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Investigating the potential circularity of a motorboat using Life Cycle Assessment

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1 Introduction

Sweden has one of the highest number of boats per capita in the world, ranking in the top four countries (Group, 2015). Two million people in Sweden have access to the estimated fleet of 880,000 leisure boats in Sweden. The market for boats in Sweden has been grown since the 1920's, nearing its peak in the 1980's (Group, 2015).

This report focuses on small recreational boats of approximately 10 metres. At this length, over 70% of boats are constructed from glass reinforced polyester (GRP), a thermoset polymer composite. It has a high strength to weight ratio and is a long living material, resistant to the marine environment. Therefore, it is common that well-maintained boats manufactured in the 1970s are still operational today. However, some of these are reaching the end of their operational life and their recycling disposal is an environmental challenge due to their size and material composition. They are difficult to dismantle and recycle, particularly the GRP, which is typically incinerated. In addition, it is necessary of today's boats to be designed with the circular economy in mind, so that they are more conducive to refurbishment, reuse and recycling.

Several institutions and organizations are focusing on environmental issues of recreational boating. These include the International Maritime Organisation (IMO) and the United Nations Environment Programme (UNEP). In parallel, the European Union has set out strategies for the protection (Moreau, 2009). Boating activity can have a direct impact on sensitive ecosystems, whilst at the same time, a high environmental quality is desired by its users. One of the most responsible and comprehensive methods for evaluating the environmental impacts of a product or service, is the life cycle assessment (LCA). In this methodology, the environmental impact is considered from the extraction of raw materials, production, use, through to disposal. A key task of LCA is often to identify the hotspots of environmental impact, which can be a particular life cycle phase, a material or a component.

This report presents research on utilising LCA to understand the environmental impacts of a leisure motorboat in order to incorporate this information into a circular economy model (CE-model). The CE-model is a general equilibrium model that analyses how market actors and outcomes (i.e. raw material extraction, material flows and emissions) react to changes in policy instruments along the product life cycle. The overall project aim of the POLICIA project is to combine these models into an integrated assessment that will be able to address market failures and quantify policy effects of efficient combinations along the entire life-cycle of a certain product, from raw material extraction, production, consumption and waste management to recycling, reuse and remanufacturing.

The aim of the LCA work was therefore to enable the information and knowledge obtained through an LCA of a motorboat, to be incorporated into the CE-model, so that environmental impacts of policies can be directly modelled and optimised.

1.1 About this report

The research presented in this report therefore focused on the first part of this research task. First an initial base case LCA of a representative motorboat (Nimbus 305) was performed to identify hotspots of environmental impacts. Based on the identified hotspots, scenarios were developed and modelled for comparison with the base case. The scenarios are based on potential business models which focus on potential strategies to lower the environmental impacts of the boat throughout the life cycle. The quantification of impacts for the materials and components of the boat across the life cycle provides the knowledge to developed equations that can then be integrated into the economic based policy CE-model. For this purpose, the variables for integration were chosen and formulas developed for the integration.

The report is structured as follows:

- It begins with a literature review that covers the state of the art in knowledge on environmental impacts of the motorboat.
- The LCA method and assumptions are presented in the main report so that they are accessible to non-LCA practitioners, but the report also contains several appendices that will deepen the knowledge of the modelling choices and boundaries of the LCA. The information in the appendix are mainly targeted towards LCA practitioners and included for the purpose of review, reproducibility and transparency of data.
- Scenarios setting and business model assessments follow with the base case hotspots finding. The final part is the integration of LCA and CE-model.

1.2 What is Life Cycle Assessment - LCA?

Life cycle assessments (LCA) investigate the environmental impacts related to a product or a system during its whole life cycle. This includes evaluating energy and resource consumption as well as emissions, from all life cycle stages including; material production, manufacturing, use and maintenance, and end-of-life. A schematic overview of a life cycle is shown in Figure 1.1 .

LCA is a widely used and accepted method for studies of environmental performance of various products and systems, for more details on how an LCA is performed and what parts it contains, see Appendix A.

The LCA in this report is performed in accordance with ISO 14040:2006 and ISO 14044:2006 standards.

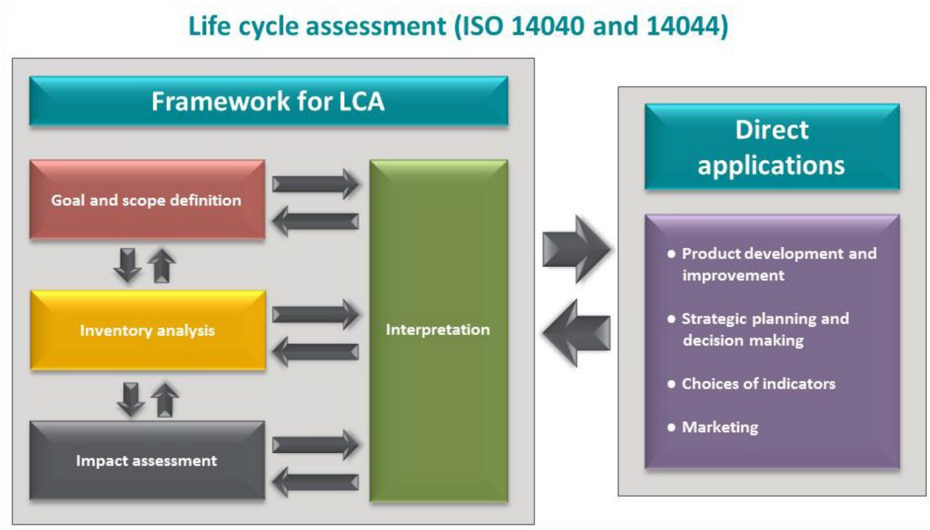


Figure 1.1 Illustration of the LCA system

2 Background and Literature review

This section provides an overview of the available literature related to the environmental impacts of a motorboat intended for recreation. The main environmental impacts can be divided into the life cycle phases:

- Raw materials and construction – boats are typically constructed of glass fiber reinforced polyester for the hulls and tops, and contain components such as wood, engine, electronics and furniture.
- Use phase and maintenance – including the fuel used, maintenance requirements, and anti-fouling paints.
- End-of-life and disposal – disposal of the boat materials for recycling, incineration or landfill disposal.

These will be discussed in the following sections.

2.1 Raw materials and construction

Glass reinforced polyester (GRP) is a thermoset polymer composite and is the dominate material used in the construction of boat. It has advantages compared to alternatives as it is a long living material, resistant to the marine environment and has a high strength to weight ratio (Önal and Neşer, 2018). In boat building under 50 m of length composite materials account for over 70% of the share in materials used with a market of around 200,000 tonnes in 2018 (Neşer, 2017)

In the production phase, impacts are primarily the result of energy (electricity), transport and raw material manufacture. There are two primary techniques for boat building, namely the Hand Lay-up Method (HLM) and Vacuum Infusion Method (VIM). Whilst the latter of which requires much more energy, it has lower occupational risk due to less human contact and lower resin use. (Önal and Neşer, 2018).

However, Cucinotta et al. (2017) used LCA to demonstrate that with a 9% reduction in hull weight due to the VIM, the fuel consumption would be reduced by 656 t of diesel fuel over the lifetime.

Moreau et al. (2009) compare three different construction materials used in the production of a catamaran as shown in Table 2.1. The reduced weight of the composite boat together with a smaller engine resulted in a 52% reduction in fuel consumption in the study.

Table 2.1 Comparison of different materials and the life cycle impacts for a catamaran

Comparison for the production of a catamaran:

Body Production with Material input (T/body)	Composite Version	Steel Version	Aluminium Version
Abiotic Raw Materials	22,6	39,4	68,6
Water	641	337	2194
Air	9,9	14,1	22,2

Comparison for the life time of a catamaran:

Usage Phase Material input (T/25 years)	Composite Version	Steel Version	Aluminium Version
Abiotic Raw Materials	9 997	20 981	20 981
Water	58 082	121 900	121 900
Air	27 851	58 453	58 453

Research on natural composites has increased in recent years, due to the use of fossil fuels as raw materials in GRP production and the poor recyclability at the end of life (Deng and Tian, 2015). One example is the use of corn-starch based bioplastic combined with natural fibres such as cotton, jute, hair and wool (Jethoo, 2019) .However, one of the main drawbacks in the use of bio-composites is the high moisture absorption and low impact strength (Kuciel et al., 2010).

2.2 Use phase and maintenance.

The two main concerns during the use phase are fuel use and anti-fouling paints. There are several risks of pollution during the use phase of boats, primarily from the use of hydrocarbon fuel that include (Moreau et al., 2009):

- Use of marine engines (e.g. unnecessary idling, or running at full throttle)
- Fueling (e.g. spilling of fuel)
- Poor operation and maintenance of marine engines (e.g. not following manufacturer's maintenance schedules)
- Legal oil discharges
- Engine oil
- Oily water discharge
- Tank washing

Other impacts includes sewage discharges, noise and municipal solid waste that might be disposed intentional or accidentally into the marine environment (Moreau et al., 2009).

2.2.1 Fuel use

Fuel used in boats is typically diesel or petrol and has environmental impacts from GHG emissions and emissions of toxic elements to water. In the majority of engine designs the exhaust emissions from the engines is emitted to the water to reduce the potential for a back draft to the passenger craft. A significant amount of power is needed to drive boats through the water, requiring much more fuel than a typical modern car engine. One-hour operation of a boat has similar emissions to about fifty cars travelling at a similar speed [1].

However, the consequences of these emissions to water appears to be poorly understood and researched. One Dutch study estimated the amount of emission in kg/year for all recreational boats, based on activity rate as shown in Table 2.2.

Table 2.2 Direct emissions into water from recreational boats (kg/yr)

Substance\Year	1985	1990	1995	2000	2005	2006
Particulates	19,140	18,895	20,665	21,671	20,920	20,733
VOC	1,958,540	1,973,542	2,207,685	2,250,685	1,962,320	1,856,131
Benzene	21,398	21,515	24,011	25,902	25,122	24,258
Toluene	61,464	61,872	69,136	73,913	70,440	67,496
1.3-butadiene	3,576	3,595	4,012	4,328	4,197	4,053
Formaldehyde	24,320	24,423	27,220	27,799	24,534	23,382
Naphthalene	418	409	443	461	449	451
Phenanthrene	32.9	32.3	35.1	36.3	34.7	34.5
Anthracene	7.24	7.08	7.67	7.94	7.69	7.72
Fluoranthene	7.64	7.48	8.09	8.38	8.10	8.13
Chrysene	4.17	4.08	4.42	4.58	4.42	4.43
Benzo(a)anthracene	1.93	1.91	2.09	2.16	2.01	1.98
Benzo(b)fluoranthene	1.69	1.68	1.84	1.89	1.75	1.72
Benzo(k)fluoranthene	1.07	1.07	1.18	1.21	1.10	1.06
Indeno(1,2,3-c,d)pyrene	0.06	0.06	0.07	0.07	0.06	0.06
Benzo(g,h,i)perylene	0.21	0.21	0.23	0.23	0.22	0.22
Benzo(a)pyrene	1.70	1.68	1.85	1.90	1.76	1.73
PAH (VROM-10)	474	465	503	524	509	511
PAH (Borneff 6)	12.4	12.2	13.3	13.7	13.0	12.9

(Source: Netherlands National Water Board (2008))

Alternatives to fossil fuels have been investigated such as biodiesel, which was shown to have less than 20% of the GHG emissions compared to normal diesel (Prasad, 2020). However, other emissions in addition to GHG emissions need to be considered when comparing fuel choices. Bengtsson et al. (2012) showed that whilst GHG emissions for biofuels decreased compared to using liquefied natural gas, eutrophication potential and the primary energy use increased.

2.2.2 Anti-fouling paint

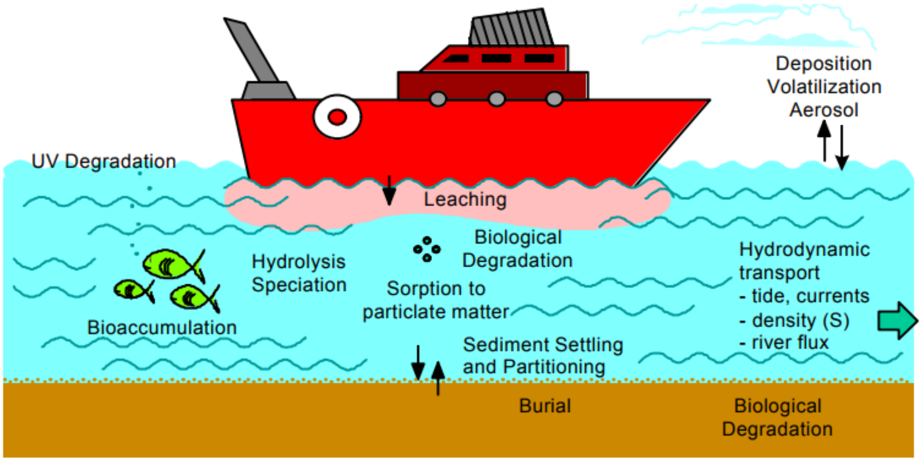
Surprisingly little is known about the fate of antifouling paints, although several paints have been phased out due to known risks to the marine environment, and the non-biodegradability and potential for bioaccumulation. Various studies have been performed on the leaching rate of the various paint used and chemicals, such as TBT, Cu, Irgarol, Sea-Nine 211, Zinc Omadine, Diuron and dichlofluanid (van Hattum et al., 2002).

Sophisticated chemical equilibrium models have been used to provide a comprehensive treatment of the subtle physico-chemical and biological processes and interactions (van Hattum et al., 2002). These help to model and understand the complex chemical fate pathways and interactions required for reliable assessment of the fate of antifouling paint, as shown in Figure 2.1.

[1] http://www.environment.gov.au/protection/publications/marine-outboards-and-personal-watercraft

Emissions of paints can occur in open sea, shipping lanes, estuaries, commercial harbours, and yachting marinas (van Hattum et al., 2002), and have been shown to occur in sediments

The leaching rate is dependent of the type of paint used, surface area in contact with the water and number of days in the water.



source: (van Hattum et al., 2002)

Figure 2.1: Chemical pathways for antifouling coatings in the marine environment

Due to increasing regulations, research into alternatives to biocidal paint products has increased. (Faÿ et al., 2019). "Efficient paints based on biodegradable polymer and with no organic biocide could be obtained by mixing copper thiocyanate and additives"

Others have shown the potential for self-polishing, water based, biocide-free, and soluble polyurethane dispersion coatings, synthesized by combining polyethylene glycol and dimethylol propionic acid (Kuok et al., 2019)

2.2.3 End of life (EoL)

The advantages of using GRP in boat building, that include strength and durability, become challenges at the end of life where the materials recycling is problematic, due to its heterogenous structure (Nicholas and Paul, 1995). This leads to problems with disposal or recycling and also provides incentive to find alternative or modified materials that will not cause such future problems (Neşer, 2017).

Current EoL treatment is currently dominated by landfill and incineration with energy recovery. There are three categories for recycling technologies: mechanical, chemical and thermal (Neşer, 2017), with mechanical involving shredding and grinding, being the current dominant path. This is followed by screening to separate the fibre and resin fractions for reuse but can be energy intensive (Neşer, 2017). Composites have a high calorific value and incineration with 10% municipal solid waste has been shown to be an practical solution (Moreau et al., 2009). Further potential EoL treatment options include use in cement manufacture, fluidised beds with thermal processes to recover fibre content, pyrolysis and disposal in landfills. Önal and Neşer (2018) used LCA to show that landfill has the highest environmental impacts except for the global warming potential and human toxicity impact categories.

2.3 Circular Business Models

2.3.1 Introduction

The purpose of this section it to provide an overview of the current literature on circular business models (CBM's) and identify suitable models that can be assessed as scenarios for the boat case study.

Circular business models have received increasing attention since the promotion of CE by the Ellen MacArthur Foundation (EMF, 2013). As Osterwalder and Pigneur (2010) state: "A business model describes the rationale of how an organization creates, delivers, and captures value." They define how a company develops value in its business (Magretta, 2002) and are strongly connected to innovation capability (Teece, 2010; Chesbrough, 2009; Yunus, et al 2010). There are nine basic elements or building blocks to a business model: Customer segments, value propositions, channels, customer relationships, revenue streams, key resources, key activities, key partnerships and cost structure (Osterwalder and Pigneur, 2010).

The choice of business model determines the architecture and potential expansion paths of the business but changing business models is challenging for companies once one is established (Teece 2010). Variations of business models applied to a technology or product innovations will yield different economic outcomes (Teece 2010).

The term "circular business model" has only recently begun to be utilised in academic research (Oghazi and Mostaghel, 2018) rising from 1 mention in the literature in 2013 to 19 in 2016 (Mostaghel et al. 2017). Even so, related practices such as leasing, and renting are well established and product service systems have gained increasing attention over the last twenty years.

CBM's by description are intended to "provide significant economic benefits in addition to new ways of forming partnerships with suppliers and connecting with customers" whilst they "generate essential environmental benefits as a result of the improved resource productivity they offer" (Guldman, 2016). CBM's have been successfully applied in a range of business sectors and for different size companies, but it is critical that they are tailored to each company (Guldman, 2016). However, a CBM represents a radical change, requiring a new approach and new business processes (Bocken et al, 2016).

The types of business models have been categorised in different ways, but in principle involve creating value within the inner loops of the CE model, extending the life or cascading the use. These aspects were highlighted by the Ellen MacArthur Foundation (2013) and Nguyen, Stuchtey and Zils (2014) who pointed to four distinct methods for value creation: power of the inner circle, power of circling longer, power of cascaded use and power of pure circles. Similarly, from a review of 120 CE case studies Accenture highlight five business models (Accenture, 2014):

- Circular supplies – which includes renewable energy, bio-based or fully recyclable input material to replace single lifecycle inputs
- Resource Recovery – recover useful resources/energy from disposed products or by-products

- Product Life Extension – extend working lifecycle of products and components by repairing, upgrading and reselling.
- Sharing platform – enable increased utilisation rate of products by making possible shared.
- Product as a service – offer product access and retain ownership to internalise benefits of circular resource productivity.

Guldman (2016) combined these to show how different business models incorporate different methods of value creation. For example, product as a service typically involves "circling for longer" as well as the "inner circle", but not pure circles or cascaded use. There is also a need to address the challenges of applying CBM's, particularly the need for customers to understand and accept the new models and services (Guldman 2016).

2.3.2 Circular design strategies

For many companies a move towards the circular economy essentially involves addressing both changes in design and changes in business models (Bocken et al. 2016). Circular business models can be distinguished from circular design strategies, which include "design for" (Sauerwien et al. 2017):

- Attachment and Trust
- Standardisation and compatibility
- Reliability and durability
- Upgradability and adaptability
- Recyclability
- Ease of Maintenance and Repair
- Dis- and Reassembly.

However, as EMF (2017) highlight in their report on CBM's in the built environment, successful CBM's will require action from a range of stakeholders including suppliers, service produces, contractors, end of life companies, in addition to designers. New business models can potentially foster: greater control of resource streams to capture value, innovation in the supply chain where new businesses develop to utilise resources, to refurbish and reverse logistics; enhanced collaboration of stakeholders in the supply chain; and services that capture value in products and resources (EMF, 2017). Bocken et al. (2016) highlights that although one of the circular strategies is durability and longer life, this approach may not be circular from a material flow perspective.

In terms of a boat, it implies that there could be different business models and stakeholders required for different lifecycle phases from design and use, through to refurbishment and recovery. However, it is necessary that they support each other. It is therefore not just one business model, but several overlapping and supportive business models that are required.

3 Methodology

This section presents the methodology of performing the LCA work to understand the life cycle environmental impacts of a motorboat in order to incorporate this information into a circular economy model (CE-model). The CE-model is a general equilibrium model that analyses how market actors and outcomes (i.e. raw material extraction, material flows and emissions) react to changes in policy instruments along the product life cycle. The overall project aim of the POLICIA project is to combine these models into an integrated assessment that will be able to address market failures and quantify policy effects of efficient combinations along the entire life cycle of a certain product, from raw material extraction, production, consumption and waste management to recycling, reuse and remanufacturing.

The aim of the LCA work was therefore to enable the information and knowledge obtained through a LCA of a motorboat, to be incorporated into the POLICIA CE-model, so that environmental impacts of policies can be directly modelled and optimised.

The objectives were to:

1. Identify the environmental hotspots throughout the life cycle of a case study motorboat
2. Model and quantify environmental impacts based on changes (scenarios) in the motorboat components and hotspots,
3. Develop ways to incorporate environmental impact data into the CE-model.

The LCA component of the research therefore consists of three main components:

1. Baseline LCA – first a baseline LCA of a Nimbus 305 motorboat and an exploratory approach of how knowledge from identifying the hotspots could be utilized with an economic based model, called the CE-model.
2. LCA modelling of circular scenario changes and business models.
3. Development of integration of LCA and CE-Model.

Each of these are explained in the following sections.

3.1 Baseline LCA model

Before integration of the LCA model with the circular economy models could be achieved a base line LCA was performed from where the data could be extracted, and important hotspots could be identified. This section describes the underlying data and modelling choice in the LCA.

For more details on the underlying LCA methodology, see Appendix B.

3.1.1 Goal and scope

A clearly defined goal and scope are crucial in order to fully understand the LCA and the results.

The goal of the LCA performed in this study is to find the most important environmental hotspots in the life cycle. Based on these identified hotspots, scenarios are investigated to assess what opportunities there are to improve on the environmental impact of these hotspots, and which parameters that influence this improvement.

The results from the LCA – which finds the impact from different stages – and the scenario analysis – which find the parameters that control potential improvements –were transformed into equations that represent the life cycle impacts. The results from the LCA are incorporated as constant impacts, and the improvement potential is included as variables that correspond to the identified parameters.

The scope of the LCA and the scenario analysis is limited to the assessment of one model of motorboat, the Nimbus 305. Although exact boat composition may vary between brands, most motorboats have similar material composition and share the same base-line boat components. For this reason, including only one motorboat in the scope still gives results that will be indicative of most motorboat in the market.

The LCA does not cover the supporting infrastructure needed to assure the full function of the motorboat in use. This means leaving out of scope things like filling station, maintenance station etc. Only the physical motorboat, and its production is included. In the use phase it is only the energy, antifouling paint and renewed components that are included.

End of life handling of the boat is included in the scope. Incineration, recycling and specific components handling are included in the scope.

3.1.2 Functional unit

A functional unit is used to relate the result to a fixed factor, to enable comparison of different cases based on the prerequisites of a certain function. This is important both when comparing results, but also important to understand in what cases the LCA results are valid as the results showing the environmental impacts are given considering this function.

The desired function is to produce one 10-meter-long motorboat including upstream material used, manufacturing, 30 years' operation and maintenance, and end of life treatment.

Chosen functional unit: ***One 10-meter-long motorboat with 30 years' lifetime***

The amount of material needed, weight, use phase, end of life, all relate to being able to perform this function.

3.1.3 Selected impact categories

The selection of impact categories was based on both the wishes of the project commissioner and an iterative analysis of the results, where we identified categories that showed significant differences in the results.

A category looking at climate change was desired by the commissioners, and additionally proves to be representative of most of the impact categories that relate to air emissions like acidification, eutrophication, particulate matter and photochemical ozone formation. In this study the CML method *Global Warming Potential (GWP 100 years), excl biogenic carbon* was used.

The project commissioners also requested a focus on toxicity and for this reason the USEtox category was included. USEtox is a standardised environmental model to evaluate impacts of chemicals on human health and organisms (http://www.usetox.org) (Rosenbaum, o.a., 2008). USEtox uses CTU= comparative toxic units (CTU) per kg of emission, a unit that estimates the increase in morbidity caused by the emission. Toxicity is based on fate, exposure and effects, which is difficult to determine from an LCA inventory. Therefore, the results will have a degree of uncertainty and should not be directly compared to other LCAs but are adequate for the project purpose of comparing the scenarios generated in the project.

Motorboat require large amount of materials for boat structure and rare metals for electrical components. For this reason, it was relevant to include a category to assess the risk of material depletion. The chosen category was the CML method *Resource depletion, mineral, fossils and renewables, midpoint (v1.09)*. The method uses a reference flow of antinomy as a unit (similar to how CO2 is the reference unit for climate change). Each materials score is calculated based on the annual production in relation to the total amount of material in the Earth's crust, and the score is set in relation to antimony (van Oers, Guinée, & Heijungs, 2020).

As a complement to these impact categories a monetary valuation method was used, both to evaluate all emissions with one method, but also to have a result in a unit that fits more closely with the economic CE modelling. The chosen method was the Environmental Priority strategy (EPS), a monetary valuation method measured in ELU, a unit that corresponds to € (Steen, 2015).

Table 3.1: Environmental impact categories used in the study

Impact category	Category indicator	Reference
Global Warming Potential (GWP 100 years), excl biogenic carbon	kg CO2 equivalents	CML2001 - Jan. 2016
Abiotic Depletion (ADP elements)	kg Sb equivalents.	CML2001 - Jan. 2016
USEtox 2.01, Ecotoxicity (recommended and interim) [CTUe]	CTUe	USEtox 2.01
EPS 2015dx - Excl impacts from second particles (Aggregation 1:1)	ELU (€)	EPS 2015dx

3.1.4 Studied product systems

This study is focused on three main life cycle stages: Raw materials and construction, Use phase and maintenance, End of life and disposal. The motorboat study is based on provided by Nimbus factory They selected one typical motorboat called "Nimbus 305" to use as reference in the study. Thus, the Nimbus 305 was set as the base case.

Raw materials and construction: The manufacturing step contains all stages from boat raw materials to the final product. In this stage is included: boat materials, inputs processes (energy, water, etc), outputs processes (air emissions, water emissions, ...).

Use phase and maintenance: Represents the boat use phase during the whole lifetime. During this phase, users' individual behaviours are highly diverse, so that user patterns can be varied a lot among different users. Thus, some assumptions are made in order to derive an average situation of boat operation. This step includes inputs of boat energy source (fossil diesel used for base case), paints used for antifouling, as well as exchange of spent batteries and engine. Outputs of emissions to water, air, etc.

End of life: This stage includes the waste treatments of the boat at end of life. Once the owner decides to get rid of the boat, different possibilities exist for the final treatment. Actually, currently, most of retired boats are just abandoned in the seaports or in the countryside without any treatment. There is only a small part of boats that will be sent to treatment station for material reuse or recycle. This study assumes the boat is sent to recycling station and been treated appropriately.

3.1.5 Limitations and key assumptions

Important limitations and key assumptions are outlined below divided on if they are methodologically related, data collection related, system boundary related.

Methodological

- Allocations
  In some situations, there are several outputs from a certain process. For example, producing a material product or an energy product. In those cases, datasets taken from Gabi database or Ecoinvent database is carried out, which calculates the impacts that are allocated to certain product.

Data collection

- Upstream data: Data linked to the raw material supply and production in Nimbus, primary data from the facilities have been used. All other data are representative for the Swedish market, for example, fossil diesel, biodiesel and electricity used in Sweden.

- Manufacturing: There are several methods and factories to produce boats. This study only chooses Nimbus 305 as one common motorboat. The results from base case are linked to this specific boat. The amount of energy use during boat life time is also linked to Nimbus 305's situation.

- Operation: In terms of boat use phase, there are a lot of uncertainties among boat owners. Assumptions made for boat life time, driving hours and driving speed, to reflect an average situation. The fuel use for Nimbus 305 is fossil diesel.

- EOL treatment: Knowledge from the boating survey that the middle life length of the boat is approximately 35 years. The life length assumption in this study was set to 30 years to be more conservative. But it won't influence the conclusion. The boat EOL was assumed go to recycling centre after 30 years operation time even though the amount of boats that go to recycling station is very low nowadays. The EOL treatment used in the study are based on available treatment methodologies for different boat components and materials.

- Improvement options are suggested in the latter part of the report in order to find possibilities of changes. Data used for these scenarios are theoretical data.

System boundary

- Geographical boundary: The boat is produced in Sweden. This means, the electricity and other energies used in the factory are specific Swedish situations. For example, electricity used is the specific Swedish electricity grid mix.

- The boat is assumed to be operated in the sea area around Swedish west and east coastline. So, the user pattern is based on Swedish users, which means the boating season is from May to October, and it is assumed 126 hours per boating season.

3.2 LCA data collection and inventory of base case

This section gives a brief overview of the data collection performed in this project. First the material composition of the studied products is shown. The subsection about site specific process data gives an overview of the process data specifically collected in this project, while the generic process data subsection list what process data that are taken from what database.

In Appendix C, details on what datasets are used to model each material flow can be found. In some cases, the flows are complex combinations of materials and processing. In these cases, a deeper look at the modelling can be found in Appendix C.

3.2.1 Material composition

The data for the boat manufacturing process were obtained from Nimbus Company. Inputs and outputs materials and energies are corresponding to the production of 1 motorboat-Nimbus 305.

Table 3.2 Boat material composition for the base case

Category	Material
Chemicals + Glass fibres	DCPD Polyester
Chemicals + Glass fibres	MEK Peroxide
Chemicals + Glass fibres	E-Glass
Chemicals + Glass fibres	PVC
Chemicals + Glass fibres	Crystic CC60
Chemicals + Glass fibres	MS polymer SIKA
Chemicals + Glass fibres	Engine + Gear Oil
Wood	Wood
Metal	Stainless steel
Metal	Brass
Metal	Alumina
Metal	Black iron
Engine	Diesel inboard
Engine	Gearbox
Glass	Glass
Electrical components	Cables
Electrical components	Electronics devises
Electrical components	Batteries
Others	Porcelain
Others	PVC
Others	Textiles
Others	Polyester
Others	Thermoplastics

Others	Vinyl
Antifouling paint	Antifouling
Antifouling paint	Primer

Datasets selected in LCA software-Gabi model can be seen in Appendix C.

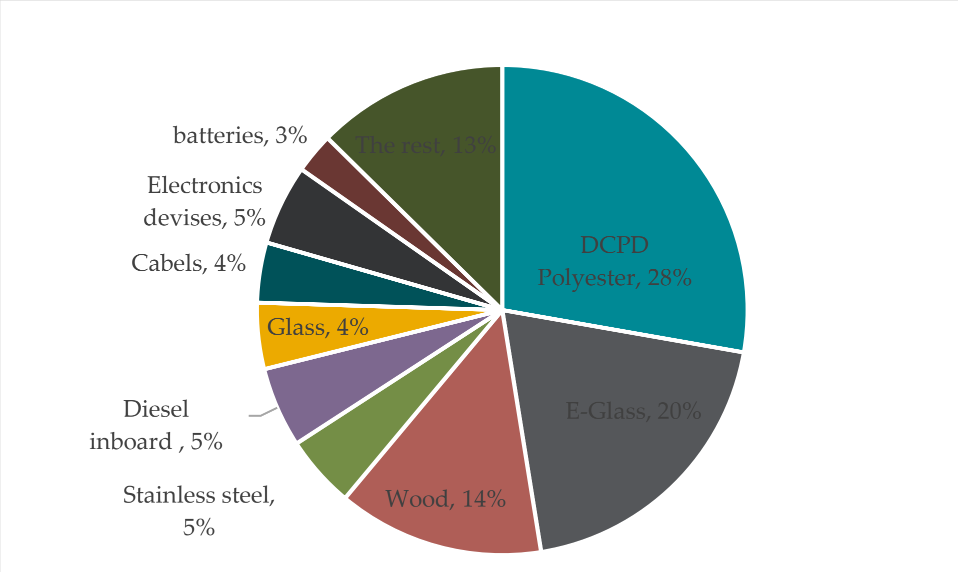


Figure 3.1 Material composition of base case.

3.2.2 Production and process

Production and process data was collected from Nimbus factory. It includes energy consumption and air emission situation. The energy use and air emissions from building one Nimbus 305 boat was calculated based on mass allocation. The factory produced around 636 tonnes of boats per year and the figure for total N305 is 238 tonne, 53 boats.

Production data

Production data include electricity and diesel used to produce one boat and also include air emissions that are allocated to one boat.

For the boat manufacturing the data was taken from Nimbus environmental report (Nimbus Boats Sweden AB Textdel Miljörapport 2016, 2016) and are modified according to the most updated factory situation. It was modelled to be using Swedish electricity grid mix and European average diesel mix. Emission data from factory is also from Nimbus factory with the allocation to one single product.

The base case for the motorboat is Nimbus 305. Production data and emissions from factory can be seen in the table below:

Table 3.3 Input to boat manufacturing process

Input	Amount	Unit
Electricity	14 086	kWh/boat
Diesel	31	kg/boat

Table 3.4 Output to boat manufacturing process

Output	Amount	Unit
NO_x	0.72	kg/ boat
CO_2	0.092	kg/ boat
VOC	16.68	kg/ boat

Emissions to air from manufacturing are mainly volatile organic compounds (VOC), carbon dioxide emissions (CO_2) and nitrogen oxide (NO_x) as reported from Nimbus environmental report.

The transportation of raw materials is included in the study. It assumed raw materials were transported by truck for 500 km. The transportation of the final boat from the factory to the harbour is not included, neither the transportation of retired boat since the user behaviour varies too much and these impacts are too minor compared to the whole environmental impacts.

3.2.3 Boat operation and maintenance

Boat operation and maintenance data were based on the customer survey which reflect the average situation in Sweden. The boat operation time for the base case was set to 30 years. The boat maintenance included the components exchange.

In terms of boat operation, fuel consumption and antifouling paint applied are two main aspects included in this life cycle phase.

For the fuel consumption, fossil diesel is the present fuel used for Nimbus 305, set as the base case. The amount of fossil diesel is calculated by the assumption to reflect the average using pattern in Sweden. Some boat driving information can be derived from Nimbus fact sheet (Smart speed concept - comfort and safety before speed) . It is assumed that the average operation hours per year are 126 hours and 15 litres fossil diesel consumed per hour with speed around 10 knots, according to fact sheet (Smart speed concept - comfort and safety before speed).

Table 3.5 has listed the boat driving situation that is modelled in this study. The Swedish average data were applied such as boating hours, speed.

Table 3.5 Fuel consumption situation for the base case

Category	Amount	Unit	Comment
Boating hours	126	h/year	Average boating hour assumed in Sweden
Speed	10	knots	From the customer survey.
Fuel consumption	15	l/h	Fuel consumption is quite stable around 1.5 L/NM when the speed is higher than 10 knots. (Smart speed concept - comfort and safety before speed)
Fuel density	0.87	kg/l	Diesel fuel density
Boat lifetime	30	years	Average assumption
Diesel engine efficiency	30%	efficiency	Assumption
Fuel amount	49 329	kg/30 years	Calculated

In recent years, antifouling paint is a hot topic since the toxic antifouling paint is dangerous to marine organism.

In this study, two antifouling paints have been chosen to be analysed. These two paints are existed in the Swedish market and come from the same company. The first one is called "Biltema Antifouling BS, Svart" with a higher copper oxide content (12.5-15%). Another one is called "Biltema Antifouling Svart" with a lower copper oxide content (7-10%) which meet the regulation of low copper oxide on east coast, while it has 20-25% zinc oxide which is relatively high. Detailed antifouling paint composition can be found in Table 10.7 and Table 10.8.

The applied amount of antifouling paint per year on the boat hull is 2.8 kg through the calculation. More details can be seen in Appendix C.

Table 3.6 Antifouling paint consumption situation for the base case

Antifouling paint name	Amount	Unit	Comment
Biltema Antifouling BS, Svart	2.8	kg/year	Based on average antifouling consumption per boat in one year. 12.5-15% copper oxide, 8-9% zinc oxide
Biltema Antifouling Svart	2.8	kg/year	Based on average antifouling consumption per boat in one year. 7-10% copper oxide, 20-25% zinc oxide
Antifouling paint used for 30 years	84	kg/ 30 years	Calculated

During the boat lifetime, some components need to be changed or updated. For example, the boat engine lifetime is usually shorter than 30 years. Boat battery needs to be renewed several times. Other electrical devices or internal furniture may also require maintenance in a certain extend.

For the base case study, it is assumed that only the diesel engine and boat battery are included in the maintenance step since these two components are the biggest contributor to the environment. Usually the engine works for 15-20 years. The battery usually has 10-15 years' lifetime.

The boat may be owned by more than one user. In this case, we assume that all boat owners are in Sweden, so they have the same use pattern and same energy sources. The environmental impacts caused by boat transportation from one owner to another one is not included in this study.

Table 3.7 Boat component maintenance situation

Maintenance category	Replace times	Comment
Engine	1	Usually the engine will be replaced once during the lifetime.
Battery	2	Assume battery needs to be renewed every 10 years

3.2.4 End of life treatment

A motorboat can be expected to have a lifetime of over 30 years if it is well maintained. With the booming sale peak in 1970s, it is expected the large number of boats will come to the end of their useful life in the coming years. Even if these retired boats are not polluting the land or water, there is a risk that they occupy valuable space, or will be abandoned and dumped illegally (Moreau, 2009).

There are some forerunner actions started in Sweden even though the boat recycling amount is still very low currently. Recent studies undertaking in France, Finland, Japan, Norway all established that it is feasible to scrap recreational boats at the end of their life. Metals and part of materials and major items can be recovered and recycled, composites can be reduced to fragments but still has problems of recycling or disposal. Previous studies recommended the treatment of dead boats to be dismantled then crushing and sorting (Moreau, 2009).

In Sweden, one boat recycling development project called "A Swedish nationwide recycling system for end of life boats "was started up by Sweboat, Båtskroten Sverige AB and Stena Recycling. The purpose is to increase the boat recycling rate and give vacant space of the boat storage ground. The recycling system is called Båtretur which is a national network for environmentally correct collection and recycling of pleasure boats. Boat owner could call the service but need to pay the fee (Båtretur, 2020).

Knowledge from the Workshop is that generally there is a lack of incentives for the collection of scrap boats. Boating clubs in Sweden usually have boats that no one want but may not move without owner's permission. It is urgently that the boat end of life management needs to be improved. Figure 3 below shows the boat EOL situation in Sweden.

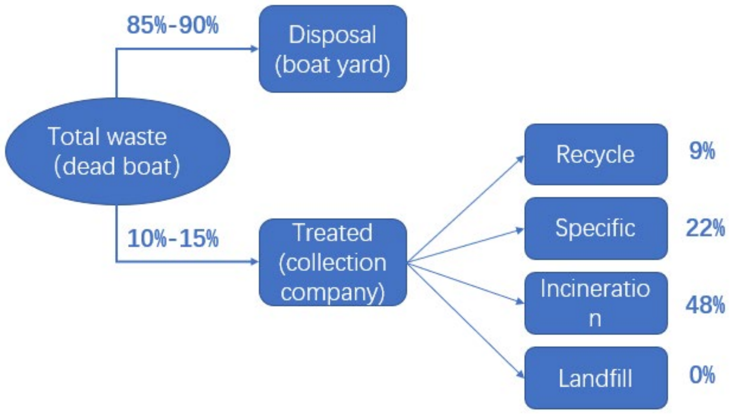


Figure 3.2 Illustration of the boat collection system

According to the statistic from Båtretur, around 2000 boats retired in one year while only 200-300 boats have been handled. It means the percentage of collected boats only shares 10-15%. In this study, the base case was supposed that the motorboat has been treated after the use phase. Boat materials will be recycled as ordinary, like metals, plastics, etc. FRP is an exception since it has very low heating value after combustion. Components like engines, batteries, electronic scraps were assumed to follow the standard treatment processes.

It should be noted that the boat EoL didn't include credit for energy (electricity, heat) from the incineration process. The result only reflects the impact through the EoL treatment processes if the material or component has been treated in a standard way.

The boat waste treatment is not so developed like vehicle so the site-specific-data of motorboat EOL treatment was not available. In this study, the EOL treatment has focus on key components and major materials. Table 3.8 presents the treatment situation of motorboats based on assumptions. See Table 6.9 in Appendix.

It can be seen that around half of the boat weight will normally go to incineration and 30% of weight (components and recyclable materials) will go to recycling and reuse. There was around 20% of materials that cannot be well treated, such as fibre glass which has no value for incineration.

Table 3.8 Motorboat EOL treatment

Treatment	Amount (kg)	Share of total boat weight(%)
Incineration	**18 08.6**	**48%**
Hull combustible part	1 130	30%
Wood	514.6	14%
Textiles	13	0%
Polyeter	64	2%
Plastics	87	2%
Recycling	**344**	**9%**

Stainless steel	180	5%
Brass	31	1%
Alumina	75	2%
Black iron	8	0%
PVC	50	1%
Specific treatment	**815**	**22%**
Glass	165	4%
Cables	150	4%
Electronics devises	200	5%
Batteries	100	3%
Diesel inboard	200	5%
Landfill	**7**	**0%**
Porcelain	7	0%

3.3 LCA modelling of circular changes and business models

According to the LCA base case results, environmental impacts were aimed to be investigated and quantified. These were divided into two parts:

1. Firstly, scenario analysis was performed. In this, the major hotspots, such as life cycle, stages, lifespan and the energy source were investigated in order to quantify the effects on the life cycle environmental impact.
2. Based on the baseline LCA and scenario analysis three key business models were identified and an LCA was performed on a motorboat within each business model.

The review of potential business models could be implemented to reduce the environmental impact of motorboats. These were reviewed in terms of how they could be modelled within the LCA model, for example in terms of extended life, use of other energy source etc. The following three business models, representing quite different approaches, and together representing all the potential changes of business models were therefore selected:

1. Electric boat business model
2. Prolonged lifespan with recycled components for boat maintenance business model
3. Company leasing

Table 3.9 shows the main actions and purpose that were investigated by the implementation of these business models.

Table 3.9 Implied changes to the motorboat life cycle from the three business models

Business model	Actions	Purpose
Electric boat	Electricity use as boat operating energy source; Several components changed associated with electric boat design.	Less environmental impacts from boat operation phase
Prolonged lifespan	Lifetime extended to 50 years; Recycled components used for boat maintenance.	Longer life Reduce impacts from boat manufacturing average to each year.
Company leasing	Boat leasing by company; Recycled components used for boat maintenance.	Increase the boat use rate Reduce impacts from boat manufacturing average to each use.

For more detail business models description, please check Chapter 5.

3.4 Development of equations for CE-Model

In this project the goal was to integrate life cycle environmental impacts into CE-modelling. In order to achieve this, it was important for all research groups to understand the principles of CE and LCA modelling and integrate them.

The base case LCA was used as a starting point and from this it was highlighted how hotspots can be identified from the thousands of flows included in specific and generic life cycle inventories. It was also clear that the CE-model required variable input in the form of equations, where the variables in each equation should represent choices or actions that are possible to make by different actors.

To achieve the goal of creating equations from the LCA results both the base case LCA and a scenario assessment was used. The base case LCA helped in identifying hotspots that would be the target areas for creating equations to represent the impacts over the life cycle. The scenario assessment results were used to identify which parameters to include as variables, as well as how the resulting impacts (equations) depend on these variables. These steps are further broken down below.

3.4.1 Identification of variables and constants

When attempting to integrate the LCA result with the CE modeling, a first important step was to take the LCA results and turn them into equations corresponding to the impact of each life cycle stage (or actor). It also had to be possible to vary the results in a way so that the identified hotspots in the LCA could be influenced, in other words variables had to be created from the LCA hotspots.

An LCA result is achieved by modeling all the different processes and actions that occur during the life of the product. All the data and inputs that are collected specifically for the study (i.e not generic datasets) can be alternated, varied and studied. This fact has been used when converting the LCA results to equations for the integrated model.

Although it would have been possible to have every input parameter as a variable in the equations this was deemed irrelevant for the integration. The result is not sensitive to variation in all data and thus varying them does not give additional information.

Instead the hotspot analysis together with the scenario analysis was used as a basis to determine the most important parameters in the LCA. These where then turned into variables in the equations by determining which actor had the power to change and then inserting the variable into the LCA result equation of the stage and actor.

The LCA results that were not identified as hotspots, or that where not technically possible to vary, were included in the LCA equations as constants. The constants were extracted from the LCA results in a format that would match the variables. When the variable for example is the percentage of battery and electronic devices, the corresponding constants needed to calculate the results are the rest boat materials impact

With all this information the impact equation for boat materials and components would be:

$I_{materials}=I_{component}+ I_{Electronic}*\%(weight\ reduction) +I_{battery} *\%(weight\ reduction)$

3.4.2 Finalizing the equations

When the variables had been identified equations were created to represent the environmental impact of the different life cycle stage. Every impact that was a function of one of the variables was included in the assessment, see Appendix E.

The identified variables are completely free and are open to modifications in the integration stage. There are also constants in the equations, like the impact per kg of a certain material. Between these two there are also parameters in the equations that are not subject to variation themselves, but that are influenced by the variables

In each equation there was thus a task to identify which parts that were true constants and which that were functions of other variables that those directly linked to that stage.

4 Results

Life cycle impact assessment implies taking the inventory results for all flows (material, energy and emissions) and evaluating each material and emission's impact on different impact categories. This LCA uses the following impact categories:

- Global warming potential
- UseTox Ecotoxicity
- Abiotic Depletion (ADP element)
- EPS

The results in these categories are presented below, with focus on the most impactful components and stages (hotspots).

4.1 Base case results and environmental hotspots

The results were presented for the base case of motorboat along its life cycle stages of raw material use, transportation, manufacturing, operation and End of Life.

4.1.1 Climate change hotspots

In the base case the single largest life cycle impact comes from the diesel used for the boat operation phase. Besides, the electronic devices, batteries and boat hull materials are most significant impactful resources.

The result in the climate change category is indicative also of the results in several other environmental impact categories. These impacts have in common that they relate to air emissions. Examples of impact categories with similar profiles include particle matter, acidification, eutrophication and photochemical ozone formation.

While climate change mainly is impacted by CO2-emissions these categories relate to other emissions like particles, NOx and SO_2 PM, but regardless of this they share a similar impact profile, with similar hotspots.

Table 4.1 GWP results of base case life cycle stages

Global Warming Potential (GWP 100 years), excl biogenic carbon	ton CO2 equivalents	Percent (%)
Base case: Total	224	100.00%
Raw material	23	10.22%
Transportation	0,10	0.04%
Manufacturing	0,8	0.36%
Operation	198	88.27%
End of Life	2,9	1.29%

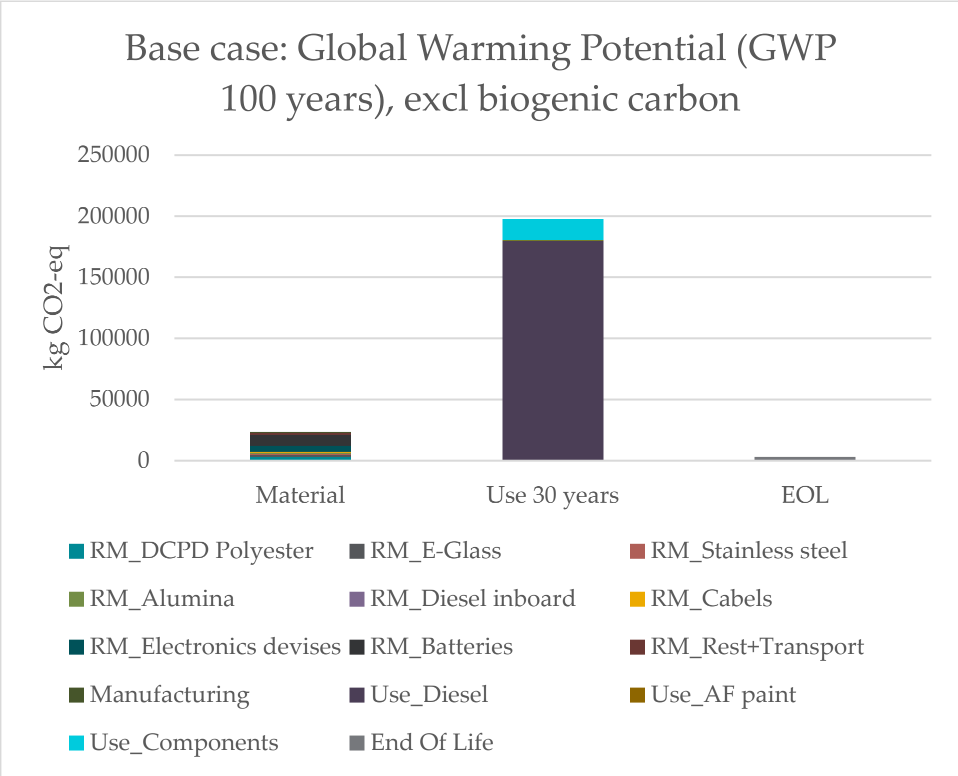


Figure 4.1 GWP of base case in terms of life stages and specific impact contributors.

In order to further break down the results presented in Figure 4.1, the top eight most impactful raw material parts of the motorboat are shown in table 4.2. Use phase impact and the EOL impacts are also indicated in the table. All life cycle stages, including use and end of life treatment are included in the assessment, but it is only the components and energy consumption that show up as hotspots.

Table 4.2 Top contributors of GWP impact category

Part/Stage	(%) contribution
Total	100%
RM_DCPD Polyester	1.4%
RM_E-Glass	0.6%
RM_Stainless steel	0.4%
RM_Alumina	0.3%
RM_Diesel inboard	0.3%
RM_Cables	0.3%
RM_Electronics devises	2.4%
RM_Batteries	3.8%
RM_Rest+Transport	0.8%
Manufacturing	0.4%
Use_Diesel	80.4%
Use_AF paint	0.1%
Use_Components	7.8%
End of Life	1.3%

Table 4.2 indicates that it is the diesel consumption that has the highest impact on climate change (80.4%), but it also helps us determine which components that are hotspots. The batteries, electronic devices and the material used for boat hull.

4.1.2 Abiotic Depletion Potential hotspots

The impact category of abiotic depletion potential (ADP) as defined by CML comprises the depletion of environmental resources. The model defined in the ADP is a function of the annual extraction rate and geological reserve of a resource. Depletion of a resource means that its presence on Earth is reduced which refers to nature stocks (Lauran van Oers, 2016).

The biggest contributor of the motorboat to the abiotic depletion (elements) category is material and components use. The materials use during production phase shares more than 40% of the total ADP impacts. See Table 4.3. Impacts from operation phase for 30 years shares more than half (around 59%), while in which, more than 58% comes from components exchanges, batteries and engines. In short, materials and components use are hotspots.

Table 4.3 ADP results of base case life cycle stages

Abiotic Depletion (ADP elements)	Amount (kg Sb eq.)	Percent (%)
Base case: Total	2.15E+01	100.00%
Raw material	8.82E+00	41.03%
Transportation	7.75E-06	0.00%
Manufacturing	1.50E-03	0.01%
Operation	1.27E+01	58.99%
End of Life	-2.66E-02	-0.12%

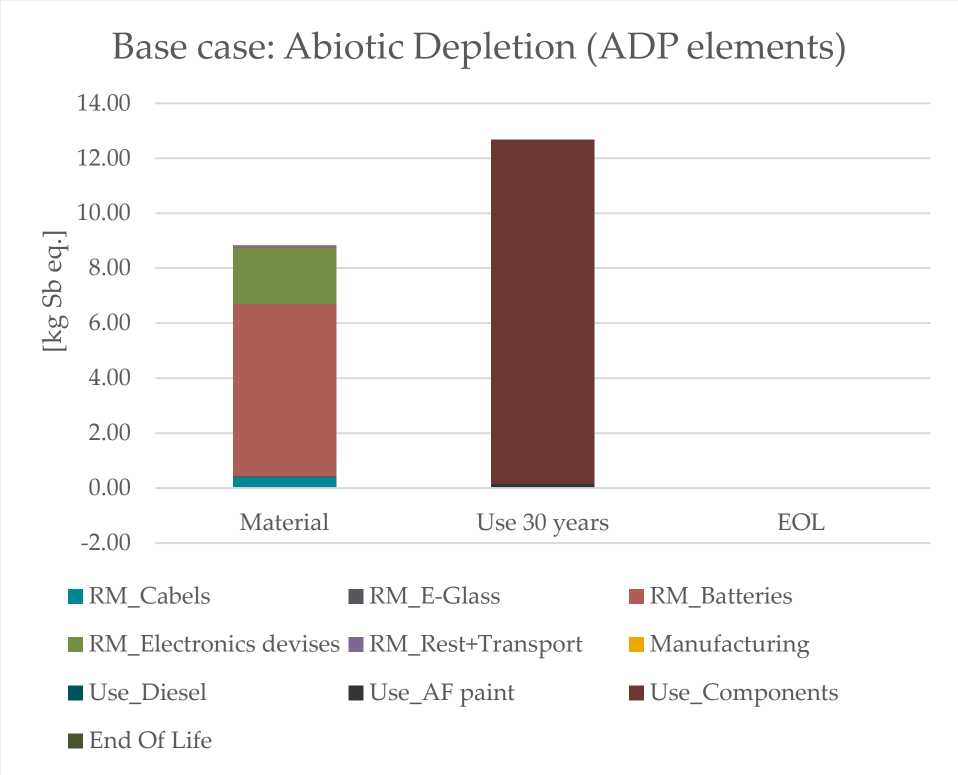


Figure 4.2 ADP of base case in terms of life stages and specific impact contributors

In order to further break down the results presented in Table 4.3, the top three most impactful components parts of the motorboat are shown in Table 4.4. It is obviously that for ADP category, battery use, and electronic devices are biggest contributors.

Table 4.4 Top contributors of ADP impact category

Part/Stage	(%) contribution
Total	100.0%
RM_Cabels	1.7%
RM_E-Glass	0.3%
RM_Batteries	29.1%
RM_Electronics devises	9.5%
RM_Rest+Transport	0.4%
Manufacturing	0.0%
Use_Diesel	0.1%
Use_AF paint	0.7%
Use_Components	58.3%
End Of Life	-0.1%

It is indicated that the hotspots are batteries, electronics and boat hull building. The negative value of End of Life treatment shows a good management of material recycling or reuse will help to prevent the scarcity of resource.

4.1.3 Ecotoxicity hotspots

The reason for the analysis on ecotoxicity is because protecting the marine environment is vital for developing and sustaining recreational marine activities in the long term. The sustainability and long-term future of these activities can only be guaranteed if appropriate measures are taken to protect and preserve the environment. USEtox Ecotoxity methodology consists of five compartments: air, agricultural soil, natural soil, freshwater, and sea water. This category was thought as the most suitable category to reflect impacts to the marine for several reasons. First, ecotoxicity to the marine is not only from boating but also from human land activities, such as painting antifouling paint, etc. Besides, the boating activity is usually along the coastline and also has a long time stay in the harbour. It means the evaluating needs to include more broader (soil, freshwater) than only evaluate impacts to deep marine.

The main output of USEtox are interim and recommended characterization factors, which should always be used together. The model and database include environmental fate, exposure, and effect parameters for ecotoxicity. USEtox 2.01, Ecotoxicity (recommended and interim) was selected as the impact category used to show ecotoxicity.

The biggest contributor come from operation phase, which shares around 60%. Raw material parts shares around 39% of total.

Table 4.5 Ecotoxicity results of base case life cycle stages

USEtox 2.01, Ecotoxicity (recommended and interim) [CTUe]	Amount (CTUe)	Percent (%)
Base case: Total	2.13E+09	100.00%
Raw material	8.34E+08	39.17%
Transportation	5.79E+02	0.00%
Manufacturing	3.25E+05	0.02%
Operation	1.27E+09	59.72%
End of Life	2.77E+07	1.30%

The Figure 4.3 below investigated the specific parts and components which has highest contribution. For the material part, battery and electronic devices are two major impact sources. The use phase has the most significant impact, but the source also comes from component exchange (battery and engine). To be noted here is that, impacts from using antifouling paint is notable.

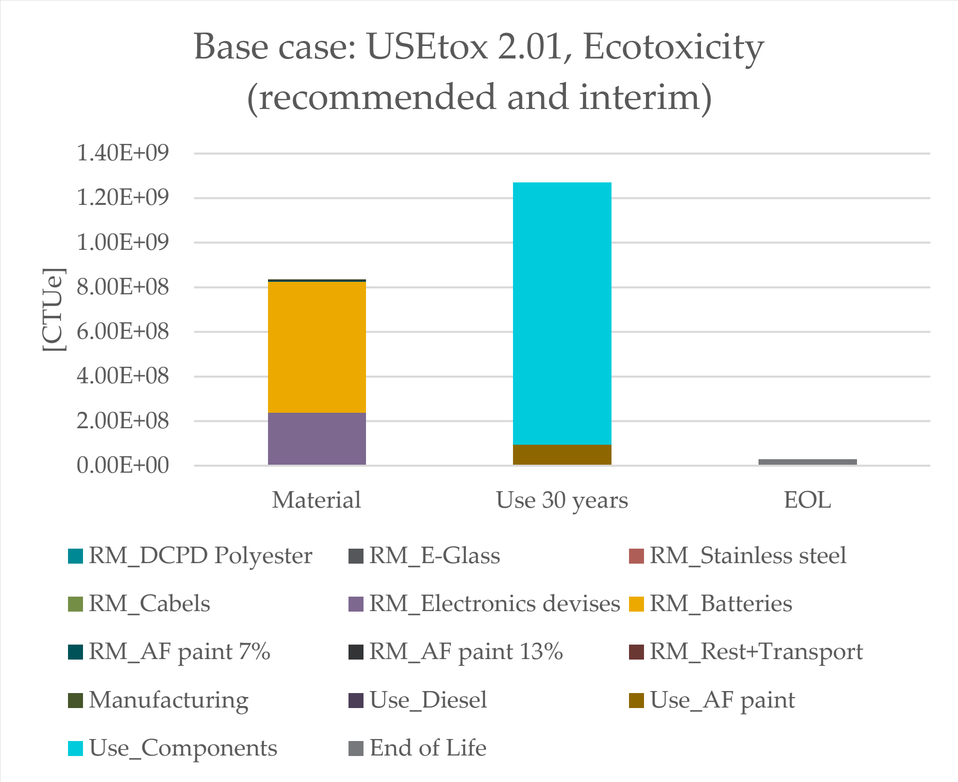


Figure 4.3 Ecotoxicity of base case in terms of life stages and specific impact contributors

Table 4.6 Top contributors of Ecotoxicity impact category

Part/Stage	(%) contribution
Total	100%
RM_DCPD Polyester	0.006%
RM_E-Glass	0.004%
RM_Stainless steel	0.004%
RM_Cables	0.005%
RM_Electronics devises	11.1%
RM_Batteries	27.6%
RM_AF paint 7%	0.15%
RM_AF paint 13%	0.23%
RM_Rest+Transport	0.007%
Manufacturing	0.015%
Use_Diesel	0.049%
Use_AF paint	4.4%
Use_Components	55.2%
End of Life	1.3%

The Table 4.6 above indicated that battery, electronic devices and antifouling paints are hotspots for ecotoxicity.

4.1.4 Environmental damage cost – EPS method

EPS (Environmental Priority Strategies) is a systematic approach to choose between design options in product and process development. Its basic idea is to make a list of environmental damage costs available to the designer in the same way as ordinary costs are available for materials, processes and parts. The designer may then calculate the total costs over the product's life cycle and compare design options (Environmental Priority Strategies (EPS), 2020).

The results of the EPS impact assessment method are damage costs for emissions and use of natural resources expressed as ELU (Environmental Load Units). One ELU represents an externality corresponding to one Euro environmental damage cost.

Table 4.7 indicated the EPS results from the base case life cycle stage. Both the raw material life stage and the operation stage have highest impacts. The End of Life stage shows a negative result since the waste handling which involves recycling and specific treatment give benefit to the EPS category.

Table 4.7 EPS results of base case life cycle stages

EPS 2015dx - Excl impacts from second particles (Aggregation 1:1)	Amount (ELU)	Percent (%)
Base case: Total	1.04E+06	100.00%
Raw material	4.07E+05	39.10%
Transportation	2.89E+01	0.00%
Manufacturing	6.16E+02	0.06%
Operation	6.41E+05	61.61%
End of Life	-6.80E+03	-0.65%

To further investigate the contributors to EPS categories, more specific information can be found in Figure 4.4 and Table 4.8. For the raw material part, battery, electronic devices and cables are rank top 3 contributors. In which, battery shares almost one fourth of total EPS impact of the total result. For the use phase part, the biggest contributor is also the renewed components, which include battery and engine renewed. It indicated that components like battery, electronics should be paid more attention.

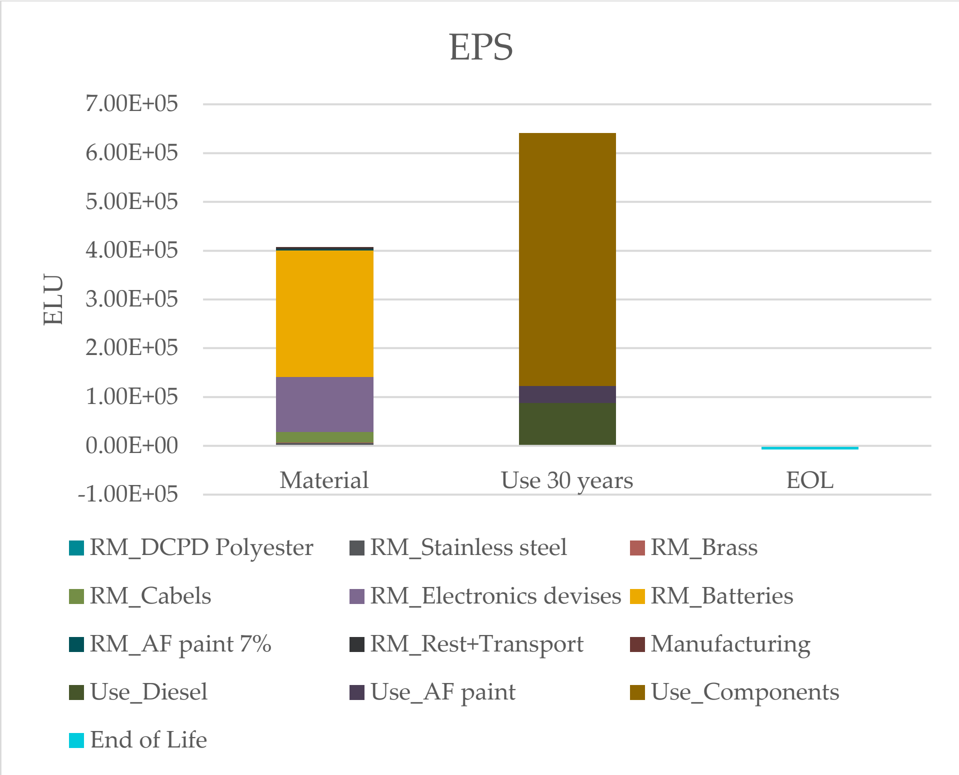


Figure 4.4 EPS of base case in terms of life stages and specific impact contributors

Table 4.8 Top contributors of EPS impact category

Part/Stage	(%) Contribution
Total	100.0%
RM_DCPD Polyester	0.1%
RM_Stainless steel	0.4%
RM_Brass	0.1%
RM_Cables	2.1%
RM_Electronics devises	10.8%
RM_Batteries	24.8%
RM_AF paint 7%	0.2%
RM_Rest+Transport	0.4%
Manufacturing	0.1%
Use_Diesel	8.5%
Use_AF paint	3.4%
Use_Components	49.8%
End of Life	-0.7%

4.2 Identified improvement scenarios

The table below is the summary of hotspots from each environmental category. There are some overlapped hotspots such as fossil fuel and electronics. Fossil fuel is the biggest impact contributor in category of climate change. Electronics, battery, cables are also the main contributor of almost all categories.

Table 4.9 Hotspots summary

Hotspots	Electronics	Battery	Hull	Fossil fuel	Antifouling paint
Global warming potential	X	X	X	X	
Abiotic depletion potential	X	X			
USEtox Ecotoxicity	X	X			X
EPS	X	X		X	X

Base case LCA results identified several hotspots. To fulfil the aim of the study, improvement approaches are proposed which in total reduce negative environmental impacts and improve the overall performance of boat life cycle.

Focused on hotspots that found in the study, some options were proposed to improve the current situation.

4.2.1 Use phase – fossil fuel

Fossil diesel is the biggest problem in GWP category which shares more than 80% of total impacts. It is easy to understand that with the boat lifespan extending, the more obvious impact will show up from fuel consumption. There are some other energy types which though can replace fossil diesel use.

- **Biodiesel option**
  Environmental impacts from boat operation phase are the largest contributor. For the base case, fossil diesel is under using nowadays. Since biodiesel is carbon neutral and is also technical available in the market. Compared to fossil diesel which is 3.65 kg CO2-eq/ kg, biodiesel is only 0.96 kg CO2-eq/ kg. There will be more than 70% of CO2 emission saved by using biodiesel.

- **Electric boat option**
  Electricity is one option to replace fossil diesel use. The diesel engine is assumed to have 30% efficiency, which means 0.3 MJ electricity required if the electrified boat working the same functions as the diesel boat. Since the Swedish electricity has a very low GWP impact which is around 0.0594 kg CO2-eq/ MJ electricity, the EU average electricity is also involved into the discussion.

Below are two chats, Figure 4.5 and Figure 4.6, that show the global warming potential and EPS categories among those three energy types in a 30 years' life operation period.

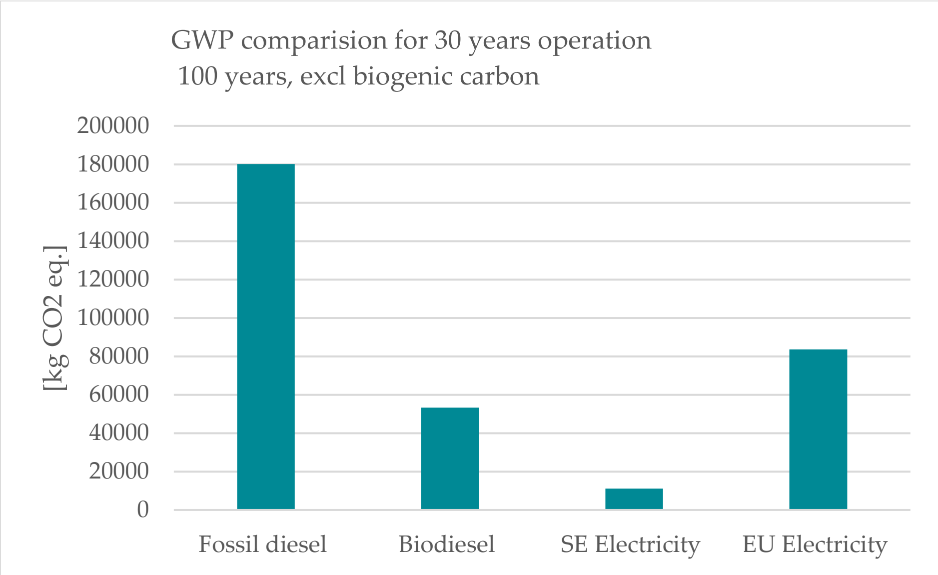


Figure 4.5 Comparison of GWP results of three types of energy during lifetime

It shows the fossil diesel has the highest GWP compared to biodiesel and electricity. Swedish electricity has big advantages since its energy resource is very green. European electricity compared to fossil diesel still shows big advantages.

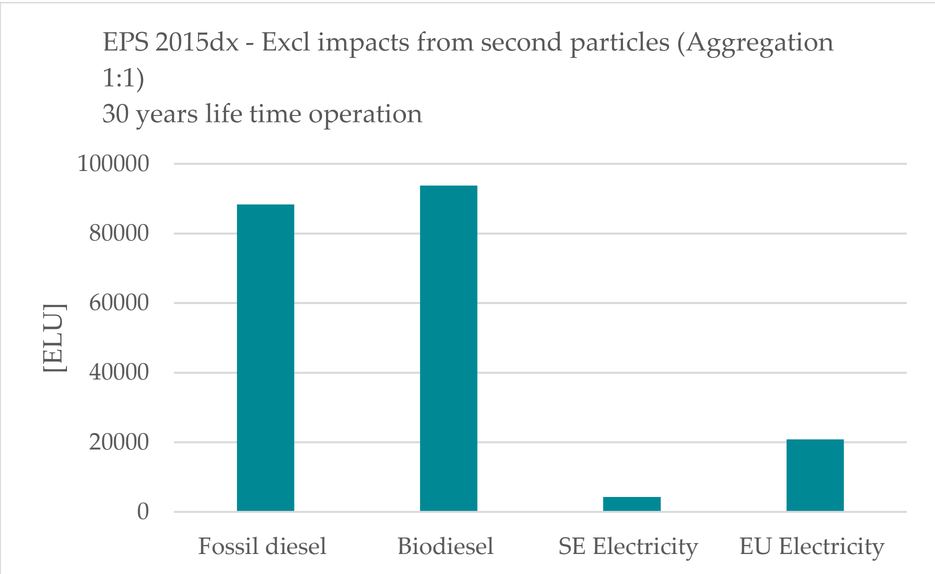


Figure 4.6 Comparison of EPS results of three types of energy during lifetime

Looking at the EPS category, there is no big difference between fossil diesel and biodiesel. But the advantages of electricity are very obvious.

4.2.2 Use phase – antifouling paint

A pressing issue for most leisure boats is biofouling which due to the increased fuel consumption from the accumulation of microorganisms on the hull of the boat. While combating the biofouling is usually using toxic antifouling paints, which is problematic from a marine environmental standpoint.

It shows obviously from Table 4.6 and Table 4.8 that in the category of USEtox and EPS, antifouling paint plays an important role of the whole picture even though the applying amount that assumed is 2.8 kg per year. The reality of using amount can be much higher if boat owners paint more frequently or more amount than the instruction.

In the study, two types of antifouling paint have been selected. The first one is with higher copper oxide content (12.5-15%). Another one is with a lower copper oxide content (7-10%) which is meet the regulation of low copper oxide on east coast, while it has 20-25% zinc oxide which is relatively high. Chart below shows the comparisons between those two.

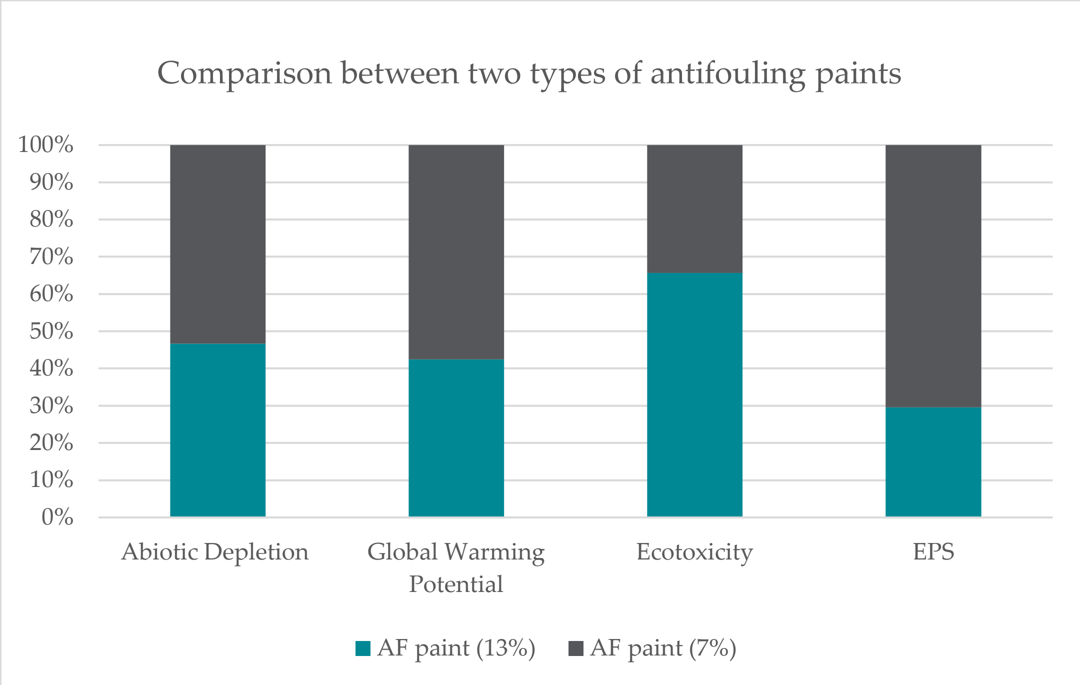


Table 4.10 The comparison between two types of antifouling paints in terms of selected impact categories.

From the chart, it can be seen that these two types of paints show quite similar performance in the category of ADP and GWP. While considering the ecotoxicity and EPS categories, higher copper oxide content paint has higher impact on ecotoxicity category but lower impact on EPS. This is mainly because the lower copper oxide content paint added more zinc oxide. From the results, it is hard to give the conclusion which paint is better. So, the option to reduce the impact of antifouling paint is to use less, or even stop using antifouling paint. Instead by using other technical such as mechanical prevention.

4.2.3 Reduce the consumption of materials

Even though the boat use phase can be more than 30 years, which is much longer than the boat manufacturing phase which can be counted in days, impacts from boat materials are still significant in almost all categories, especially EPS.

Among all materials and components used for building a boat, electronics and the hull are most critical. Electronic part includes battery, cables and other electronic components. Boat hull includes polyester, glass fiber and PVC.

Strategies to reduce impacts from materials were listed below:

- **Strategy 1: Encourage boat owner to use renewed battery and renewed electronic devices during boat maintenance phase.**
  During the boat maintenance, battery will be renewed twice, and engine will be renewed once during 30 years' boating life. This part of renewal will cause significant impacts on especially Ecotoxicity and EPS category. More of that, battery and other electronic devices are anyway the hotspots in all categories. It could be difficult to give advices to boat company use renewed components or recycled devices regarding the quality issue and other market reasons. While during the operation phase, the renewed components can be suggested to be used for boat maintenance.

  For the renewed battery and engine, it is assumed that the renewed product share half of the impact from virgin product.

- **Strategy 2: Reduce the boat hull weight by vacuum infusion technique instead of hand lay-up.**
  Hand lay-up and vacuum infusion are two technique used for boat building process. From the study of (Filippo Cucinotta*, 2016) stated, that for the boat total structure, the vacuum infusion technique could reduce around 25% of materials than the hand lay-up technique. The ratio accessed by weight of glass fiber used in hand lay-up is about 0.40. With the infusion technique, the value of this ratio is about 0.65. Consequently, in the laminates with hand lay-up technique there is a greater amount of resin, and also during the process is released a bigger quantity of styrene in the environment. For the infusion technique, there is a vacuum condition during the process. This reduce the thickness of laminate, and, to have the same strength, it is necessary to increase the amount of glass fiber (Filippo Cucinotta*, 2016).

  In short, for the boat structure, the resin has the potential to reduce 57%, with the change of glass fiber increase 21% by weight.

The scenario based on material consumption was following Strategy 1 and Strategy 2 for a deeper analysis.

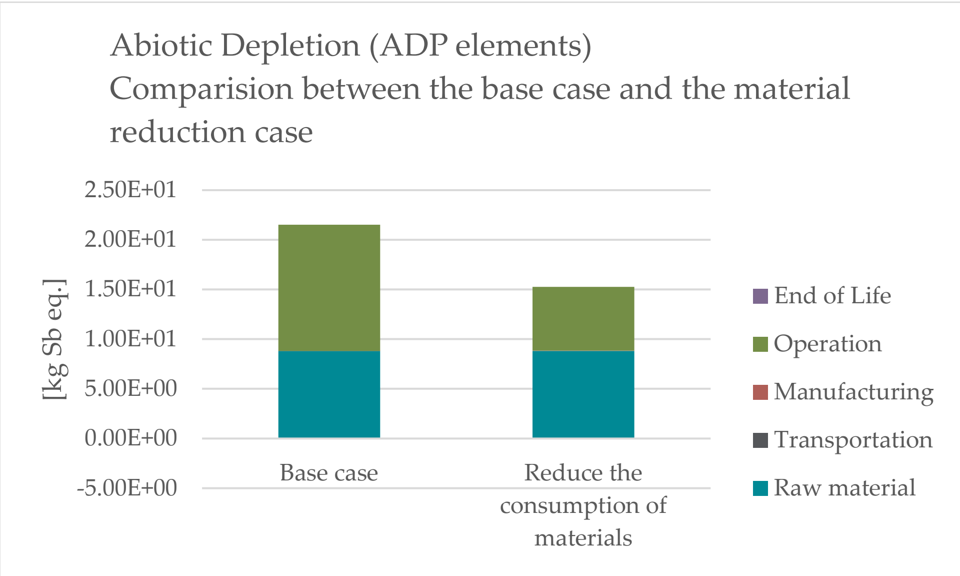


Figure 4.7 The comparison between the base case and the material reduction case in the category of Abiotic Depletion.

The base case results show obviously that the hotspots of ADP are material use especially the battery and electronic devices. Based on the changes made by strategy 1 and strategy 2, with less material use for the boat hull and use renewed components for maintenance, the improvements can be seen in Figure 4.7. The operation step, which refer to the boat maintenance, the impact has been reduced almost half.

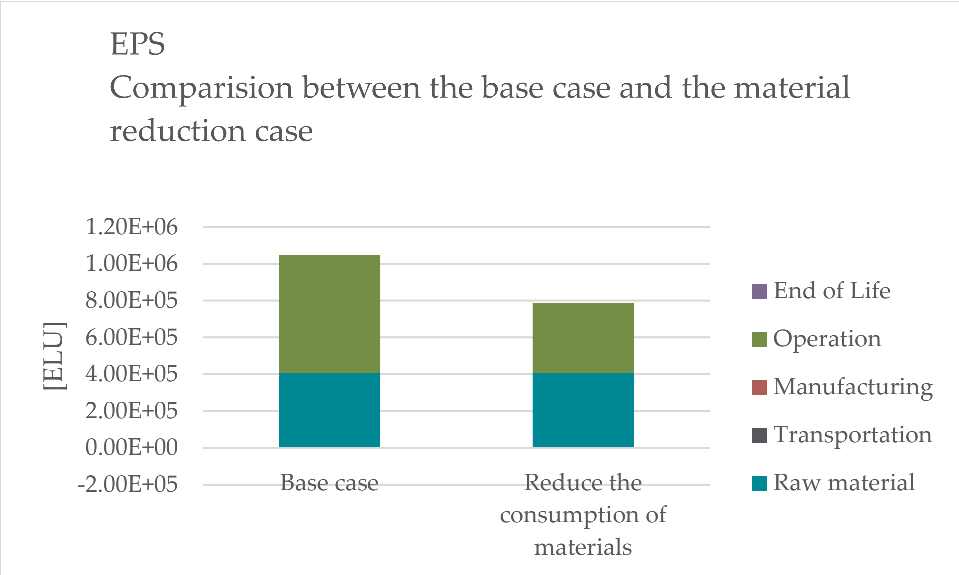


Figure 4.8 The comparison between the base case and the material reduction case in the category of EPS.

EPS category is also one impact category much related to material use. The Figure 4.8 above indicated that with changes of material reduction, the impacts from operation phase reduced more than 30% which is obviously to the total impacts.

4.3 Business models

From the study of results part and improvement options, it can be found that there are several ways applicable to have a better management for the boat life cycle to lower environmental impacts in general.

A business model is a description of the rationale of how a company creates, delivers and captures value for itself as well as the customer. Business model includes business processes and policies that a company adopts and follows are part of the business model. It is a conceptual structure that supports to achieve the goal.

Every business model intrinsically has two parts: the first part deals with designing and manufacturing the product, the second part deals with everything related, such as selling, distributing, etc. There are different types of business models meant for different businesses. There are 3 different business models included in this study for different purpose and target people.

4.3.1 Model 1: Electric motorboat

Electric motorboat refers to the boat using electricity during operation. This type of electrified boat requires special boat battery and engine at the manufacturing step.

The summary of this business model related to the changed part compared to base case can be seen in the table below:

Table 4.11 Business model of electric motorboat information

Life cycle stage	Changed part	Electric motor boat	Base case
Manufacturing	Engine	Electric engine	Diesel engine
Manufacturing	Battery	Electric boat battery (256 kg)	Normal boat battery (100 kg)
Operation	Energy resource	Swedish Electricity grid mix	Fossil diesel
Maintenance	Component replacement	Replace electric boat battery and electric engine	Replace normal battery and diesel engine
EOL	Component treatment	Treatment on electric boat battery and electric engine	Treatment on normal one boat waste

In this business model, the lifetime and user pattern are keeping the same as the base case, which is 30 years lifetime and 126 using hours per year. Engine and battery that are used for the electric motorboat are different from base case. The specific information can be seen in Appendix C. During the operation phase, energy supply is the Electricity, which select the Swedish electricity into calculation. The EOL treatment follows the change in manufacturing step.

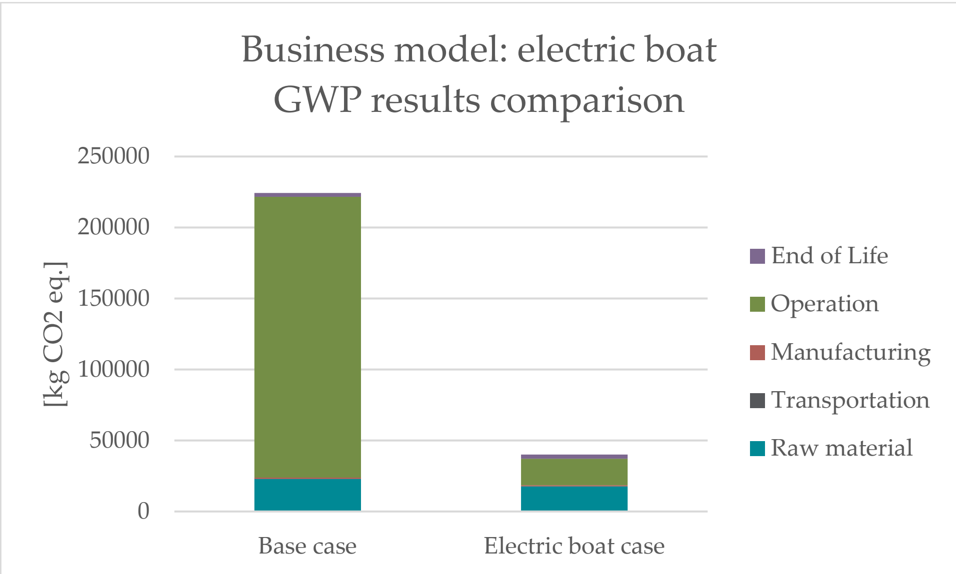


Figure 5.9 The comparison between the performance of electric boat business model and the base case in the GWP impact category.

Using the electricity as the energy source during boat operation phase largely reduce the climate emissions. See the comparison between the base case and the electric boat case. The total GWP impact reduced more than 80%.

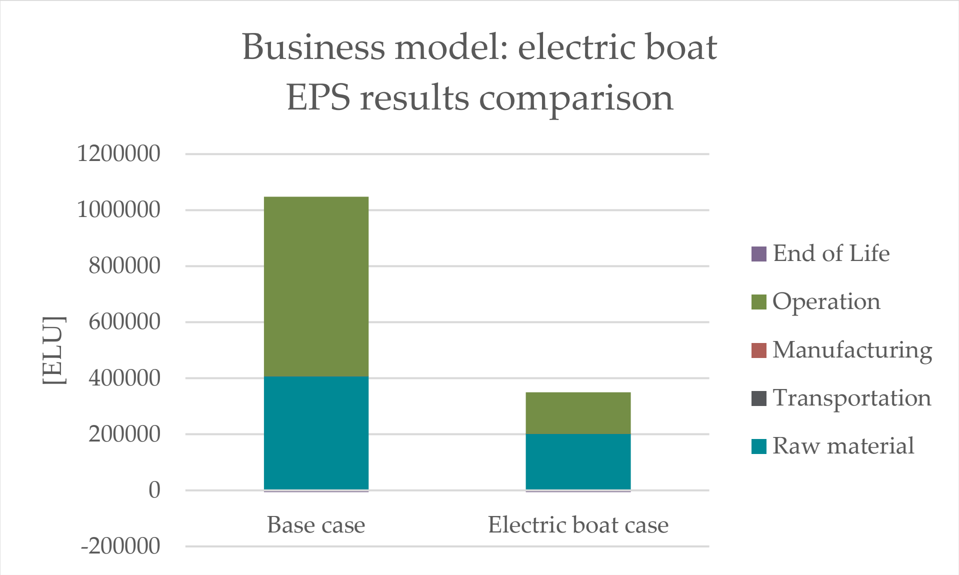


Figure 5.10 The comparison between the performance of electric boat business model and the base case in the EPS category.

For the EPS category, electric boat case shows also significant advantage. Especially for the boat operation time. The EPS impact from operation reduced around 80%.

4.3.2 Model 2: Prolonged lifespan with recycled components for maintenance

Lifetime extension is the concept to extend the boat using time to 50 years compared to the base case, 30 years lifetime. The boat is still keep using the same materials and components during manufacturing step but renewed components more times for maintenance in order to reach another 20 years life extension.

The table below indicated the changed parts during the boat life cycle.

Table 4.12 The comparison between the lifetime extension business case and the base case

Life cycle stage	Changed part	Lifetime extension	Base case
Manufacturing	Resin and glass fibre weight	Resin: 451.5 kg (57% reduction) Glass fibre: 901.5 kg (21% increasing)	Resin: 1 050 kg Glass fibre: 745 kg
Operation	More energy required for longer life span	Fossil diesel	Fossil diesel
Maintenance	Change diesel engine, battery amount and virgin or renewed components.	Battery: 4 renewed batteries Engine: 3 renewed engines	Battery: 2 brand new batteries Engine: 1 brand new engine
End Of Life	No change applied	Treatment on normal one boat waste (the renewed batteries and engines are not included in the assessment)	Treatment on normal one boat waste

Since the life extension for 20 years, so the boat requires two more engines and two more batteries. In terms of the resin and glass fibre used for the boat structure, the material composition ratio change has been applied. The end of life treatment keeps the same as the base case.

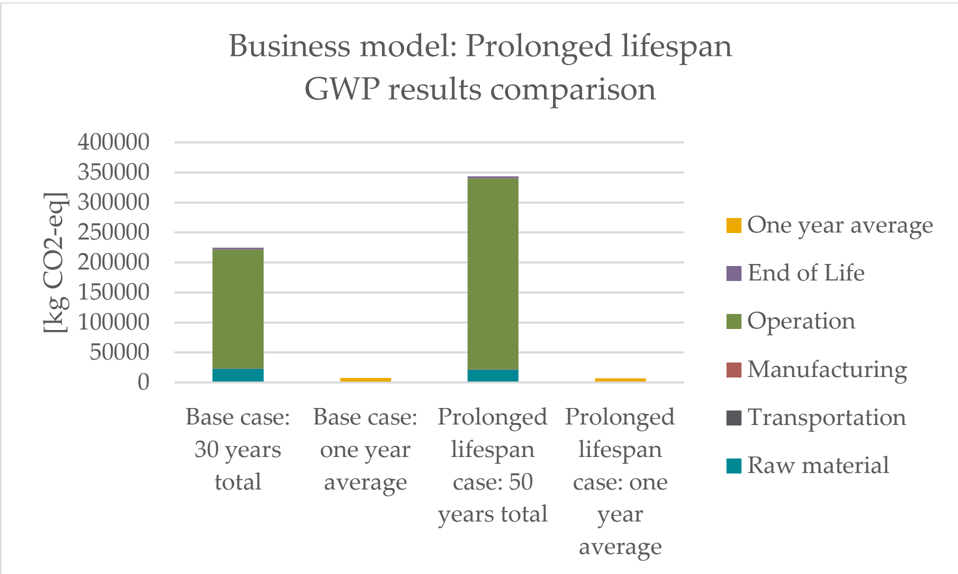


Figure 5.11 The comparison of GWP results between the base case running for 30 years and the prolonged lifespan case running for 50 years.

The GWP results presented in 3. Total GWP impacts of prolonged lifespan case is around 50% higher than the base case with 30 years lifetime. If averaged to one year, the prolonged lifespan business model will have around 600 kg CO2-eq per year been reduced during the lifetime.

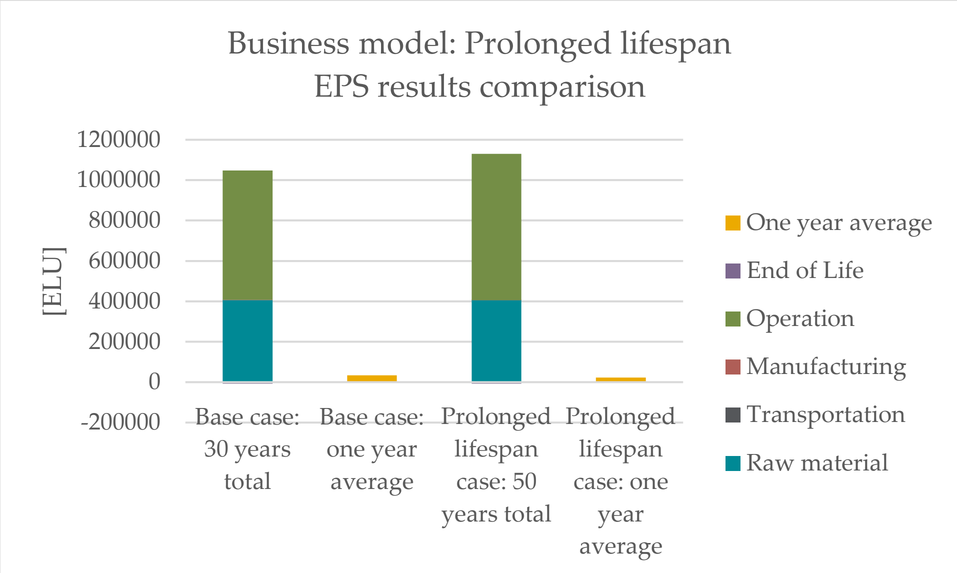


Figure 5.12 The comparison of EPS results between the base case running for 30 years and the prolonged lifespan case running for 50 years.

The EPS result presented in Figure 5.4 shows a significant advantage of the prolonged lifetime business case. The total EPS impacts from prolonged lifespan case is slightly higher than the base case, while the lifetime is 20 years longer. This is the message expressed that the longer lifetime of the boat has, the lower average one-year impact has. The one-year result shows the business model get 35% reduction from the base case.

4.3.3 Model 3: Company leasing

The company leasing model was considered from the boat owner standpoint. Instead of owning the boat individually, company leasing business model provide the possibility of sharing the boat with other people or families. With this business model, boat resource will be fully used, and equipment will be under better maintenance.

In terms of company leasing model, it is assumed that with the increasing rate of usage, the boating hours can be up to five times as normal boating hours (126 hours/year). The company leasing business model can also been considered as five families sharing one boat. Of course, the company leasing business model is very flexible to share among families while the change needs to be considered in the LCA analysis is the operation hours change. For the boat maintenance, it is assumed that the recycled battery and engine will be used instead of the new components. The assessment made in this study is to increase the boating hours for one year. Along with the boating hour increase, the fuel consumption is increasing as well. More detail information can be checked in Table 5.3.

Table 4.13 The comparison between the company leasing business case and the base case

Life cycle stage	Changed part	Sharing with 4 families	Base case
Manufacturing	No changes applied	Same	Same
Operation	Fuel consumption	630 boating hours per year (5 times as normal)	126 boating hours per year
Maintenance	Use recycled components	Use recycled components	Use new components
EOL	No changes applied	Same	Same

The company leasing business model was assumed the use rate will be 5 times as the base case. The function of company leasing will work the same as 5 individual boats. In the figures below shows the comparison between the base case, base case results times five and the company leasing business model.

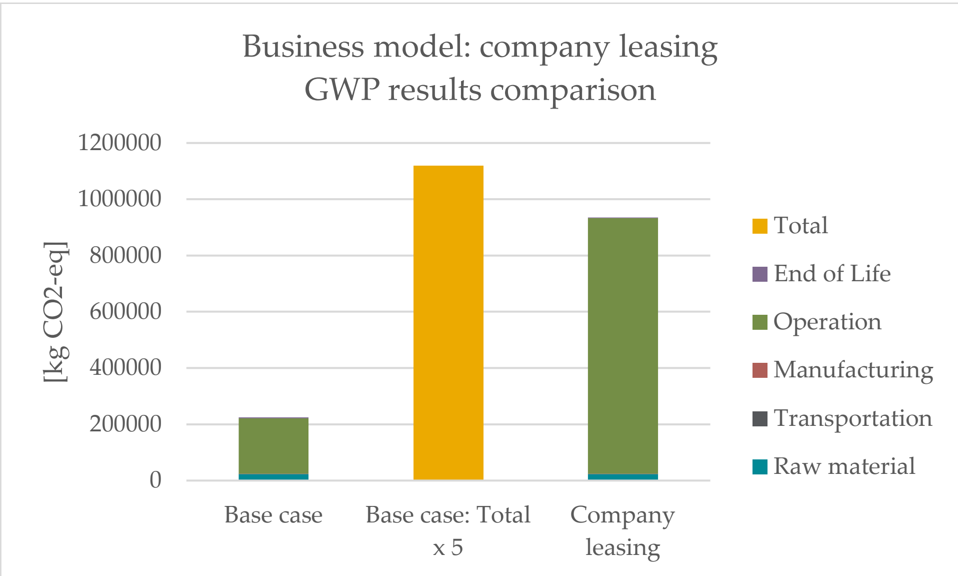


Figure 5.13 GWP results comparison between the base case and the company leasing business model. The impacts of base case results times five included as well for the same function comparison.

The GWP results are mainly influenced by the fuel use during boat operation time. The business model of company leasing will save the GHG emission from the boat construction material use but not too much saving from the operation phase. Thus Figure 5.5 indicated that the business model will be a certain lower than the base case works for the same function.

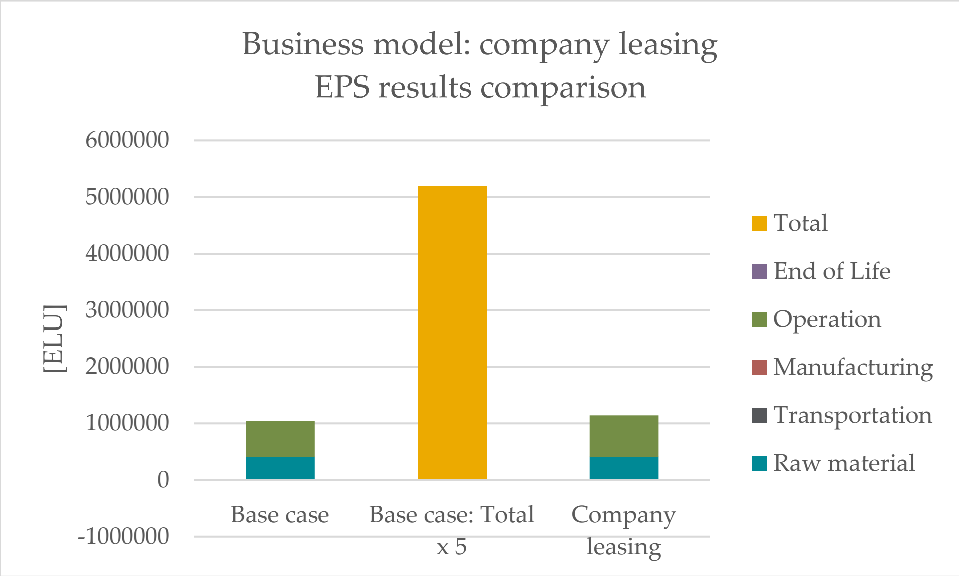


Figure 5.14 EPS results comparison between the base case and the company leasing business model. The impacts of base case results times five included as well for the same function comparison.

The company leasing business model shows a very outstanding performance in EPS category. The business model will only cause one fifth of the impacts as base case working for the same function. EPS is related much to the boat material use; thus the leasing strategy avoid much material consumption so improve the performance of EPS category.

5 Conclusions and recommendations

The most important conclusions from the LCA presented in this report relate to the identification of hotspots, improvement potentials and business model results. From this it was able to develop a set of equations that represented the impacts of the leisure boat's life cycle for input into the LCA-CE model.

The linear base case assessment identified the following conclusions in relation to the investigated impact categories:

Climate change:

- The single largest life cycle impact comes from the diesel used for the boat operation phase which stands for more than 80% of the total life cycle climate changes.
- The batteries, electronic devices and the material used for boat hull are determined as hotspots as well.

EPS and resource depletion (ADP):

- Materials and components are hotspots which stands for more than 90% of both ADP and EPS category.
- Battery, electronic devices standout as clear hotspots for components and materials stage.
- Although impacts from antifouling paint and fuel are not as large as components, they were still listed as hotspots since antifouling paint has relatively high impact for every single unit and fuel consumption is influenced by boat life length.

Ecotoxicity:

- Operation phase shares around 60% impacts and raw materials shares around 39% of total impacts.
- Battery and electronic devices are two major impact sources. The use phase has the most significant impact, but the source also comes from component exchange (battery and engine).
- Impacts from using antifouling paint is notable.

An overarching conclusion from the base case is that the majority of the impact over the life cycle occurs in the raw materials and operation stage. The impact from the manufacturing, transportation is relatively small.
The end of life, with the treatment assumption made in this study, could not fully represent the reality. The main reason for this is that most of retired boats don't go to formal treatment processes instead of been abandoned. For a small amount of recycling treatment, the site-specific data is not available, and its impacts are not well understood or quantified, and therefore not characterised within LCA databases. The EOL assessment in this study is based on the normal treatment strategy and reflect the potential recovery value.

Armed with the knowledge of the life cycle environmental hotspots, the next part of the study focused on finding how circular business models could influence the total results by aiming to improve or influence parameters relating to the hotspots. The three business models chosen to highlight the changes were "Electric motorboat", "Prolong lifespan" and "company leasing".

Electric motorboat business model held clear potential to reduce the impact caused by boat operation phase, especially for the climate change category, but also for the resource related categories EPS. Since Swedish electricity use much renewable resources so it is much cleaner than fossil fuels. It reduces more than 80% of total GWP impact and 80% of EPS impact from operation stage.

Prolong lifespan and company leasing business models are both the strategies to reduce the percent of impact from raw materials from the total impact. The "prolong lifespan" business model implying that the same materials and components can be used to get more function. The trade-off is that the life is extended by exchanging certain components, battery and engine implied in the study. The prolonged lifespan business model will have around 600 kg CO_2-eq per year been reduced during the lifetime and the EPS result will get 35% reduction from the base case. Company leasing case was set as standing on the market perspective. Considering leasing motorboat could reduce negative environmental impacts and at the same time, work for more functions and meet more family demand. The conclusion gave out that EPS category with outstanding performance which only cause one fifth of the impacts as base case if working for the same function. While the GWP results doesn't show significant improvement if still use the same energy source (fossil diesel).

From the base case and scenario assessment a number of variables were chosen to represent the most important hotspots of the LCA. By looking at the linear as well as the circular business model results conclusions were drawn on how these variables impact the results, and this was in turn converted into equations for the CE-LCA integration.
These equations were the goal of this study and the inventory and result assessment were performed with this goal in mind. The conclusions are therefore valid for integration and are not a footprint of existing circular business models or motorboat. The main take away is the relation between different life cycle stages and components and how this knowledge can be used to create input to a CE-model.

The results are also valid for highlighting important parameters and differences in future circular business models. The importance of considering certain components and life length are key take-aways, while the numerical results and magnitude of improvements can be misleading if used out of context.

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Appendix A. Brief introduction to LCA

Environmental life cycle assessment (LCA) is the calculation and evaluation of the environmentally relevant inputs and outputs and the potential environmental impacts of the life cycle of a product, material or service (ISO 14040:2006 and 14044:2006).

Environmental inputs and outputs refer to demand for natural resources and to emissions and solid waste. The life cycle consists of the technical system of processes and transports used at/needed for raw material extraction, production, use and after use (waste management or recycling). LCA is sometimes called a "cradle-to-grave" assessment (figure 1).

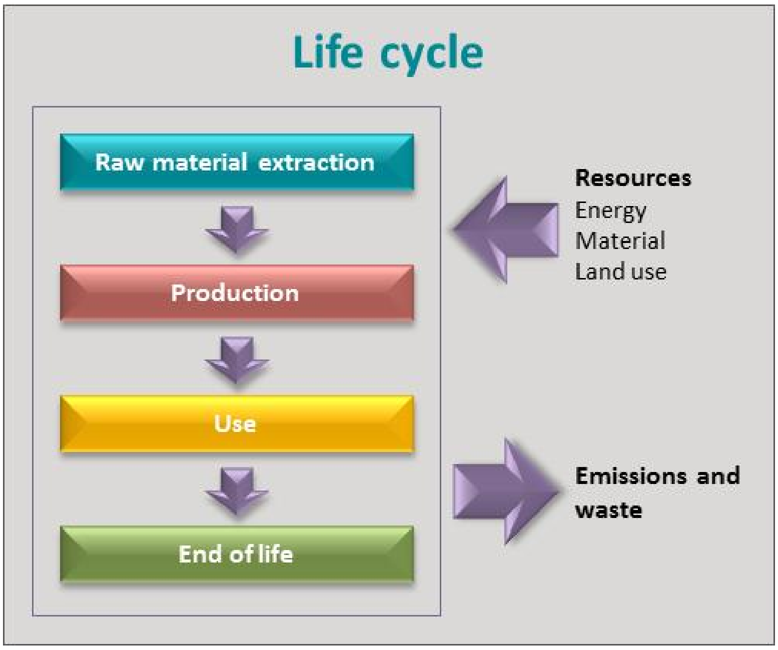

Figure 1: Illustration of the LCA system.

An LCA is divided into four phases. In accordance with the current terminology of the International Organization for Standardization (ISO), the phases are called goal and scope definition, inventory analysis, impact assessment, and interpretation (figure 2).

An LCA can be used in many different ways, depending on how the goal and scope are defined. Product development, decision making, indicator identification and marketing are examples of areas where the information retrieved from an LCA may be valuable.

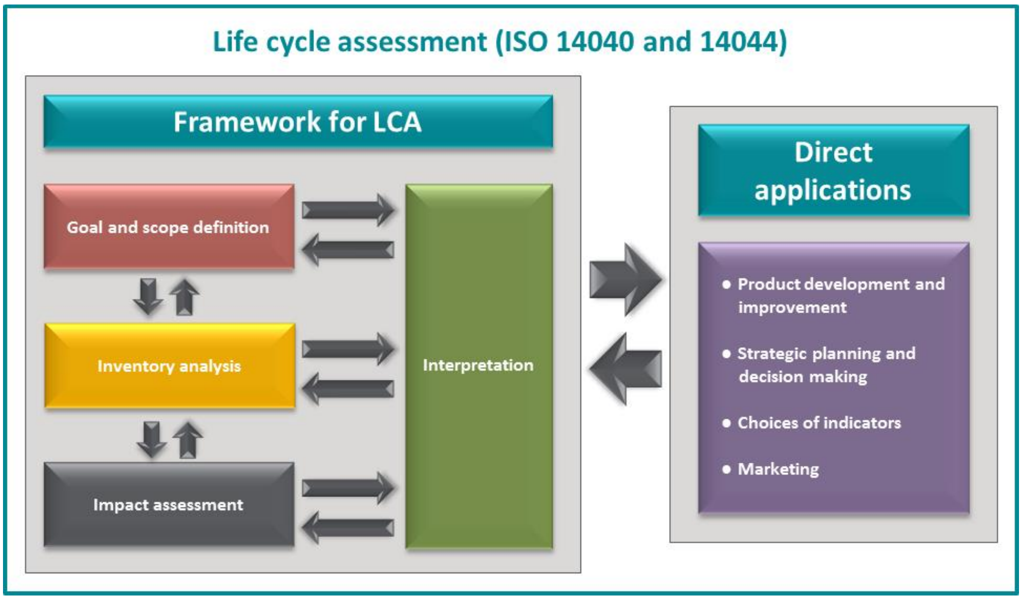

Figure 2: Illustration of the phases of an LCA.

Goal and Scope

In the first phase the purpose of the study is described. This description includes the intended application and audience, and the reasons for carrying out the study. Furthermore, the scope of the study is described. This includes a description of the limitations of the study, the functions of the systems investigated, the functional unit, the systems investigated, the system boundaries, the allocation approaches, the data requirements and data quality requirements, the key assumptions, the impact assessment method, the interpretation method, and the type of reporting.

Inventory analysis

In the inventory analysis, data are collected and interpreted, calculations are made and the inventory results are calculated and presented. Mass flows and environmental inputs and outputs are calculated and presented.

Impact assessment

In the life cycle impact assessment (LCIA), the production system is examined from an environmental perspective using category indicators. The LCIA also provides information for the interpretation phase.

For comparative assertions, there are four mandatory elements of LCIA:

Selection of impact categories, category indicators and models,

Assignment of the LCIA results (classification),

Calculation of category indicator results (characterization) and

Data quality analysis.

The following elements are optional:

Calculating the magnitude of category indicator results relative to a reference value (normalization),

Grouping and

Weighting.

Interpretation

The interpretation is the phase where the results are analysed in relation to the goal and scope definition, where conclusions are reached, the limitations of the results are presented and where recommendations are provided based on the findings of the preceding phases of the LCA.

An LCA is generally an iterative process. The impact assessment helps increasing the knowledge about what environmental inputs and outputs are important. This knowledge can be used in the collection of better data for those inputs and outputs in order to improve the inventory analysis.

The conclusions of the LCA should be compatible to the goals and quality of the study.

EPS method – Environmental damage cost

To show environmental impacts not on the level of impact categories but aggregated in a single value ("single score"), a methodological weighting of environmental impacts against each other is necessary. How important is for example acidification compared to global warming?

In comparison to the results of impact categories, which are based on scientific models, it is important to understand that "single-score"-methods always rely on subjective value choices. Results are therefore depended on subjective preferences integrated in the respective method and should be understood as representative only under the valued conditions.

The Environmental Priority Strategy (EPS) (Steen, 2015) method strives to minimize the subjectivity by introducing it only in the last stage (Steen, 2015). Only the monetary valuation is subjective. The harm (for example lives lost) caused by different environmental impacts is taken from scientific studies, implying that the harm is not evaluated subjectively, only the value of the harm. Compare this to evaluating the value/cost of human lives lost due to CO2 (EPS case) and evaluating the cost of CO2 emissions directly.

EPS 2000d is value based, meaning it aims to assess actual real-life impacts and their financial implications. In this method the environmental impacts evaluated and expressed in terms of "willingness to pay" to hinder the damage of five safeguard subjects: human health, biological diversity, eco-system production, natural resources and aesthetic values. The calculation is based on an average OECD citizen (Steen, 2015).

Appendix B. Goal and scope details

B.1 System boundaries

The LCA includes all processes contributing significantly to the environmental impacts of the system investigated.

Boundary towards nature

For inputs of fuels, electricity and raw materials the cradle of the life cycle is nature. The boundary between nature and the product life cycle is crossed when the natural resources (e.g. crude oil or uranium) are extracted from the ground. The "grave" of the life cycle is the air (e.g. emissions from combustion of fuels) or water (e.g. water emissions from wastewater treatment).

Boundary in the technical system

The technical system is limited to the motorboat and its supporting components. The larger system containing for example servers and towers is not included. No auxiliary impact from the producing company was included in the study, for example office spaces or business travel.

Temporal boundaries

The study considers current conditions, although some stages like recycling may occur in the future this is not modelled in the study.

Geographical boundaries

The study aims to study the motorboat in Sweden through its life cycle. Where available, the boat raw materials were chosen for EU data. Where these were not available EU averages dataset, global average was a last choice. For the production of the boat, data for Sweden were performed.

Non-elementary inputs and outputs

The production of inputs such as chemicals and auxiliary materials used in a process is excluded from the LCA if the amount is small and if the production is not expected to contribute significantly to any of the studied impact categories.

Valuable material outputs from recycling as well as waste along the production chain and use are not followed to grave.

B.2 Data quality

The bill of materials for the motorboat, used to model the cradle to gate impact of the material production was taken from Nimbus boat company in Sweden. Small flows were excluded already when the inventory was received. This exclusion was not deemed to impact the results of this study.

The data for energy consumption in the production stage was also taken directly from Nimbus factory. Electricity and diesel use were given in one-year total which were allocated to one studied motorboat by mass allocation. The same methodology was applied to calculate the output emissions.

In addition to this specific information, generic data was used for the upstream flows. Generic data are defined as data sets mainly based on literature and other publications (sometimes from several data sources). In this study most generic data correspond to:

- production of raw materials (such as metals, plastics etc.)
- energy (production of fuels and electricity) and,
- transportation data (energy use and emissions per tonne km) for different transport modes.
- End of life treatment (such as impacts from incineration, recycling etc.)

Most generic data in this study have been based on data sets from the Gabi Professional database [Gabi] 2018, as well as the Ecoinvent version 3.3 database.

B.3 Allocation approaches

The following stepwise allocation procedure is required by ISO 14044: 2006:

The first step of the procedure is: "wherever possible, allocation should be avoided by dividing the unit process to be allocated into two or more sub-processes and collecting the environmental data related to these sub-processes, or by expanding the product system to include the additional functions related to the co-products."

The second step of the procedure recommended by ISO 14044: 2006 is: "where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way which reflects the underlying physical causal relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products and functions delivered by the system”.

The third and final step of the ISO procedure is: "where physical causal relationships alone cannot be established or used as the basis for the allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.”

Note that ISO 14044 does not require that “other relationships” should be causal relationships. This means that virtually any allocation method is allowed as a final option.

The allocation procedures used in this project are described in sub-sections below.

Heijungs and Guinée [Heijungs et al., 1992] discuss two main approaches to solve the multi-functionality problem, e.g. at waste treatment; the partitioning method (i.e. allocation) and the substitution method (i.e. avoiding allocation through system expansion). According to them, there are both practical and theoretical reasons to prefer partitioning to substitution: Partitioning involves much fewer data; just a couple of allocation factors per multi-functional process, instead of a whole process specification of a number of avoided processes. The fact that one must make technological specifications of avoided processes is according to Heijungs and Guinée a problem that makes all attempts futile, since it introduces a component of speculation that is more dubious than any other speculations in LCA and leads to an accumulation of “what-if” arguments. Also, the partitioning method involves the setting of allocation factors, numbers which are essentially arbitrary and can therefore be labelled as speculative as well. However, some degree of arbitrariness is inevitable given the fact that LCA should deal with the multi-functionality problem, and that isolating one function from a web of interlinked activities is an artificial exercise. In that respect, Heijungs and Guinée are of the opinion that the partitioning method is honest: it provides an artificial solution to an artificial question.

B.4 Key assumptions and limitations

B.4.1 Limits enforced by goal and scope

The main limitation in the study is introduced by the goal and scope definition. The study focuses on the integration of LCA and CE-model, thereby focusing on hot-spot identification, finding how varying certain parameters impact the results and creating equations describing the LCA.

Based on this, several important inputs are based on rough assumptions. Important examples include the number of maintenance components and the life length of the motorboat.

This implies that the results are not suitable as footprints of a motorboat but should be seen as inputs for a CE-model. The results can also be used to highlight potentials of different business models, but the numerical results and magnitude of improvements can be misleading if used out of context.

B.4.2 Data gaps

Based on the scope of the study, the inventory analysis did not deep dive into the detailed material content or production specification of the motorboat.

Supporting materials in production, like chemical, are not included. Production electricity is based on Nimbus own monitoring. It is also likely that the actual material content may be more detailed in terms of specific alloys and special materials than what is stated in the bill of materials that this study is based on. None of these factors in concluded to have any impact on the results and conclusions in this study, although it does influence the potential to draw more overarching conclusions from the study.

Appendix C. Details on data collection

C.1 Material composition datasets

In Table 8.4 listed materials used to build one motorboat.

Table 6.1 Motorboat material used, and datasets modelled in Gabi software

Material	Dataset used in Gabi	Data source
DCPD Polyester	DE: Polyester Resin unsaturated (UP)	Gabi ts, Version 8.5
MEK Peroxide	Methyl ethyl ketone peroxide (MEKP)	IVL database
E-Glass	DE: Glass fibres	Gabi ts, Version 8.5
PVC	RER: Polyvinyl chloride sheet (PVC)	PlasticsEurope
Crystic CC60	EU-28: Glue for gypsum boards (EN15804 A1-A3)	Gabi ts, Version 8.5
MS polymer SIKA	DE: Styrene Maleic Anhydride Copolymer (SMA) Mix	Gabi ts, Version 8.5
Engine + Gear Oil	EU-28: Lubricants at refinery	Gabi ts, Version 8.5
Wood	EU-28: Solid construction timber (softwood) (EN15804 A1-A3)	Gabi ts, Version 8.5
Stainless steel	RER: Stainless steel cold rolled coil (304)	Eurofer
Brass	EU-28: Brass (CuZn20)	Gabi ts, Version 8.5
Alumina	EU-28: Aluminium sheet mix	Gabi ts, Version 8.5
Black iron	DE: Cast iron component (EN15804 A1-A3)	Gabi ts, Version 8.5
Diesel inboard	Modeled (See Table 10.5)	/
Gearbox	Modeled (See Table 10.6)	/
Glass	EU-28: Window glass simple (EN15804 A1-A3)	Gabi ts, Version 8.5
Cabels	EU-28: Cable 1 wire (EN15804 A1-A3)	Gabi ts, Version 8.5
Electronics devises	RER: electronics production, for control units	ecoinvent 3.3
batteries	GLO: battery production, Li-ion, rechargeable, prismatic	ecoinvent 3.3
Porsline	DE: Kaolin	Gabi ts, Version 8.5
PVC	RER: Polyvinylchloride pipe (PVC)	PlasticsEurope
Textiles	GLO: Textile Manufacturing - Knit Fabric (Batch Dyed) CottonInc <p-agg>	CottonInc
Polyeter	EU-28: Polyester (PET) fabric	Gabi ts, Version 8.5
Thermoplastics	EU-28: Polypropylene fibers (PP)	Gabi ts, Version 8.5
Vinyl	DE: Polyvinyl chloride granulate (Suspension; S-PVC) mix	Gabi ts, Version 8.5
Antifouling 1	Modeled (See Table 10.7)	/
Antifouling 2	Modeled (See Table 10.8)	/

The motorboat diesel engine and gearbox were modelled by using the data information of a truck situation as a proxy. SeeTable 8.5 and Table 8.6 below.

Table 6.2 Material composition for diesel inboard engine

Input	Dataset used in Gabi	Data source	Amount (%)
Cast iron	DE: Cast iron component (EN15804 A1-A3)	Gabi ts, Version 8.5	48.3%
Aluminium	EU-28: Aluminium sheet mix	Gabi ts, Version 8.5	13.3%
Stainless steel	RER: Stainless steel cold rolled coil (304)	Eurofer	0.6%
Steel	GLO: Steel hot rolled coil (ILCD)	worldsteel/ELCD	28.1%
Copper	EU-27: Copper Sheet Mix	DKI/ECI	1.5%
Brass	EU-28: Brass (CuZn20)	Gabi ts, Version 8.5	5.2%
Rubber	DE: Styrene-Butadiene Rubber (SBR) Mix	Gabi ts, Version 8.5	1.5%
Nylon	RoW: nylon 6 production	ecoinvent 3.3	1.5%

Table 6.3 Gearbox material composition

Material	Datasets	Data source	Amount
Steel	GLO: Steel hot rolled coil (ILCD)	worldsteel/ELCD	80%
Cast iron	RER: Stainless steel cold rolled coil (304)	Eurofer	10%
Cast aluminium	EU-28: Aluminium sheet mix	Gabi ts, Version 8.5	7%
Stainless steel	RER: Stainless steel cold rolled coil (304)	Eurofer	1%
Copper	EU-27: Copper Sheet Mix	DKI/ECI	1%
Plastic	DE: Styrene-Butadiene Rubber (SBR) Mix	Gabi ts, Version 8.5	1%

There are two types of antifouling paints included in the study, their specific information is listed in Table 8.7 and Table 8.8.

Table 6.4 Material use, and datasets used for "Antifouling paint 1: Biltema Antifouling Svart" in Gabi software

Antifouling paint 1: Biltema Antifouling Svart				
Material input	Dataset use	Data source	Amount (kg)	Comment
Xylene	EU-27: Xylenes, mixed	PlasticsEurope	0.34	11.5-12.5%
Zinc oxide	Zinc oxide, dry powder	IVL database	0.24	8-9%
copper oxide	Cuprous oxide (copper (I) oxide)	IVL database	0.36	12.5-15%
Hydrocarbons, C9 aromatics	EU-28: Aromatics (BTX) at refinery	Gabi ts, Version 8.5	0.50	15-20%
Ethylbenzene	RER: Ethyl benzene	PlasticsEurope	0.07	2-3%
Carbon black / Kim smoke	DE: Carbon black (furnace black; general purpose)	Gabi ts, Version 8.5	0.07	2-3%
Total			2.8	
Water emission				
Copper	Copper [Heavy metals to fresh water]	Gabi ts	0.260	
Zinc	Zinc [Heavy metals to fresh water]	Gabi ts	0.184	
Soil/Ground emission				
Copper	Copper [Heavy metals to sea water]	Gabi ts	0.015	Estimated 15% Cu removed during scraping

Table 6.5 Material use, and datasets used for "Antifouling paint 2: Biltema Antifouling BS" in Gabi software

Antifouling paint 2: Biltema Antifouling BS				
Material input	Dataset use	Data source	Amount (kg)	Comment
Xylene	EU-27: Xylenes, mixed	PlasticsEurope	0.39	12.5-15%
Zinc oxide	Zinc oxide, dry powder	IVL database	0.63	20-25%
copper oxide	Cuprous oxide (copper (I) oxide)	IVL database	0.24	7-10%
Solventnaftta (petroleum), lightweight	EU-28: Aromatics (BTX) at refinery	Gabi ts, Version 8.5	0.50	15-20%
aromatic, <0.1% benzene"	RER: Ethyl benzene	PlasticsEurope	0.07	1-3%
Total			2.8	
Water emission				
Copper	Copper [Heavy metals to fresh water]	Gabi ts	0.082	
Zinc	Zinc [Heavy metals to fresh water]	Gabi ts	0.199	
Soil/Ground emission				
Copper	Copper [Heavy metals to sea water]	Gabi ts	0.019	Estimated 15% Cu removed during scraping

The engine used for electric boat is specifically modelled. Materials use for engine composition, emissions are listed in Table 8.9.

Table 6.6 Electric boat engine: material composition and emissions

Electric boat engine material input	Dataset use	Data source	Amount	Unit
Aluminum	RER: aluminium alloy production, AlMg3	ecoinvent 3.3	6.09	kg
Boron carbide	GLO: boron carbide production	ecoinvent 3.3	0.007	kg
Copper	RoW: copper production, primary	ecoinvent 3.3	2.2	kg
Ferrosilicon	RoW: ferrosilicon production	ecoinvent 3.3	0.37	kg
Liquid enamel, polyester share	RoW: polyester resin production, unsaturated	ecoinvent 3.3	0.098	kg
Liquid enamel, xylene solvent share	RoW: xylene production	ecoinvent 3.3	0.052	kg
Liquid epoxy resin	RoW: epoxy resin production, liquid	ecoinvent 3.3	0.104	kg
Liquid varnish, solid share	RoW: alkyd resin production, long oil, product in 70% white spirit solution state	ecoinvent 3.3	0.11	kg
Liquid varnish, solvent share	RoW: market for naphtha	ecoinvent 3.3	0.101	kg

Low-alloy carbon steel	RoW: steel production, converter, low-alloyed	ecoinvent 3.3	1.04	kg
Magnet fixation resin, methacrylate ester	RoW: methyl methacrylate production	ecoinvent 3.3	0.023	kg
Mica tape, glass fiber cloth content	RoW: glass fibre production	ecoinvent 3.3	0.005	kg
Mica tape, mica content	RoW: silica sand production	ecoinvent 3.3	0.018	kg
Mica tape, silicone bond content	RoW: silicone product production	ecoinvent 3.3	0.003	kg
Nickel	GLO: market for nickel, 99.5%	ecoinvent 3.3	0.005	kg
Nylon lacing cord	RoW: nylon 6 production	ecoinvent 3.3	0.006	kg
PBT granulates	RoW: polyethylene terephthalate production, granulate, bottle grade	ecoinvent 3.3	0.068	kg
PET granulates	RoW: polyethylene terephthalate production, granulate, bottle grade	ecoinvent 3.3	0.082	kg
Phenolic resin	RoW: phenolic resin production	ecoinvent 3.3	0.015	kg
Silica filler in epoxy resin	RoW: silica sand production	ecoinvent 3.3	0.033	kg
Silicone granulates	RoW: silicone product production	ecoinvent 3.3	0.013	kg
Stainless steel, 18/8 grade	RoW: steel production, chromium steel 18/8, hot rolled	ecoinvent 3.3	0.44	kg
Unalloyed steel	RoW: steel production, converter, unalloyed	ecoinvent 3.3	17.4	kg
Energy input	RoW: market for heat, central or small-scale, natural gas	ecoinvent 3.3	61.3 MJ	kg
Argon shielding gas	RoW: argon production, liquid	ecoinvent 3.3	0.017	kg
Caustic soda	GLO: market for sodium hydroxide, without water, in 50% solution state	ecoinvent 3.3	0.0005	kg
Cutting fluid	RoW: market for naphtha	ecoinvent 3.3	0.278	kg
Graphite (anode)	GLO: market for anode, graphite, for lithium-ion battery	ecoinvent 3.3	0.05	kg
Hydrogen	RoW: market for hydrogen, liquid	ecoinvent 3.3	0.3	kg
Lithium fluoride	RoW: lithium fluoride production	ecoinvent 3.3	0.002	kg
Propane/LPG	RoW: market for liquefied petroleum gas	ecoinvent 3.3	0.18	kg
Quenching fluid, concentrated	RoW: propylene glycol production, liquid	ecoinvent 3.3	1.37	kg
Quicklime powder	RoW: quicklime production, milled, packed	ecoinvent 3.3	0.019	kg
Rolling/lubricating oil	RoW: lubricating oil production	ecoinvent 3.3	0.16	kg

Sulfuric acid	RoW: sulfuric acid production	ecoinvent 3.3	0.291	kg
Water	RoW: tap water production, conventional treatment	ecoinvent 3.3	15.6	kg
Emissions				
Aluminum	Aluminium, unspecified	Gabi ts	2.3	g
Carbon dioxide	Carbon dioxide	Gabi ts	0.718	kg
Dust (neodymium oxide)	Particulates, > 2.5 µm, < 10 µm	Gabi ts	0.8	g
Hydrocarbons	Hydrocarbons, aliphatic, unsaturated	Gabi ts	5	g
Hydrogen fluoride	Hydrogen fluoride	Gabi ts	1	g
Nickel	Nickel, unspecified	Gabi ts	2.1	mg
Nitrogen oxides	Nitrogen oxides	Gabi ts	1.5	g
Sulfur oxides	Sulphur dioxide	Gabi ts	0.91	g
VOC	NMVOC	Gabi ts	107	g
Xylene	Xylene	Gabi ts	52	g
Nickel sulfamate	Nickel, ion	Gabi ts	2.5	mg
Aluminum scrap	Aluminum scrap for recycling	Gabi ts	0.38	kg
Copper scrap	Copper scrap for recycling	Gabi ts	58	g
Neodymium-iron-boron scrap	Iron scrap, unsorted	Gabi ts	98	g
Sludge, dry content	Sludge, NaCl electrolysis	Gabi ts	15	g
Sludge, dry content	Hazardous waste, optional	Gabi ts	151	g
Steel scrap	Steel scrap for recycling	Gabi ts	9.47	kg
Waste aluminum, not recovered	Waste aluminium	Gabi ts	0.341	kg
Waste oil, concentrated share in dilution	Waste mineral oil	Gabi ts	278	g
Waste quenching fluid, conc. share in dil.	Spent antifreezer liquid	Gabi ts	1.37	kg
Complete electrical machine, PMSM	System reference flow	Gabi ts	17.6	kg

Electric boat battery compositions are listed in Table 8.10.

Table 6.7 Battery used for electric boat

Electric boat battery for 1 kg	Amount	Unit
Material input		
Battery packaging	0.32	kg
BMS	0.037	kg
Cooling	0.04	kg
Cell	0.603	kg
Water	380	kg
Electricity	28	kWh

In the study, the electric boat battery was assumed to be 256 kg.

C.2 Boat use phase datasets

Use phase emissions in terms of fossil diesel presented in Table 8.11

Table 6.8 Motorboat use phase in terms of using fossil diesel

Input	Amount(kg)	Flow name in Gabi
Diesel	1	EU-28: Diesel mix at refinery ts
Emission to air		
NOx	0.0370272	Nitrogen oxides [Inorganic emissions to air]
CO	0.0201096	Carbon monoxide [Inorganic emissions to air]
NMVOC	0.007068	NMVOC (unspecified) [Group NMVOC to air]
.PM10	0.0042864	Particulates, > 10 um [ecoinvent long-term to air]
PM2.5	0.0042864	Particulates, < 2.5 um [ecoinvent long-term to air]
BC	0.0023712	Total organic carbon [Other emissions to air]
NH3	7.3872E-06	Ammonia [Inorganic emissions to industrial soil]
CO2	3.15	Carbon dioxide [Inorganic emissions to air]
Emission to water		
VOC	0.00184	VOC (unspecified) [Organic emissions to air (group VOC)]
Benzene	0.0000348	Benzene [Group NMVOC to air]
Toluene	0.0000256	Toluene (methyl benzene) [Group NMVOC to air]
1,3-butadiene	0.000006	Butadiene [Hydrocarbons to fresh water]
Formaldehyde	0.000104	Formaldehyde (methanal) [Hydrocarbons to sea water]
Naphthalene	1.24E-05	Naphthalene [Organic emissions to sea water]
Phenanthrene	8.80E-07	Phenanthrene [Hydrocarbons to sea water]
Acenaphthylene	0.00000022	Acenaphthylene [Hydrocarbons to sea water]
Anthracene	0.000000228	Anthracene [Hydrocarbons to sea water]
Fluoranthene	0.000000124	Fluoranthene [Hydrocarbons to sea water]
Benzo(a)pyrene	3.84E-08	Benzo(a)pyrene [ecoinvent long-term to air]
Benzo(b)fluoranthene	3.08E-08	Benzo(b)fluoranthene [Hydrocarbons to fresh water]
Benzo(k)fluoranthene	1.16E-08	Benzo(k)fluoranthene [ecoinvent long-term to fresh water]
Indeno(1,2,3-cd)pyrene	1.84E-12	Indeno(1,2,3-cd)pyrene [ecoinvent long-term to fresh water]
PAH	0.000014	Polycyclic aromatic hydrocarbons (PAH, unspec.) [Hydrocarbons to sea water]

Fuel use pattern related to the speed of motorboat presented in Figure 8.1

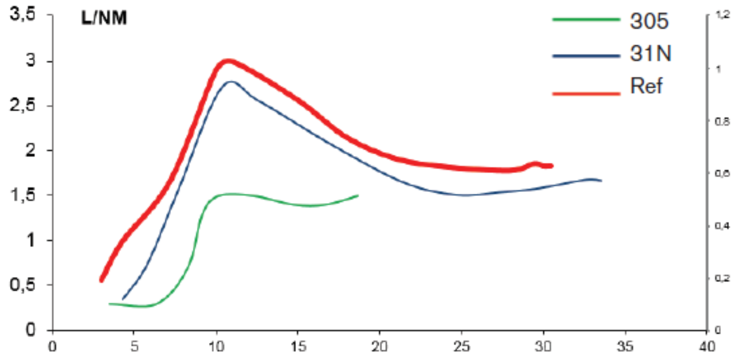

Figure 8.1 The fuel use pattern

Reference: (Smart speed concept - comfort and safety before speed)

C.3 Boat EOL treatment datasets

Table 6.9 include the information about Gabi datasets selected for the motorboat EOL modelling.

Table 6.9 Motorboat End of life treatment dataset used in Gabi software and its source

Material	Treatment	Gabi datasets	Data source
DCPD Polyester	Incineration	DE: Polyvinyl chloride (PVC) in waste incineration plant	Gabi ts
MEK Peroxide	NA	/	/
E-Glass	NA	/	/
PVC	Incineration	DE: Polyvinyl chloride (PVC) in waste incineration plant	Gabi ts
Wood	Incineration	RoW: treatment of waste wood, untreated, municipal incineration	ecoinvent 3.3
Stainless steel	Recycling	GLO: Credit for recycling of stainless-steel scrap	IVL database
Brass	Recycling	Brass recycling - gate to gate-poxy	IVL database
Alumina	Recycling	EU-27: Aluminium recycling (2010)	EAA
Black iron	Recycling	GLO: Credit for recycling of steel scrap	IVL database
Diesel inboard	Specific	GLO: market for used internal combustion engine, passenger car	ecoinvent 3.3
Gearbox	Incineration	RoW: treatment of waste plastic, consumer electronics, municipal incineration	ecoinvent 3.3
Glass	Specific	EU-27: End of life of glass (landfill/incineration)	IVL database
Cabels	Specific	GLO: treatment of used cable	ecoinvent 3.3
Electronics devises	Specific	GLO: treatment of waste electric and electronic equipment, shredding	ecoinvent 3.3
batteries	Specific	GLO: treatment of used Li-ion battery, hydrometallurgical treatment	ecoinvent 3.3
Porsline	Landfill	/	/
PVC	Recycling	EU-28: Plastic granulate secondary (low metal contamination)	Gabi ts
Textiles	Incineration	EU-27: Waste incineration of textile fraction in municipal solid waste (MSW)	ELCD/CEWEP

Polyester	Incineration	RoW: treatment of waste plastic, consumer electronics, municipal incineration ecoinvent 3.3	ecoinvent 3.3
Thermoplastics	Incineration	EU-28: Polyethylene terephthalate (PET) in waste incineration plant	Gabi ts

Appendix D. Equations for the LCA-CE integration

D.1 GWP impacts equations

$$\boldsymbol{I_{total} = I_{material} + I_{use\ phase} + I_{EOL}} \quad \text{(A1)}$$

Part 1: Materials

$$\boldsymbol{I_{materials} = I_{component} + I_{\underset{Alter}{Hull}} + I_{Electronic} * y_1 + I_{battery} * y_2 + I_{trp} + I_{Assembly}} \quad \text{(A2)}$$

$I_{component}$ = 4107 [kgCO_2-eq]

includes all materials impact except "Hull", Electronics" and "Battery". Suggest to keep as constant

$I_{\underset{Alter}{Hull}}$ = xxx [kgCO_2-eq] impact from boat hull (alternative: hull weight reduction scenario)

(Base case: 4876 [kgCO_2-eq] from fibreglass hull.)

$I_{Electronic}$ = 5425 [kgCO_2-eq]. Impacts from electronic devices. Suggestion to keep as constant

$I_{battery}$ = 8480 [kgCO_2-eq] Impacts from battery. Suggestion to keep as constant

y_1 = weight of electronics compared to base case [%]

y_2 = weight of battery compared to base case [%] (base case 100 kg)

I_{trp} = 96 [kgCO_2-eq] Impact from material transportation. Suggestion to keep as constant.

$I_{assembly}$ = 810 [kgCO_2-eq] Suggestion to keep as constant.
(It includes results of electricity use in the factory and emissions.)

If include remanufacturing and recycling flows into consideration to Box "Producer", the equation:

$$\boldsymbol{I_{subsupplier} = I_{component} + I_{\underset{Alter}{Hull}} + (I_{\underset{Virgin}{Electronic}} * a_{el.v} + I_{\underset{Reman}{Electronic}} * a_{el.Re}) * y_1 + (I_{\underset{virgin}{battery}} * a_{en.v} + I_{\underset{Reman}{battery}} * a_{en.Re}) * y_2} \quad \text{(A3)}$$

$I_{\underset{Virgin}{xx}}$ = xxx [kgCO_2 − eq] from virgin "xx". Suggestion to keep as constant

$a_{xx.v}$ = allocation rate of virgin "xx" compared to total electronic devices [%]

$I_{\underset{Reman}{xx}}$ = xxx [kgCO_2-eq] from remanufactured "xx".

$a_{xx.Re}$ = allocation rate of remanufactured "xx"compared to total electronic devices [%]

Part 2: Operation and maintenance

$$\boldsymbol{I_{use\ phase}} = \boldsymbol{I_{fuel\ combustion}} + \boldsymbol{I_{maintenance}}$$

$$= \boldsymbol{T_{lifespan}} * \boldsymbol{I_{fuel\ combustion}} + \left(\boldsymbol{T_{lifespan}} * \frac{\boldsymbol{1}}{\boldsymbol{10}} - \boldsymbol{1}\right) * \boldsymbol{I_{battery}} + \left(\boldsymbol{T_{lifespan}} * \frac{\boldsymbol{1}}{\boldsymbol{15}} - \boldsymbol{1}\right) * \boldsymbol{I_{engine}} + \left(\boldsymbol{T_{lifespan}} * \boldsymbol{2.4}\right) * \boldsymbol{I_{AF\ paint}} \qquad \text{(B1)}$$

$T_{lifespan}$ = [year] The life time of the boat.

Base case set the lifetime is 30 years.

$I_{fuel\ combustion} = XXX \frac{[kgCO_2 - eq]}{year}$. The fuel combustion impact for one year. Base case: fossil diesel with 6000 kg $\frac{CO2_{eq}}{year}$.

$I_{battery} = xxx \frac{[kgCO_2 - eq]}{piece}$. The renewed battery impact. Can select to use virgin or remanufacturing battery.

$I_{engine} = xxx \frac{[kgCO_2 - eq]}{piece}$. The renewed engine impact. Can select to use virgin or remanufacturing battery.

$I_{AF\ Paint} = 4.65 \frac{[kgCO_2 - eq]}{year}$. The antifouling paint impact for one year use. Suggestion to keep as constant

Part 3: EOL

$$\boldsymbol{I_{EOL}} = \boldsymbol{2896}\ [\boldsymbol{kg\ CO2 - eq}] \qquad \text{(C1)}$$

Constant value and variables

Constant value used in GWP equations see in Table 6.10

Table 6.10 Constant value used in formula of GWP impact category

Formula	Constant	Value	Unit
A2	I_component	4.11E+03	kgCO2-eq/boat
A2	I_Hull Alter	4.88E+03	kgCO2-eq/boat
A2	I_Electronic	5.43E+03	kgCO2-eq/boat
A2	I_battery	8.48E+03	kgCO2-eq/piece
A2	I_trp	9.60E+01	kgCO2-eq/boat
A2	I_Assembly	8.10E+02	kgCO2-eq/boat
A3	I_component	4.11E+03	kgCO2-eq/boat
A3	I_(Hull Alter)	4.88E+03	kgCO2-eq/boat
A3	I_Electronic Virgin	5.43E+03	kgCO2-eq/boat
A3	I_Electronic Reman	2.71E+03	kgCO2-eq/piece
A3	I_Battery virgin	8.48E+03	kgCO2-eq/piece
A3	I_Battery Reman	4.24E+03	kgCO2-eq/piece
B1	I_fuel	6.00E+03	kgCO2-eq/year
B1	I_battery	8.48E+03	kgCO2-eq/piece
B1	I_engine	6.04E+02	kgCO2-eq/piece
B1	I_AF paint	4.65E+00	kgCO2-eq/year
C1	I_EOL	2.90E+03	kgCO2-eq/boat

Variables used in GWP equations see in Table 6.11.

Table 6.11 Variables used in formula of GWP impact category.

Formula	Variable	Range	Unit
A2	y_1	0%-100%	Weight reduction Percent
A2	y_2	0%-100%	Weight reduction Percent
A3	a_(el.v)	0%-100%	Percent
A3	a_(el.Re)	1-a_(el.v)	Percent
A3	a_(en.v)	0%-100%	Percent
A3	a_(en.Re)	1-a_(en.v)	Percent
A3	y_1	0%-100%	Weight reduction Percent
A3	y_2	0%-100%	Weight reduction Percent
B1	T_lifespan	30-50	years

D.2 EPS impacts equations:

$$I_{total} = I_{material} + I_{use\ phase} + I_{EOL} \quad (A1)$$

Part 1: Materials

$$I_{subsupplier} = I_{component} + I_{Electronic} * y_1 + I_{battery} * y_2 + +I_{trp} + I_{Assembly} \quad (A2)$$

$I_{component}$ = 35464 [ELU]

includes all materials impact except " Electronical components" ,and "battery"

Suggestion to keep as constant

$I_{Electronic}$ = 112722 [ELU]. Impacts from electronic devices. Suggestion to keep as constant

$I_{battery}$ = 258434[ELU]. Impact from battery. Suggestion to keep as constant

I_{trp} = 28.9 [ELU] Impact from material transportation. Suggestion to keep as constant.

$I_{assembly}$ = 616 [ELU] Suggestion to keep as constant.
(It includes results of energy use and emissions from the factory .)

y_1 = weight of electronic devises compared to base case [%]

(base case: cable: xx kg, batteries: xx kg, other electronic devices: xx kg)

y_2 = weight of battery compared to base case [%] (base case xx kg)

If include remanufacturing and recycling flows into consideration to Box "Producer", the equation:

$$I_{subsupplier} = I_{component} + (I_{\substack{Electronic\\Virgin}} * a_{el.v} + I_{\substack{Electronic\\Reman}} * a_{el.Re}) * y_1 + (I_{battery} * a_{battery.v} + I_{battery} * a_{battery.Re}) * y_2 \quad \text{(A3)}$$

$I_{\substack{Electronic\\Virgin}}$ = xx [ELU]. Impact from virgin electronics. Suggestion to keep as constant

$I_{\substack{Electronic\\Reman}}$ = xx [ELU]. Impact from remanufacturing electronics. Suggestion to keep as constant

$I_{\substack{Battery\\Virgin}}$ = xx [ELU]. Impact from virgin battery. Suggestion to keep as constant

$I_{\substack{Battery\\Reman}}$ = xx [ELU]. Impact from remanufacturing battery. Suggestion to keep as constant

$a_{xx.v}$ = allocation rate of virgin "xx" compared to total "xx" [%]

$a_{xx.Re}$ = allocation rate of "xx" compared to total "xx" [%]

(Note: 1. "xx" represents electronics or battery.)

Part 2: Operation and maintenance

$$I_{use\ phase} = I_{fuel\ combustion} + I_{maintenance}$$

$$= T_{lifespan} * I_{fuel\ combustion} + \left(T_{lifespan} * \frac{1}{10} - 1\right) * I_{battery} + \left(T_{lifespan} * \frac{1}{15} - 1\right) * I_{engine} + \left(T_{lifespan} * 2.4\right) * I_{AF\ paint} \quad \text{(B1)}$$

$T_{lifespan}$ = [year] The life time of the boat.

Base case set the lifetime is 30 years.

$I_{fuel\ combustion} = \text{xxx}\ \frac{[\text{ELU}]}{\text{year}}$. The fuel combustion impact for one year. Suggestion to keep as constant

$I_{battery} = \text{XXX}\frac{[\text{ELU}]}{\text{piece}}$. The renewed battery impact. Can select to use virgin or remanufacturing battery.

$I_{engine} = \text{XXX}\frac{[\text{ELU}]}{\text{piece}}$. The renewed engine impact. Can select to use virgin or remanufacturing battery.

$I_{AF\ Paint} = \text{XXX}\frac{[\text{ELU}]}{\text{year}}$. The antifouling paint impact for one year use. Suggestion to keep as constant

Part 3: EOL

$$I_{EOL} = -6800\ [ELU/boat] \quad \text{(C1)}$$

Constant value and variables

Constant value used in EPS equations see in Table 6.12

Table 6.12 Constant value used in formula of EPS impact category

Formula	Constant	Value	Unit
A2	I_component	3.55E+04	ELU/boat
A2	I_Electronic	1.13E+05	ELU/boat
A2	I_battery	2.58E+05	ELU/piece
A2	I_trp	2.89E+01	ELU/boat
A2	I_Assembly	6.16E+02	ELU/boat
A3	I_component	3.55E+04	ELU/boat
A3	I_(Electronic Virgin)	1.13E+05	ELU/piece
A3	I_(Electronic Reman)	5.64E+04	ELU/piece
A3	I_(battery Virgin)	2.58E+05	ELU/piece
A3	I_(battery Reman)	1.29E+05	ELU/piece
B1	I_fuel	2.94E+03	ELU/year
B1	I_battery	2.58E+05	ELU/piece
B1	I_engine	8.08E+02	ELU/piece
B1	I_AF paint	1.17E+03	ELU/year
C1	I_EOL	-6.80E+03	ELU/boat

Variables used in EPS equations see in Table 6.13.

Table 6.13 Variables used in formula of EPS impact category

Formula	Variable	Range	Unit
A1	y_1	0%-100%	Weight reduction Percent
A1	y_2	0%-100%	Weight reduction Percent
A3	a_(el.v)	0%-100%	Percent
A3	a_(el.Re)	1-a_(el.v)	Percent
A3	a_(battery.v)	0%-100%	Percent
A3	a_(battery.Re)	1-a_(battery.v)	Percent
A3	y_1	0%-100%	Weight reduction Percent
A3	y_2	0%-100%	Weight reduction Percent
B1	T_lifespan	30-50	years

D.3 Toxicity impacts equations:

$$I_{total} = I_{material} + I_{use\ phase} + I_{EOL} \quad \text{(A1)}$$

Part 1: Materials

$$I_{materials} = I_{component} + I_{Electronic} * y_1 + I_{battery} * y_2 + I_{trp} + I_{Assembly} \quad \text{(A2)}$$

$I_{component}$ = xxx [CTUe]

includes all materials impact except "Electronics" and "Battery". Suggest to keep as constant

$I_{Electronic}$ = xxx [CTUe]. Impacts from electronic devices. Suggestion to keep as constant

$I_{battery}$ = xxx [CTUe] Impacts from battery. Suggestion to keep as constant

y_1 = weight of electronics compared to base case [%]

y_2 = weight of battery compared to base case [%] (base case 100 kg)

I_{trp} = xxx [CTUe] Impact from material transportation. Suggestion to keep as constant.

$I_{assembly}$ = xxx [CTUe] Suggestion to keep as constant.
(It includes results of electricity use in the factory and emissions.)

If include remanufacturing and recycling flows into consideration to Box "Producer", the equation:

$$I_{subsupplier} = I_{component} + (I_{\underset{Virgin}{Electronic}} * a_{el.v} + I_{\underset{Reman}{Electronic}} * a_{el.Re}) * y_1 + (I_{\underset{virgin}{battery}} * a_{en.v} + I_{\underset{Reman}{battery}} * a_{en.Re}) * y_2 \quad \text{(A3)}$$

$I_{\underset{Virgin}{xx}}$ = xxx [CTUe] from virgin "xx". Suggestion to keep as constant

$a_{xx.v}$ = allocation rate of virgin "xx" compared to total electronic devices [%]

$I_{\underset{Reman}{xx}}$ = xxx [CTUe] from remanufactured "xx".

$a_{xx.Re}$ = allocation rate of remanufactured "xx"compared to total electronic devices [%]

Part 2: Operation and maintenance

$$I_{use\ phase} = I_{fuel\ combustion} + I_{maintenance}$$

$$= T_{lifespan} * I_{fuel\ combustion} + \left(T_{lifespan} * \frac{1}{10} - 1\right) * I_{battery} + \left(T_{lifespan} * \frac{1}{15} - 1\right) * I_{engine} + \left(T_{lifespan} * 2.4\right) * I_{AF\ paint} * y_3 \quad \text{(B1)}$$

$T_{lifespan}$ = [year] The life time of the boat.

Base case set the lifetime is 30 years.

$I_{\text{fuel combustion}} = xxx\frac{[CTUe]}{year}$. The fuel combustion impact for one year. Suggestion to keep as constant

$I_{\text{battery}} = xxx\frac{[CTUe]}{piece}$. The renewed battery impact. Can select to use virgin or remanufacturing battery.

$I_{\text{engine}} = xxx\frac{[CTUe]}{piece}$. The renewed engine impact. Can select to use virgin or remanufacturing battery.

$I_{\text{AF Paint}} = xxx\frac{[CTUe]}{year}$. The antifouling paint impact for one year use. Base case is xxx [CTUe]

y_3 = weight of antifouling paint compared to base case [%]

Part 3: EOL

$$\boldsymbol{I_{EOL} = xxx\ [CTUe]} \qquad (C1)$$

Constant value and variables

Constant value used in the formula of toxicity impact category see in Table 6.14.

Table 6.14 Constant value used in formula of Toxicity impact category

Formula	Constant	Value	Unit
A2	I_component	8.72E+06	[CTUe]/boat
A2	I_Electronic	2.37E+08	[CTUe]/piece
A2	I_battery	5.88E+08	[CTUe]/piece
A2	I_trp	5.79E+02	[CTUe]/boat
A2	I_Assembly	3.25E+05	[CTUe]/boat
A3	I_component	8.72E+06	[CTUe]/boat
A3	I_Electronic Virgin	2.37E+08	[CTUe]/piece
A3	I_Electronic Reman	1.19E+08	[CTUe]/piece
A3	I_battery Virgin	5.88E+08	[CTUe]/piece
A3	I_battery Reman	2.94E+08	[CTUe]/piece
B1	I_fuel	3.49E+04	[CTUe]/year
B1	I_battery	5.88E+08	[CTUe]/piece
B1	I_engine	3.51E+04	[CTUe]/piece
B1	I_AF paint	3.14E+06	[CTUe]/year
C1	I_EOL	2.77E+07	[CTUe]/boat

Variables used in the formula of toxicity impact category see in Table 6.15.

Table 6.15 Valuables used in the formula of toxicity impact category.

Formula	Variable	Range	Unit
A1	y_1	0%-100%	Weight reduction Percent
A1	y_2	0%-100%	Weight reduction Percent
A3	a_(xx.v)	0%-100%	Percent
A3	a_(xx.Re)	1-a_(el.v)	Percent
A3	y_1	0%-100%	Weight reduction Percent
A3	y_2	0%-100%	Weight reduction Percent
B1	T_lifespan	30-50	years
B1	y_3	0%-100%	Weight reduction Percent

D.4 ADP impacts equations

$$I_{total} = I_{material} + I_{use\ phase} + I_{EOL} \quad (A1)$$

Part 1: Materials

$$I_{materials} = I_{component} + I_{Electronic} * y_1 + I_{battery} * y_2 + I_{trp} + I_{Assembly} \quad (A2)$$

$I_{component}$ = 0.53 [kgSb-eq]

includes all materials impact except "Electronics" and "Battery". Suggest to keep as constant

$I_{Electronic}$ = 2.0 [kgSb-eq]. Impact from electronic devices. Suggestion to keep as constant

$I_{battery}$ = 6.2 [kgSb-eq] Impact from battery. Suggestion to keep as constant

y_1 = weight of electronics compared to base case [%]

(y_2 = weight of battery compared to base case [%] (base case 100 kg)

I_{trp} = 7.75E − 06 [kgSb-eq] Impact from material transportation. Suggestion to keep as constant.

$I_{assembly}$ = 0.0015 [kgSb-eq] Suggestion to keep as constant.
(It includes results of electricity use in the factory and emissions.)

If include remanufacturing and recycling flows into consideration to Box "Producer", the equation:

$$I_{subsupplier} = I_{component} + (I_{\substack{Electronic\\Virgin}} * a_{el.v} + I_{\substack{Electronic\\Reman}} * a_{el.Re}) * y_1 + (I_{\substack{battery\\virgin}} * a_{en.v} + I_{\substack{battery\\Reman}} * a_{en.Re}) * y_2 \quad (A3)$$

$I_{\substack{xx\\Virgin}}$ = xxx [$kgCO_2$ − eq] from virgin "xx". Suggestion to keep as constant

$a_{xx.v}$ = allocation rate of virgin "xx" compared to total electronic devices [%]

$I_{\substack{xx\\Reman}}$ = xxx [$kgCO_2$-eq] from remanufactured "xx".

$a_{xx.Re}$ = allocation rate of remanufactured "xx"compared to total electronic devices [%]

Part 2: Operation and maintenance

$$\boldsymbol{I_{use\ phase}} = \boldsymbol{I_{fuel\ combustion}} + \boldsymbol{I_{maintenance}}$$

$$= \boldsymbol{T_{lifespan}} * \boldsymbol{I_{fuel\ combustion}} + \left(\boldsymbol{T_{lifespan}} * \frac{\mathbf{1}}{\mathbf{10}} - \mathbf{1}\right) * \boldsymbol{I_{battery}} + \left(\boldsymbol{T_{lifespan}} * \frac{\mathbf{1}}{\mathbf{15}} - \mathbf{1}\right) * \boldsymbol{I_{engine}} + \left(\boldsymbol{T_{lifespan}} * \mathbf{2.4}\right) * \boldsymbol{I_{AF\ paint}} \qquad \text{(B1)}$$

$T_{lifespan}$ = [year] The life time of the boat.

Base case set the lifetime is 30 years.

$I_{fuel\ combustion} = xxx \frac{[kgSb-eq]}{year}$. The fuel combustion impact for one year. Suggestion to keep as constant

$I_{battery} = xxx \frac{[kgSb-eq]}{piece}$. The renewed battery impact. Can select to use virgin or remanufacturing battery.

$I_{engine} = xxx \frac{[kgSb-eq]}{piece}$. The renewed engine impact. Can select to use virgin or remanufacturing battery.

$I_{AF\ Paint} = xxx \frac{[kgSb-eq]}{year}$. The antifouling paint impact for one year use. Suggestion to keep as constant

Part 3: EOL

$$\boldsymbol{I_{EOL}} = -\mathbf{2.66}\boldsymbol{E} - \mathbf{02}[\boldsymbol{kg\ Sb} - \boldsymbol{eq}] \qquad \text{(C1)}$$

Constant value and variables

Constant value used in the formula of ADP impact category see in Table 6.16.

Table 6.16 Constant value used in the formula of ADP impact category.

Formula	Constant	Value	Unit
A2	I_component	5.30E-01	kgSb-eq/boat
A2	I_Electronic	2.00E+00	kgSb-eq/boat
A2	I_battery	6.20E+00	kgSb-eq/piece
A2	I_trp	7.75E-06	kgSb-eq/boat
A2	I_Assembly	1.50E-03	kgSb-eq/boat
A3	I_component	5.30E-01	kgSb-eq/boat
A3	I_Electronic Virgin	2.00E+00	kgSb-eq/boat
A3	I_Electronic Reman	1.00E+00	kgSb-eq/boat
A3	I_battery Virgin	6.20E+00	kgSb-eq/piece
A3	I_battery Reman	3.10E+00	kgSb-eq/piece
B1	I_fuel	4.67E-04	kgSb-eq/year
B1	I_battery	6.20E+00	kgSb-eq/piece
B1	I_engine	8.76E-03	kgSb-eq/piece
B1	I_AF paint	4.74E-03	kgSb-eq/year
C1	I_EOL	-2.66E-02	kgSb/boat

Variables used in the formula of ADP impact category see in Table 6.17

Table 6.17 Variables used in the formula of ADP impact category

Formula	Variable	Range	Unit
A2	y_1	0%-100%	Weight reduction Percent
A2	y_2	0%-100%	Weight reduction Percent
A3	a_(el.v)	0%-100%	Percent
A3	a_(el.Re)	1-a_(el.v)	Percent
A3	y_1	0%-100%	Weight reduction Percent
A3	y_2	0%-100%	Weight reduction Percent
B1	T_lifespan	30-50	years

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