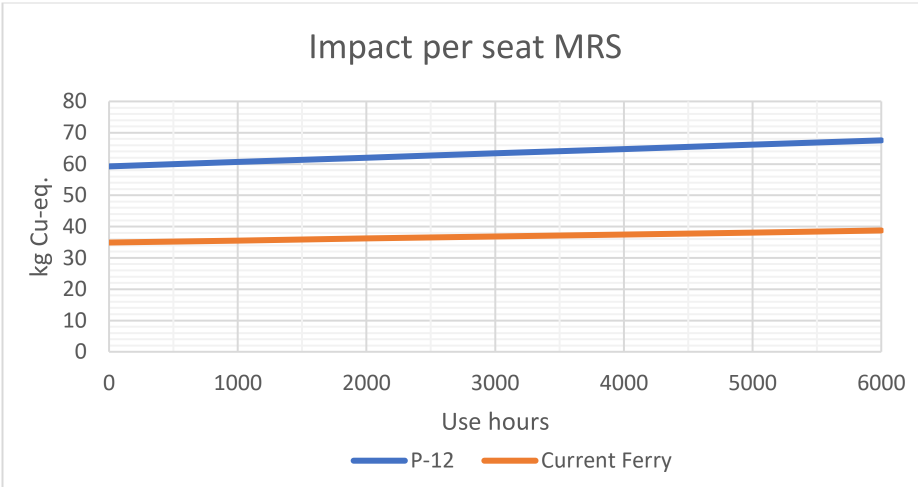


Figure 32: Ferry comparison Impact per seat MRS

The impact per seat for CED is the impact category where the use phase is the dominant factor over time for both ferries, as can be seen in Figure 33 below. The current ferries have a higher impact per hour driven, mainly due to the high fuel consumption. Since the impact per hour driven is higher from the current ferries in relation to the P-12´s, the trend will continue over time.

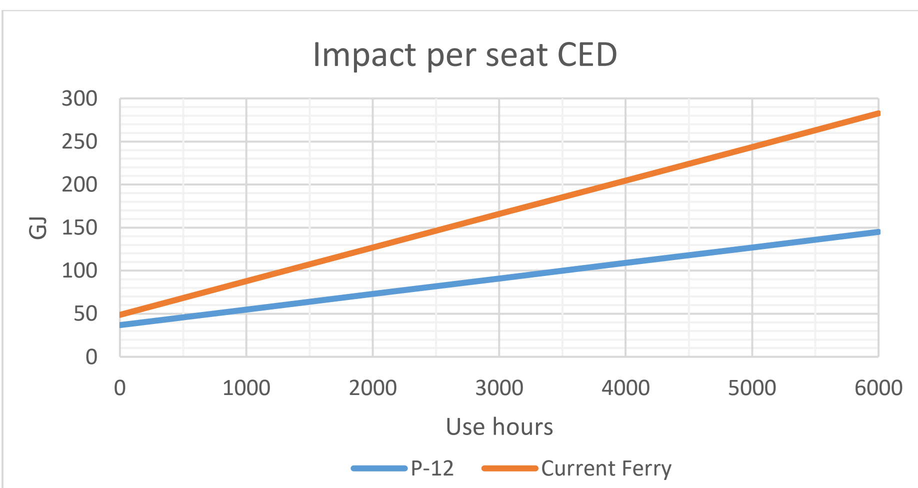


Figure 33: Ferry comparison Impact per seat CED

11.1.2 Impact per occupied seat

This section takes the occupancy rate of the P-12 and the current ferries into consideration, which is based on the passenger volume on Ekerölinjen, the speed, and the passenger capacity of the different ferries. The average occupancy rate for the P-12 is calculated to 40.8% and for the current ferries the occupancy rate is 17.3%. The method behind these numbers can be found in section 15.2.4 in the appendix. The inclusion of the occupancy rate gives an insight into the relation between ferry emissions and used seats.

Figure 34 shows the impact per occupied seat in relation to GWP. The result shows that relative impact between the use phase for the two ferries is the focus point for this impact category. After 4000 hours driven, the impact per occupied seat has increased by almost 60 tons CO_2-equivalents for the current ferries, whereas the P-12 increased its emissions by merely 1 ton.

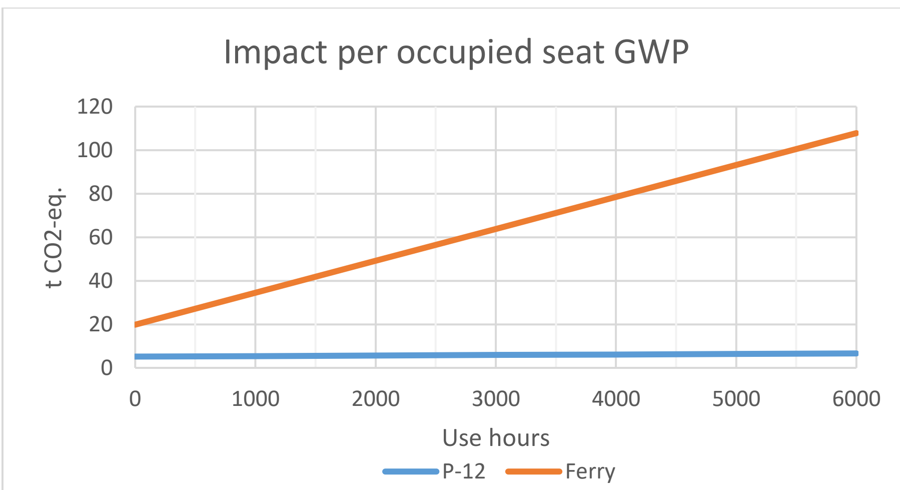


Figure 34: Ferry comparison Impact per occupied seat GWP

The comparison between the ferries in relation to MRS can be found in Figure 35. When the occupancy rate is applied, the result changes in favor of the P-12. Since the P-12 has a higher occupancy rate, the impact per passenger decreases in relation to the current ferries. The trend shows that the P-12 consistently has a mitigated impact by approximately 25% in relation to the current ferries.

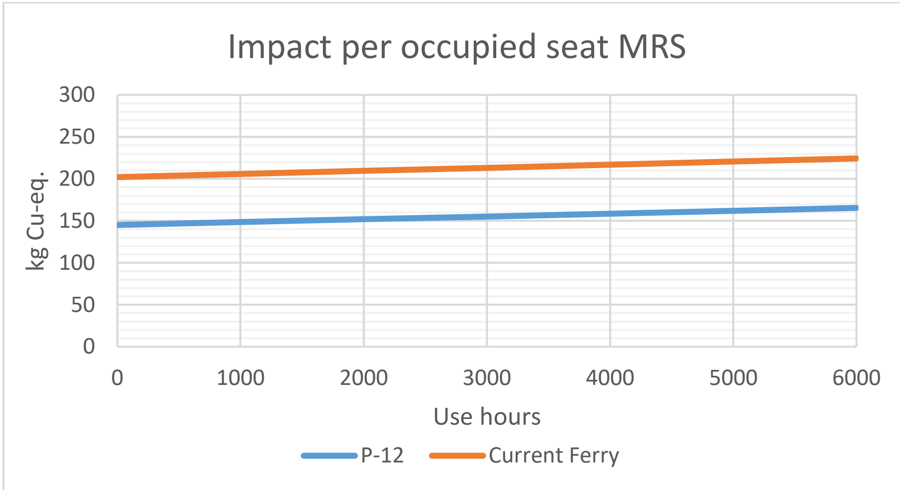


Figure 35: Ferry comparison Impact per occupied seat MRS

Figure 36 shows the impact per occupied seat in relation to CED. Just as for the GWP, the use phase is set to be the main focus point for this impact category.

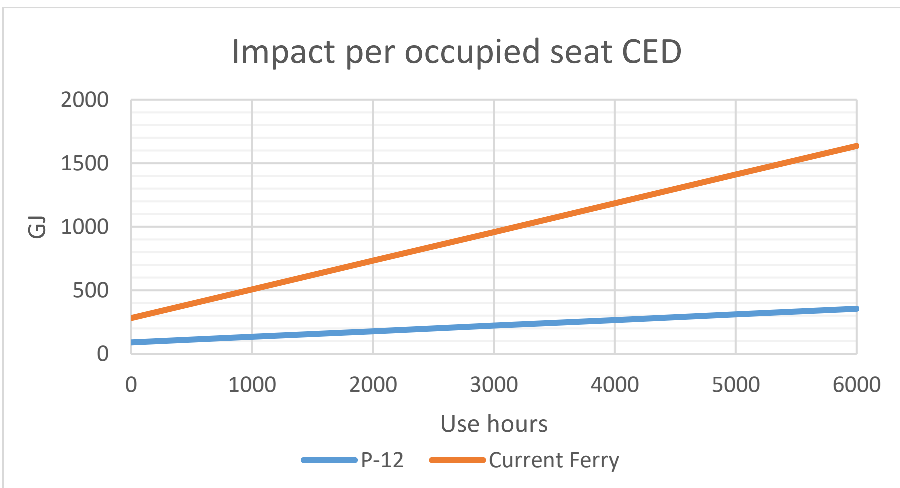


Figure 36: Ferry comparison Impact per occupied seat CED

11.1.3 Total fleet impact

The total fleet impact takes the number of boats into consideration along with the manufacturing, end of life, and use phase. The result displays the environmental impact when comparing the scenario of using only P-12´s in relation to using the two current ferries on Ekerölinjen. For all three impact categories, different numbers of P-12´s were applied in order to simulate the difference in impact if more P-12´s would be used. The number of P-12´s chosen for the different scenario's ranges between 3 and 7 ferries. Thus, giving the opportunity to investigate the fleet impact if the passenger load would increase and additional P-12´s would be needed.

As could be seen in Figure 37 below, the impact from the use phase in relation to GWP results in significantly higher impacts from the current ferries. After 10 000 hours driven, the fleet impact from the current ferries is 40 times higher compared to three P-12´s, and 17 times higher than if seven P-12´s were to be used.

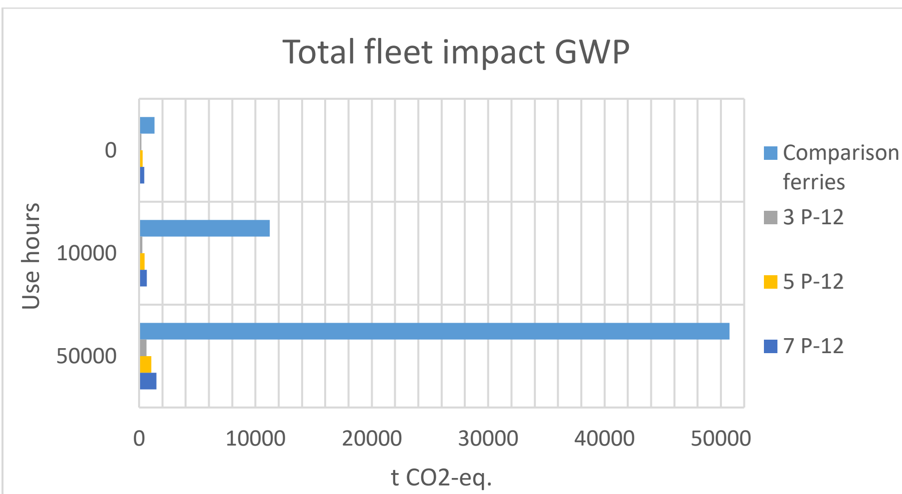


Figure 37: Total fleet impact GWP

When comparing the fleet impact in relation to MRS, the impact between the scenarios of using P-12´s and the current ferries becomes more even, as displayed in Figure 38. The impact related to manufacturing takes up a higher share compared to the use phase, in relation to the other impact categories. Based on the manufacturing, the result shows that the impact of implementing three P-12´s has a 39% mitigation on MRS in relation to the two current ferries. When extending the scenario to seven P-12´s, the total impact is lower than for the current ferries. Over time its noticeable that the trend stays the same for the three scenarios, except for the seven P-12´s, which have surpassed the current ferries after 50 000 hours driven.

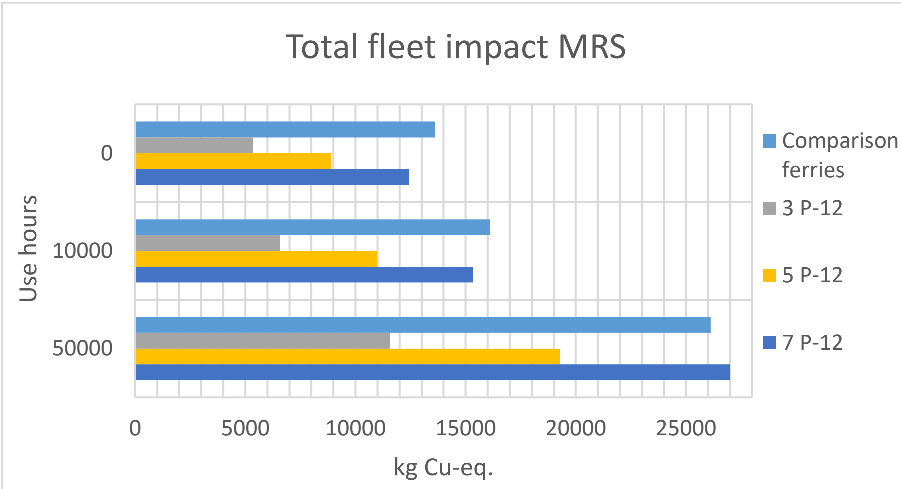


Figure 38: Total fleet impact MRS

Figure 39 shows that the total fleet impact in relation to CED is just as for GWP heavily dominated by the use phase. There is a big difference in impact, when comparing the relation in CED of the fuel consumed in MJ for the different ferries. The P-12 is using 541 MJ per hour driven, whereas the current ferries are using 7600 MJ per hour driven. As such, even if seven P-12´s are applied in the scenario, there is still a higher impact from the current ferries per hour driven.

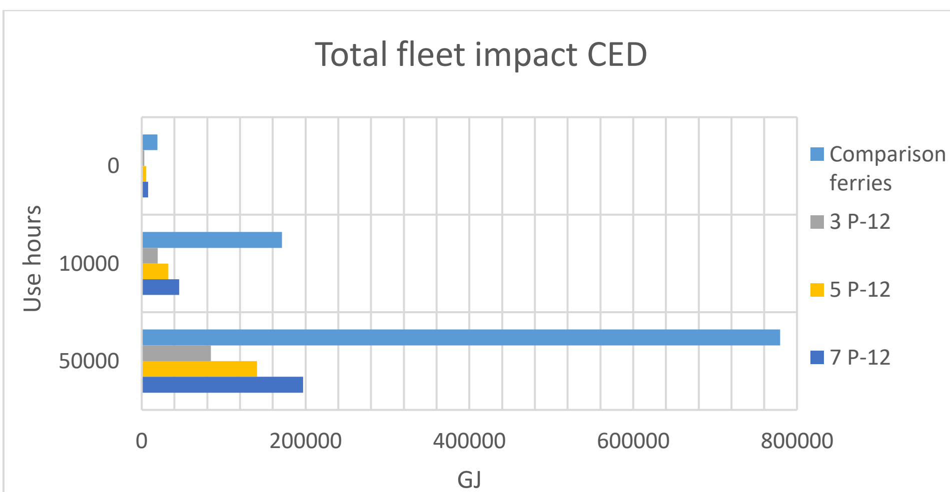


Figure 39: Total fleet impact CED

11.1.4 Impact per passenger km

The impact per passenger kilometer provides the impact per passenger for every kilometer they travel with a specific vehicle. The number is highly dependent on how many hours the ferries will be used during their lifetime. Since the numbers of hours driven throughout the lifetime are uncertain for both ferries, the Table 13 below shows impact per passenger kilometer based on different hours driven. Furthermore, the number represents one ferry, based on its average passenger load, speed and fuel consumption. The details about the calculations can be found in section 15.2.4 in the appendix.

As can be seen in Table 13, the P-12 has a much smaller impact than the current ferries. For example, with an expected running time of 10 000 hours, the P-12 has a reduced impact by 98.4%. When higher estimations on the use hours throughout the lifetime of the ferries are applied, the difference in impact gets bigger. If 40 000 hours is assumed, the mitigated impact from using the P-12 becomes 99.1%. The main reason for the increased relation in impact is linked to the different energy sources used, in combination with fuel consumed per hour driven. Furthermore, the low occupancy rate of 17.3% for the current ferries is a big contributor to the difference in impact between the ferries.

Table 13: Impact per passenger kilometer GWP

	[kg CO_2-eq /passenger-km]	
Hours driven	**P-12**	**Current Ferries**
10 000	0.0206	0.8795
20 000	0.0135	0.8271
30 000	0.0112	0.8096
40 000	0.0100	0.8009
50 000	0.0093	0.7956

11.2 Results based on functional unit 2

For the following use case, the functional unit is to fulfill the service of operating Ekerölinjen, with its current passenger load and travel pattern over 30 years.

The applied case of Ekerölinjen compares the impact in GWP from the use of the current ferries: Sunnan and Lux, in relation to the new scenario where three P-12´s are used. The focus of this scenario comparison is to identify the trend over a whole year and how it will develop over time. For both scenarios, there are changes in the composition of ferries during the winter months compared to the rest of the year. Just as described earlier in the ferry comparison, one of the current ferries is replaced in order to manage the ice on Mälaren. Since the P12´s can't break through ice, the same composition of ferries is applied for the new scenario during the winter months. For the rest of the year (April-Dec), the current scenario consists of Sunnan and Lux and the new scenario consists of three P-12´s.

The estimated trend between the two scenarios can be seen in Figure 40. The impact for the two scenarios stays the same between December and April. However, for the rest of the year, the new scenario will have a mitigated impact, due to the application of the P-12´s.

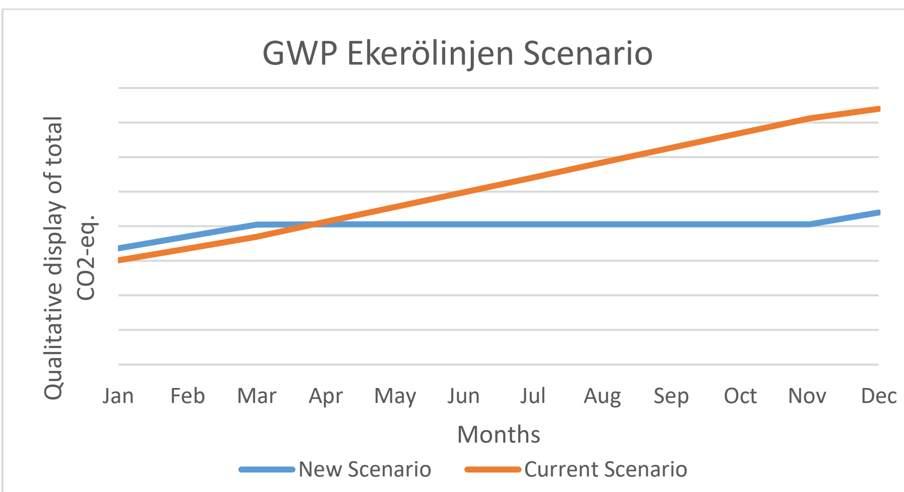


Figure 40: Ekerölinjen Scenario GWP

In order to provide data regarding environmental impact on the scenario comparison, assumptions were made. The replacement ferry in the winter uses a hybrid engine which is assumed to mitigate the combined impact of the ferries by 20%, during the winter months. The number of stops is assumed to be the same as the rest of the year. The manufacturing of the electric hybrid ferry is excluded since it is the same for both scenarios. The results show that the new scenario mitigates the impact from the use phase by approximately 1673 ton of CO_2-eq per year. In the first year, 41% of the impact on GWP is mitigated by implementing the new scenario. However, when observing the impact over 30 years, the total impact is reduced to 69% when the new scenario is applied. The reason for the stagnation in relative impact is due to the winter months, where the same composition of ferries is used for both scenarios.

Table 14: Ekerölinjen scenario impact over years

Years	**Reduced impact**
1	41%
5	62%
10	66%
30	69%

11.3 Sensitivity Analysis

In this section, assumptions used to achieve the result for the ferry comparison are assessed. The focus of the sensitivity analysis is on the occupancy factor for the P-12 since it is based on uncertain variables such as route optimization and the speed of the P-12. The calculated value for the occupancy rate for the P-12 is 40.8% and the data and equations linked to this number can be found in section 15.2.4 in appendix. Furthermore, to investigate how the impact in occupancy rate will affect the relative impact between the current ferries and the P-12, a range between 30% and 70% is applied for the impact per used seat, for all impact categories. Another sensitivity analysis is conducted on the GWP impact per passenger-km. Since its only scenarios based on the current load of Ekerölinjen, the provided occupancy rate for current ferries is deemed as certain. Thus, making a sensitivity analysis less relevant for the current ferries.

As can be seen in Figure 41, the occupancy rate influences the impact per seat for the P-12. However, the trend between the P-12 and the current ferries doesn't change, neither with a 30% nor a 70% occupancy rate.

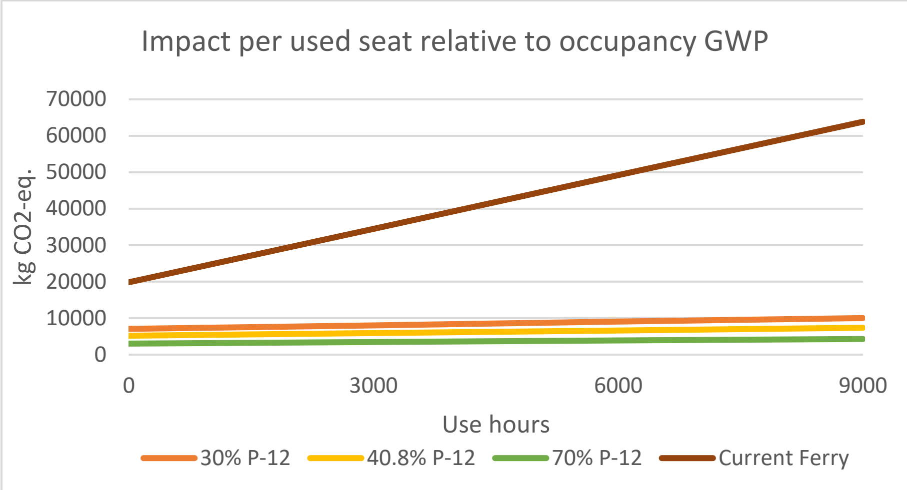


Figure 41: Impact per used seat relative to occupancy GWP

When it comes to MRS, the occupancy rate has a bigger influence on the trend, as can be seen in Figure 42 below. With a 30% occupancy rate, the P-12 surpasses the impact after approximately 3500 hours of running time. However, depending on the optimization of the P-12 routes, the impact with a 70% occupancy rate could reduce the impact to half, in relation to the current ferries.

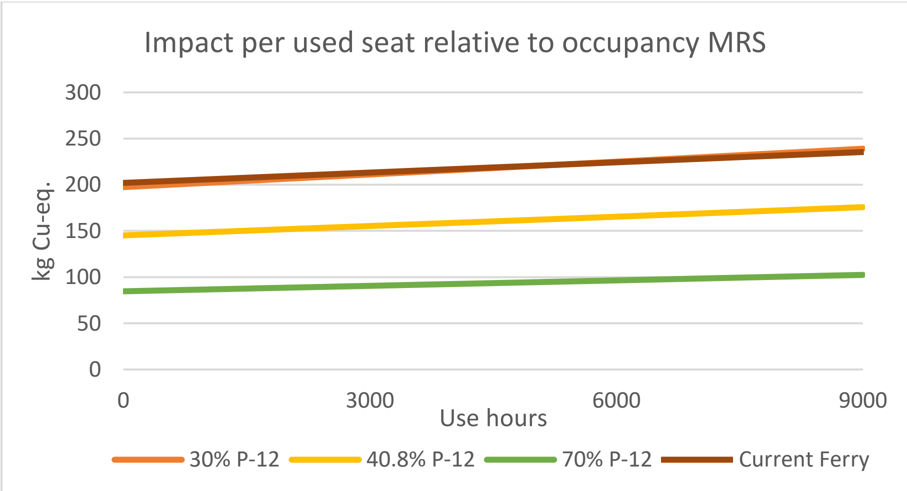


Figure 42: Impact per used seat relative to occupancy MRS

Regarding the CED impact category, the trend is still the same as for base scenario when applying the span of 30 to 70 percent of occupancy rate to the P-12. As can be seen in Figure 43, the slope of the current ferries is still higher, resulting in an increase of the difference in absolute impact for every hour the ferries are used.

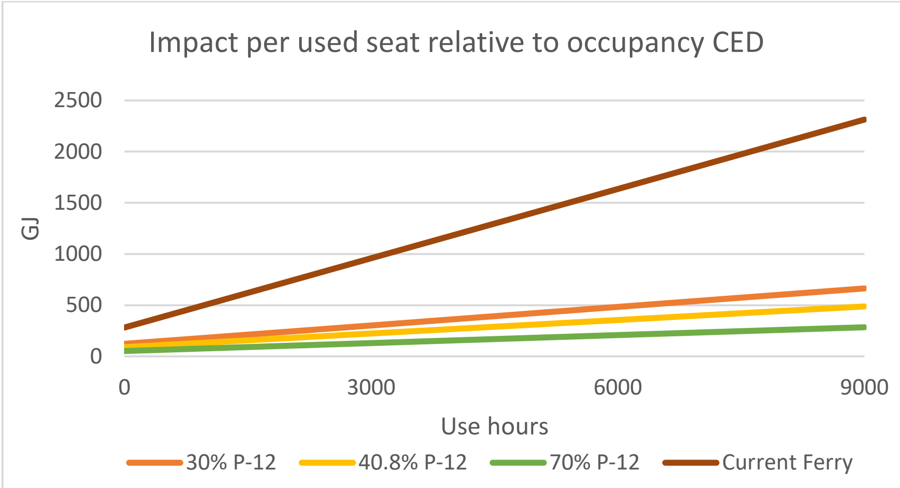


Figure 43: Impact per used seat relative to occupancy CED

Another sensitivity analysis is conducted concerning the GWP per passenger kilometer for the P-12. As displayed in Figure 44, the average number of passengers throughout the lifetime of the P-12 has a big influence on the outcome. When observing the impact after an exptected running time of 40 000 hours for the P-12, the impact with a 30% occupancy rate is 0.014 kg CO_2-eq per passenger kilmoneter, whereas the impact with a 70% occupancy rate is 0.006 kg CO_2-eq per passenger kilometer. In relation to the current ferries, with the use expectancy of 40 000 hours, the mitigated impact is 1.7% with the 30% occupancy rate and 0.7% with a 70% occupancy rate for the P-12. As such, the occupancy rate doesn't have a big influence in relative impact between the current ferries and the P-12.

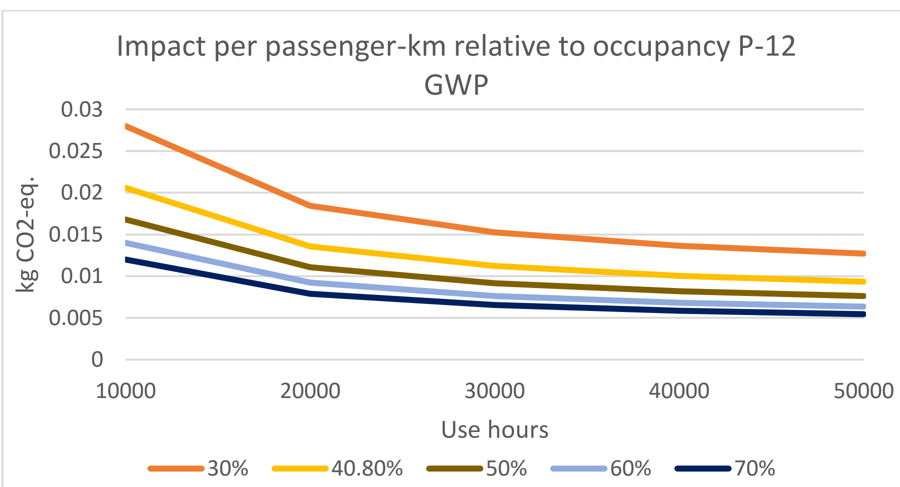


Figure 44: Impact per passenger-km relative to occupancy P-12 GWP

12 Discussion and conclusion P-12

The comparison of the different ferries shows that the P-12 has a lower impact in all three impact categories, except when the impact per available seat is compared for MRS. However, when applying the occupancy-rate related to Ekerölinjen, the P-12 results in less impact for that impact category as well, given that the occupancy rate is over 30%. In relation to GWP, the result shows that the use phase was the main differentiator between the current ferry and the P-12 from a life cycle perspective. This is also concluded in the study by Schmidt and Watson, (2013), where an electric and a fossil driven ferry is compared.

The impact category in which the ferries had the most similar result was MRS. The main reason for this is linked to the high impact from the lithium-ion batteries, for the P-12. The use phase, on the other hand, has a relatively small impact in this category for both ferries. As such, making the battery manufacturing over the lifetime of the P-12 even more significant.

To apply the passenger volume of Ekerölinjen, the occupancy rate was introduced to the calculations. The intention was to draw a more realistic picture of the relation between the emissions per passenger kilometer and the actual occupancy of the boats. As the current ferries have a low average occupancy, the emissions per passenger kilometer are higher in relation to the P-12s'. The sensitivity analysis showed that even with a 30% occupancy rate for the P-12, the reduced impact in relation to the current ferries is 98.3% per passenger-kilometer, for an expected running time of 40 000 hours. The sensitivity analysis further showed that the impact per passenger-kilometer for the P-12 ranges between 0.014 and 0.006 kg of CO_2-eq per passenger kilometer. However, in order to compare these values with other commuting options, it needs to be stated that the nature of the ferry comparison excluded parts in the manufacturing and end of life. Thus, making the value lower, than if a stand-alone analysis was conducted on the ferry. However, even if the impact from manufacturing would be increased by 50%, it would only result in a 16% increase in terms of impact per passenger-kilometer. As such, the impact would still be 84.8% lower than for a bus with an average occupancy of 12 passengers (Hill *et al.*, 2019).

The same principle applies for the current ferries, where around 20% of the weight is excluded. Comparing the current ferries to other transporting options, the impact can be considered high, with 0.8 kg CO_2-equivalents for 40 000 hours driven. Key parameters influencing this value are speed, occupancy rate, and fuel consumption. E.g., with an estimated occupancy rate of 100%, the impact per passenger-kilometer would be reduced to 0.137 kg of CO_2-eq.

The applied scenario shows that utilizing three P-12´s to fulfill the function of Ekerölinjen will mitigate the environmental impact in relation to GWP by 1670 tons for CO_2-eq per year. The limiting factor for increasing mitigation further comes down to the two scenarios running the same composition of ferries during the winter months. However, in the months between April and December, the difference in environmental impact becomes relevant. To put the tons of mitigated CO_2-eqivalents into perspective, it only takes 1.5 months for the new scenario to break-even with the manufacturing and end of life for the three P-12´s added to the fleet. The difference in fleet impact over time further emphasizes the advantages of the P-12´s. From a manufacturing perspective, it becomes clear that the P-12 is of a more suitable size for Ekerölinjen, which makes it possible to implement additional ferries and still mitigate the environmental impact, in relation to the current scenario.

Wang *et al.*, (2021) concluded in their comparison between an electric and fossil drivetrain on the same ferry in the UK, that a 30% reduction in GWP would occur if an electric drive train would be implemented. The result from the P-12 comparison and the currently used ferries shows that a reduction of 99.3% would take place if the same amount of use hours where assumed. The reason for the difference in mitigated impact can be linked to the increased efficiency from the hydrofoils, the Swedish electricity mix, and the size difference between the current ferries and the P-12s.

Compared to previous research, this study contributed to increased knowledge in the difference of the environmental impact between diesel driven and electric driven ferries of different sizes. It can be concluded that the P-12 is more environmentally friendly in all three impact categories in comparison to the current ferries on Ekerölinjen, if the occupancy rate is considered. Even though the ferry comparison is related to the case of Ekerölinjen, the difference of the total life cycle impact on GWP and CED from the use phase, shows the general difference in impact between electric and diesel driven ferries. The result can therefore suffice as an incentive for policy makers and public transport providers who want to act and reduce the environmental impact within the ferry sector. There are several variables that makes the P-12 a favorable option. The size of the P-12 is more adapted to the current passenger load on Ekerölinjen, which in combination with an increased speed makes it possible to carry out the service on Ekerölinjen with three P-12 ferries used. The main advantage for the P-12 is shown in the use phase, where the combination of hydrofoils and the electric propulsion system reduces emissions significantly.

12.1 Uncertainties

The fuel consumption of the current ferries was set to be 180 liters per hour driven, which is the numbers provided by the engine specifications when the higher rounds-per-minute values are applied. As such, assumptions are made that the engine is used on a nearly full capacity in order to achieve the speed of 10.5 knots. The range in fuel consumption ranges from 140-200 liters per hour for the engines in the current ferries. However, the impact of fuel consumption is significantly higher than the emissions resulting from electricity use. As such, the trends would stay the same, regardless of the exact fuel consumption.

Due to the lack of information regarding the material compositions of the current ferries Sunnan and Lux, the material share from another ferry was applied. As such, the share of the different components does not precisely reflect the current ferries. Furthermore, the weight of the applied ferry was almost the double of Sunnan and Lux, which could contribute to inaccurate values for parts such as the batteries, when scaled down. The applied ferry uses steel as a material for the structural components, whereas Sunnan and Lux are using aluminium. A material transformation was therefore conducted, in order to get a sufficient share of the weight for the structural components, which also increases the uncertainties.

Even though several topics of uncertainness are presented in the manufacturing part of the current ferries, the impact of that phase is relatively small compared to the use phase. After 20 000 hours driven, the manufacturing only contributes to 6.3% of the total emissions concerning GWP. As such, the overall picture can still be provided, regardless of the uncertainties in the manufacturing.

12.2 Further research

A more detailed insight in the life cycle of the C-8 could be provided by conducting a LCA study solely on the boat as an extension to the comparative approach of this study. This can lead to further understanding of the environmental hotspots of the boat and improvements e.g., concerning material choices could be made.

13 Declaration of competing interests

This thesis work was conducted as a master's degree project in cooperation with Candela Technology AB, which financially supported the project. However, no employment exists between the authors and the company.

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15 Appendix

The appendix is divided into two sections. In section 15.1 the data regarding the leisure boat comparison is presented, whereas section 15.2 includes the data and calculations used in the ferry comparison.

15.1 Leisure boat comparison

The appendix of boat comparison will be divided into the three subtopics Manufacturing, End of life, and Use phase

15.1.1 Manufacturing

In the following paragraphs, the underlying data for the manufacturing of the boats and the references are displayed to provide a better overview of the underlying data.

CFRP

The CFRP is a product consisting of two main materials: Carbon fiber and epoxy resin. Carbon fiber was not available in Ecoinvent. As such, it was created as an own material. The data used can be found in Table 15.

Table 15: Carbon fiber material composition

Component	**Specific**	**Amount per kg**	**Source**
Pan Nitrogen	Methyl acrylate {GLO}| market for | Cut-off, U	0.16	(Saeed *et al.*, 2008)
	Acrylonitrile {GLO}| market for | Cut-off, U	1.66	(Griffing, 2009)
	Total amount of PAN	1.82	(Griffing, 2009)
Water	Water, deionised, from tap water, at user {RoW}| market for water, deionised, from tap water, at user | Cut-off, U	2.88	(Griffing, 2009)
Sulfuric acid	Sulfuric acid {RoW}| market for sulfuric acid | Cut-off, U	0.02	(Griffing, 2009)
Nitrogen	Nitrogen, liquid {RoW}| market for | Cut-off, U	9	
Manufacturing	**Process**	**MJ**	
Steam	Heat, from steam, in chemical industry {RoW}| market for heat, from steam, in chemical industry | Cut-off, U	3.1	(Griffing, 2009)
Electricity	Electricity, medium voltage {RoW}| market for | Cut-off, U	6.99	

The data used to model CFRP can be found in Table 16, below. In the model of CFRP, a mixture of epoxy resin and carbon fiber was used. The manufacturing process used to create the CFRP is called vacuum infusion.

Table 16: CFRP assembling data

Component	**Specific**	**Amount of component needed per kg CFRP produced**	**Source**
Epoxy resin	Epoxy resin, liquid {RoW}, liquied	0.4	Candela
Carbon fibre	Own creation	0.6	-
Manufacturing	**Energy type**	**Amount of energy needed [MJ] per kg CFRP produced**	**Source**
Vacuum infusion	Electricity, low voltage {SE}| market for | Cut-off, U	1.1	(Önal, 2013)

GFRP

GFRP was available in Ecoinvent and therefore taken from Ecoinvent directly. Combined with the energy needed, which is based on literature findings, the GFRP assembling process is displayed in Table 17.

Table 17: GFRP assembling data

Component	**Specific**	**Amount per kg**	**Source**
GFRP	Glass fiber reinforced plastic, polyester resin, hand lay-up {GLO}| market for | Cut-off, U	1	Ecoinvent
Manufacturing	**Energy type**	**MJ per kg**	**Source**
Vacuum infusion	Electricity, low voltage {SE}| market for | Cut-off, U	1.1	(Önal, 2013)

Aluminium

Wielding and cutting were excluded in the manufacturing process due to lack of data. As such, sheet rolling was the only manufacturing process included for the aluminum parts of the petrol boat, as can be seen in Table 18.

Table 18: Aluminium assembling data

Component	**Specific**	**Amount per kg**	**Source**
Aluminium AlMg3	Aluminium alloy, AlMg3 {GLO}| market for | Cut-off, U	1	(Candela Technology AB, 2022)
Manufacturing	**Energy type**	**MJ per kg**	**Source**
Sheet rolling, aluminium {RER}| processing | Cut-off, U	Electricity	1.97	Ecoinvent
	Heat	1.91	Ecoinvent

15.1.2 Material transformation

The weight of the structural components for the comparison boats were assessed by multiplying factors for strength and density differences for the applied materials. When relating GFRP to CFRP, Potluri and Ketha (2015) state that GFRP is about 30-34% heavier. As such, GFRP was set to have a 30% higher weight in the SimaPro model. When comparing the strength and density properties of aluminum to CFRP, it was concluded by Hovorun *et al.* (2017) that aluminium increases the weight by 41%, which is also applied in this study. The weight of the different components can be found in Table 19, below.

Table 19: Material weights of different structural components

Material	**Weight [kg]**
CFRP	602.1
Aluminium	848
GFRP	781.8

Structural components for the C-8

Table 20 shows the parts and material used for the structural components of the boat.

Table 20: Structural components Candela C-8

Component	**Parts**	**Material**	**Source for weight and material**
Structural components	Hull Deck Consoles Stringer system Liners	CFRP	Candela
Hydrofoils	Front foil Front strut Front bulbs Aft foil Rudder	CFRP	Candela
	FWD aoa actuators FWD lock actuator Aft retraction actuator Aft lock actuator FWD retraction motors	Electric motor, vehicle {GLO}| market for | Cut-off, U	Candela
	Aft pitch spring steel	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U	Candela
	Rudder head box Rake box	Aluminium alloy, AlLi {GLO}| market for | Cut-off, U	Candela
	Sliders	Tetrafluoroethylene {GLO}| market for | Cut-off, U	Candela
Engine	Electric motor	Electric motor, vehicle {GLO}| market for | Cut-off, U	Candela
	Housing	Bronze {GLO}| market for | Cut-off, U	Candela
	Propeller	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U	Candela
	Shaft	Steel, low-alloyed {GLO}| market for | Cut-off, U	Candela
Battery	Lithium-ion battery	Battery, Li-ion, rechargeable, prismatic {GLO}| market for | Cut-off, U	Candela

Structural components for the petrol boat

Table *21* shows the parts and material used for the structural components of the petrol boat.

Table 21: Structural components petrol boat

Component	**Part**	**Material**	**Source for weight and material**
Structural components	Hull Deck Consoles Stringer system Liners	Glass fibre reinforced plastic, polyester resin, hand lay-up {GLO}| market for | Cut-off, U Or Aluminium alloy, AlMg3 {GLO}| market for | Cut-off, U	Material transformation
Engine	Petrol engine	Marine engine {GLO}| marine engine construction | Cut-off, U	Weight from a 300 hp engine on the market
	Propeller	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U	Same as for the C-8
	Shaft	Steel, low-alloyed {GLO}| market for | Cut-off, U	
Battery	Deep cycle battery Starting battery	Battery, Li-ion, rechargeable, prismatic {GLO}| market for | Cut-off, U	Weights from two 12V, 100 Ah batteries was chosen

15.1.3 End of life treatment

The end of life treatment for the different boat types are gathered in Table 22, below. The treatment processes used is a combination of own created and retrieved processes from Ecoinvent. Processes from Ecovinent are used for the waste management linked to batteries and engines, whereas recycling of metals such as steel, aluminium and copper were created. Furthermore, according to Damgaard, Larsen and Christensen (2009), the emissions related to the sorting of materials are deemed neglectable. As such, only recycling processes are included.

Table 22: End-of-life treatment of boat types

Material	**Treatment**	**Specific**	**Source**
CFRP and GFRP	Landfill	Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Cut-off, U	(Moreau, 2009)
Steel	Recycling- own creation in SimaPro	Electricity, medium voltage {SE}| market for | Cut-off, U 11.7GJ/ton	(Bureau of International Recycling, 2008)
Aluminum	Recycling- own creation in SimaPro	Electricity, medium voltage {SE}| market for | Cut-off, U 5 GJ/ton	(Milford, Allwood and Cullen, 2011)
Petrol Engines	Recycled	Used internal combustion engine, from passenger car {GLO}| market for used internal combustion engine, passenger car | Cut-off, U	(Stena Recycling, 2022)
C-Pod	Recycling	Used powertrain from electric passenger car, manual dismantling {GLO}| market for | Cut-off, U	(Stena Recycling, 2022)
Battery	Mix of hydro and pyro	Used Li-ion battery {GLO}| treatment of used Li-ion battery, hydrometallurgical treatment | Cut-off, U But with Swedish electricity in the process to assume recycling in Sweden	(Yonglin *et al.*, 2018)
Copper	Recycling- own creation in SimaPro	Electricity, medium voltage {SE}| market for | Cut-off, U 6.4 GJ/ton	(Bureau of International Recycling, 2008)
Bronze	Recycling- own creation in SimaPro	Electricity, medium voltage {SE}| market for | Cut-off, U 6.4 GJ/ton	Assumed to be same as copper due to the high share of copper

15.1.4 Use phase data

The energy sources used for the different boats have a vital impact on how converted energy from fuel to power will affect the environmental impact. The candela C-8 runs on electricity and the comparison boat on petrol.

Candela C-8

The impact from the electricity use is directly linked to the electricity mix in the country where the boat is located and charged. The Swedish electricity generation mix is in majority dominated by hydro power, nuclear power and wind power (IEA, 2022a).

Petrol boat

The most common contributions to the GHG-emissions from recreational boats are carbon dioxide (CO_2), nitrous oxide (N_2O), carbon monoxide (CO) and volatile organic compounds (VOC) (Burke *et al.*, 2021). In order to calculate the emissions from the use phase of the petrol boats, a fuel combustion process was created. The process uses average data of the mentioned gasses, with additions, for the combustion of petrol in leisure boats can be seen in Table 23 below (Jun, Gillenwater and Barbour, 2021).

Table 23: Emissions related to one kg petrol combusted in a recreational boat

Gas	**g/kg fuel**
Carbon dioxide (CO_2)	3200
Carbon monoxide (CO)	1000
Non-Methane Volatile Compounds (NMVOC)	34
Methane (CH_4)	1.7
Nitrous oxide (N_2O)	0.08
NO_x	9.7

In order to validate the own created combustion process, based on Table 23, a comparison was conducted. The petrol combustion processes Euro 5 vehicle standard, Euro 3 vehicle standard, and petrol burned my machinery was included, in order to investigate if the own created process would show a deviating result. As can be seen in Figure 45, the own created process follows the same trend as the other processes. The result shows that the own created combustion process has the highest impact in GWP. However, the reason for it having a lower impact on most of the impact categories except for GWP is because of a share of the infrastructure construction of the other processes are imbedded in their emissions.

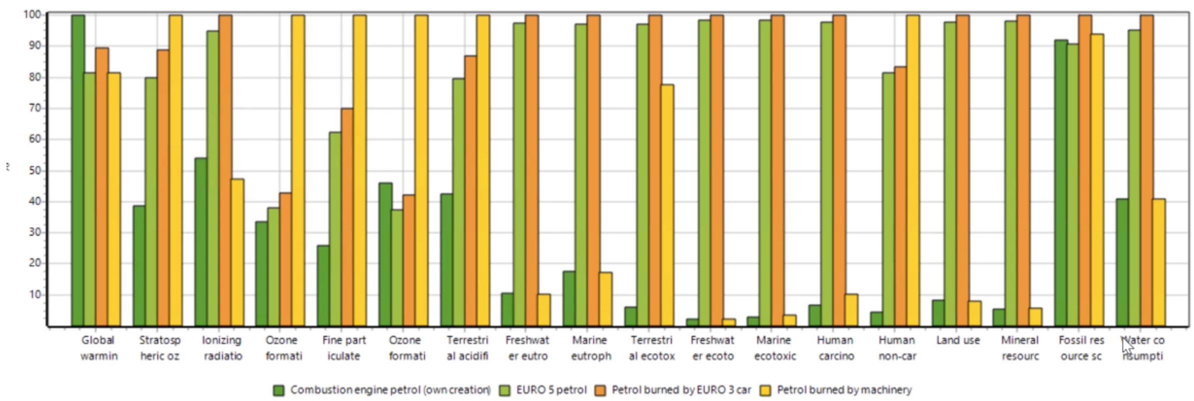

Figure 45: Impact comparison of different petrol combustion processes

To calculate the amount of petrol used of 30 years, the total amount of liters was converted into MJ, in order to suffice as input to the life cycle model to SimaPro. The variables needed to retrieve the fuel consumption can be found in Table 24.

Table 24: Use phase data

Variables	**Amount**	**Reference**
Lifespan	30 years	-
Fuel consumption	50 [liter/hour]	-
Hours driven per year	50 hour/year	-
Energy density of petrol	45 [MJ/kg]	(World Nuclear Association, 2022)
Density of petrol	0.73 [liter/kg]	(Abd *et al.*, 2018)
Oil change rate	1/100 [hours driven]	Assumption
Density of oil	0.87 [kg/l]	(Maharjan *et al.*, 2020)
Oil tank	7 [l]	(Quicksilver - Marine Parts & Accessories, 2017)

The equation displays how the total amount of petrol used over a lifespan of 30 years was calculated, expressed in MJ.

$$Amount\ of\ petrol\ = 50\ \left[\frac{liter}{hour}\right] \cdot 50\ \left[\frac{hours}{year}\right] \cdot 30\ [years] \cdot 0.73 \left[\frac{kg}{liter}\right] \cdot 45 \left[\frac{MJ}{kg}\right]$$
$$= 2463750\ [MJ]$$

The equation for the amount of oil used over the span of 30 years in kilograms can be seen below.

$$Amount\ of\ oil = 7[l] \cdot \frac{1}{100}[hours] \cdot 30[year] \cdot 50 \left[\frac{hours}{year}\right] \cdot 0.87 \left[\frac{kg}{[l]}\right] = 91.35\ [kg]$$

The calculation for electricity consumption of the C-8 over the span of 30 years can be found in the equation below.

$$Amount\ of\ electricity\ = 50\ \left[\frac{hours}{year}\right] \cdot 30[years]\ \cdot 22[kWh] = 33000\ [kWh]$$

15.2 Ferry comparison

The appendix related to ferry comparison consists of four subchapters: Manufacturing, Use phase, End of life, and impact calculations.

15.2.1 Manufacturing

The components and materials used to create the P-12 are the same as for the C-8. The weight of the different components of the P-12 were retrieved from Candela. The specific materials used for the P-12 can be found in Table 20, in section 15.1.2.

In order to get a realistic weight share for different components in the current ferries, an existing ferry from a report by Schmidt and Watson (2013) was used. The known data for Sunnan and Lux were the weight of the engines and the total weights of the boats. All the components of the existing ferry were divided into the categories: structural components, battery, and others, except for the engines. Since their share of the total weight was already known. The category "others" represented components which were excluded from the comparisons, see section 4.2 Cut-off criteria. The weights used to get the share of weight for different components can be found in Table 25.

Table 25: Weights of the existing ferry

Components	**Weight [ton]**	**Source**
Structural components (alu)	215.1	(Schmidt and Watson, 2013)
Batteries	0.9	
Engines	Weights of the current ferries in use were utilized	
Others	32.3	
Total	248.3	

A material transformation was then conducted, in order to get a value for aluminum instead of steel. According to Tisza and Czinege (2018), there is a possible weight reduction of 40% if aluminium is used instead of steel by taking the relative strength and density of the materials into consideration. The data in Table 26 below is the one applied to the ferries. The weight of the two Scania engines was fixed to 2.6 tons, whereas the share of the structural components and the batteries were scaled in relation to the weight of Sunnan and Lux.

Table 26: Average weight of components for Sunnan and Lux

Components	**Weight [ton]**
Structural components (Aluminium)	81.1
Batteries	0.6
Engines	2.6

The components used to create the comparison ferries can be found in Table 27.

Table 27: Components, parts, and materials of the current ferries

Component	**Part**	**Material**	**Source of weights**
Structural components	Hull Deck Consoles Stringer system Liners	Aluminium alloy, AlMg3 {GLO}| market for | Cut-off, U	Material transformation
Engine	Marine diesel engine	Marine engine {GLO}| marine engine construction | Cut-off, U	(Scania, 2022)
Battery	Deep cycle and starting battery	Battery, Li-ion, rechargeable, prismatic {GLO}| market for | Cut-off, U	Material transformation

15.2.2 End of life

The end of life treatment of the ferries is assumed to be conducted in the same way as the C-8 and the petrol boats. As such, more detailed information about how different materials are managed can be found in section 15.1.3.

15.2.3 Use phase

The data that was used to calculate the environmental impact in Ecoinvent can be found in Table 28.

Table 28: Use phase data for the current ferries

Variables	Amount	Reference
Fuel consumption of two engines	160 [liter/hour]	(Scania, 2022)
Energy density of diesel	35.5 [MJ/l]	(Energimyndigheten, 2021)
[redacted]		
Combustion process	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | Cut-off, U	Ecoinvent
[redacted]		
Oil change rate	1/600 [hours driven]	(MAN, 2022)
Density of oil	0.87 [kg/l]	(Maharjan et al., 2020)
Oil tank of two engines	62 [l]	(Scania, 2022)

The equation below describes how the input for the combustion of the total amount of petrol used per hour driven was calculated, expressed in MJ.

$$Diesel\ per\ hour = Fuel\ consumption[l] \cdot Energy\ density\ of\ fuel\ \left[\frac{MJ}{l}\right] = 160\ [l] \cdot 35.5\left[\frac{MJ}{l}\right] = 5680\ [MJ]$$

The equation for the amount of oil used per hour driven can be seen below.

$$Oil\,per\,hour = 62[l] \cdot \frac{1}{600}[hours] \cdot 0.87\left[\frac{kg}{l}\right] = 0.09\,kg$$

15.2.4 Impact calculations

I this section, data used, and calculations needed for creating the result in the ferry comparison are explained. The data used to calculate occupancy rate, impact per seat, impact per occupied seat, and impact per passenger-kilometer can be found in Table 29.

Table 29: Data used for the impact calculations

Variables	**P-12**	**Sunnan and Lux**	**Source**
Speed [kn]	20	10.5	Candela
Capacity	30 passengers	Average of 195 passengers	Candela & (Skärgårdsbåtar, 2022b) (Skärgårdsbåtar, 2022a)
Passenger load Ekerölinjen	130 000		Candela
Number of boats	3	2	Candela
One-way trips per year	10609	3858	Candela

Occupancy rate:

The occupancy rate for the P-12 and the current ferries were based on a number of different variables, such as speed, number of boats, passenger load of Ekerölinjen, and stops per year. The data used for the different boats is displayed in Table 29. In order to get the occupancy rate for the ferries, the total number of one-way trips per was be calculated. The equation below, is based on the assumption that three P-12´s runs in the same pattern as the current ferries. Thus, making the number of stops increase due to more boats running than in the current scenario with a higher speed.

$$Trips\ per\ year_{P-12} = \frac{Speed_{P12}}{Speed_{current}} \cdot \frac{Amount\text{ of P 12s}}{Amount\text{ of current ferries}} \cdot Trips\ per\ year_{current}$$

The occupancy rate for the different ferries was based on the relation between the passenger load of Ekerölinjen, the number of trips for each type of ferry per year, and the passenger capacity of that ferry, as can be seen in the following equation.

$$Occupancy_x = \frac{Passengers_{Eker\ddot{o}linjen}}{Capacity_x \cdot Trips_x}$$

The output of the equation results in an occupancy rate of 40.8% for the P-12 and 17.3% for the current ferries.

Impact per passenger-kilometer

The variables used for calculating the impact per passenger-kilometer are passenger capacity, occupancy rate, and the environmental impact from manufacturing, end of life and the use phase. How the variables are applied can be seen in the equation, below

$$Impact\ per\ passenger - kilometer = \frac{(Manufacturing + EOL + Use_{total})}{Occupancy * Capacity * kilometers_{\mathrm{total}}}$$

Impact per seat

The impact per seat is based on the manufacturing, end of life, and use phase on the boats, in relation to the passenger capacity on the boats, as can be seen in the calculation below.

$$Impact_{per\ seat} = \left(Manufacturing + EOL + \frac{impact}{hour\ drive} \cdot hours\right)\frac{1}{Capacity}$$

Impact per occupied seat, relates the used seats to the total capacity of the boats, as can be seen in the following equation.

$$Impact_{used\ seat} = \left(Manufacturing + EOL + \frac{impact}{hour\ drive} \cdot hours\right)\frac{Used\ seats}{Capacity}$$

15.3 SimaPro model Candela C-8

The following Figure 47 shows the different components and assemblies of the model of the Candela C-8 in SimaPro. Displayed here are the GWP emissions, and their contribution of the different parts can be assessed in the thickness of the red lines. The meaning of the color of the boxes in Figure 47 and Figure 48 is described in Figure 46, which displays the legend of colors for different processes in SimaPro.

Figure 46: Legend of SimaPro models

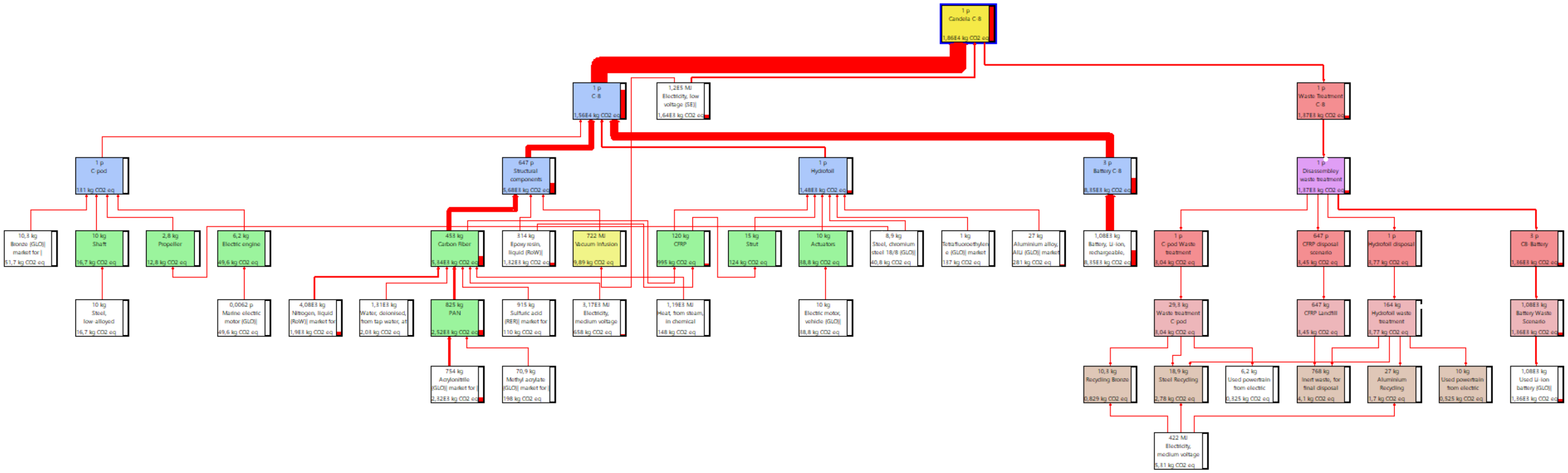

Figure 47: SimaPro model Candela C-8

15.4 SimaPro model comparison petrol boat GFRP

The GFRP petrol model is similar for the aluminium boat, except for the structural components consisting of aluminium instead. It is therefore only the GFRP model displayed here in the following Figure 48.

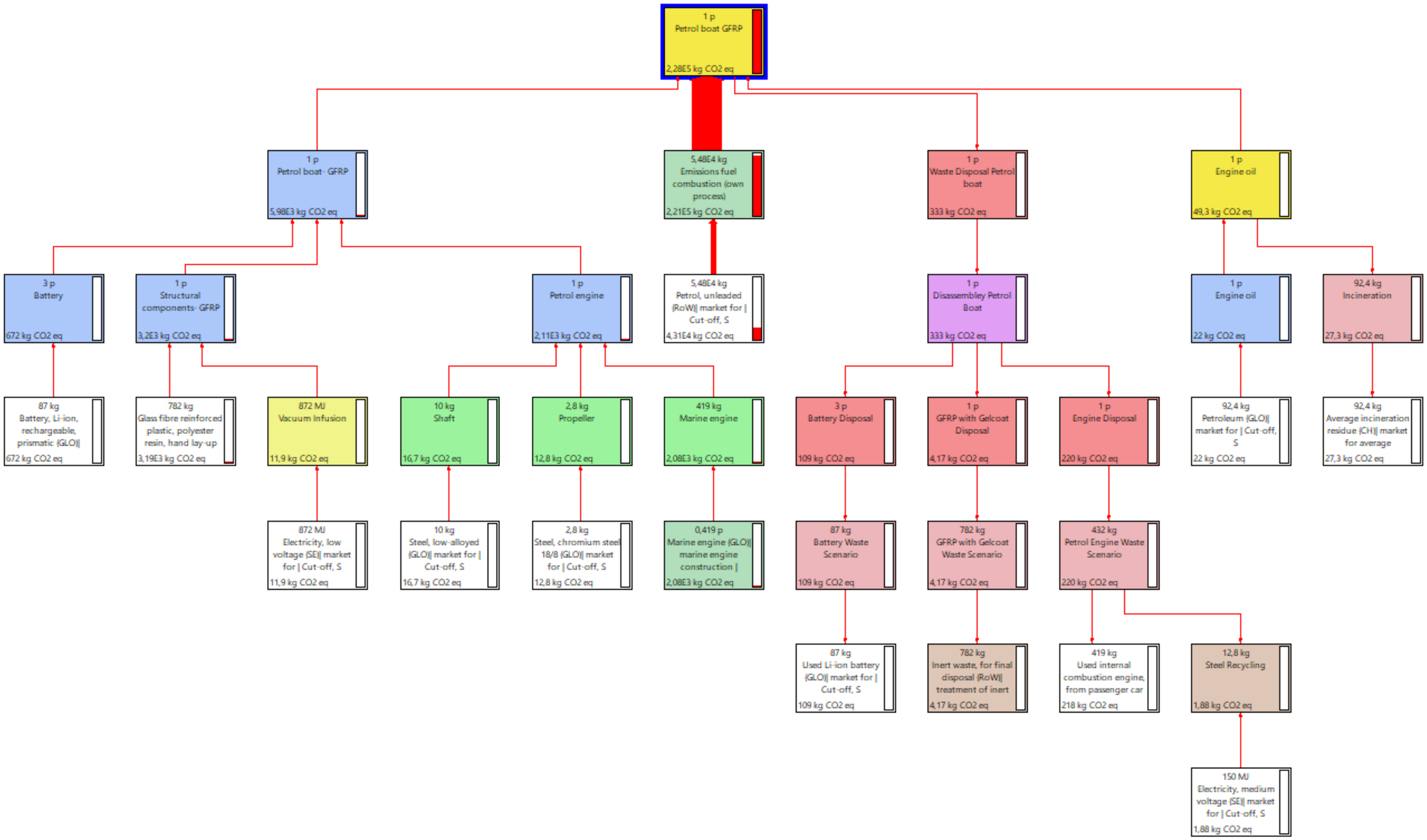

Figure 48: SimaPro GFRP boat