NTNU
Norwegian University of
Science and Technology

Master's thesis

2020

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Norwegian University of
Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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Comparative Life Cycle Assessment of a Diesel Electric and a Battery Electric Ferry

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Energy and Environmental Engineering
Submission date: June 2020
Supervisor: Anders Hammer Strømman
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Thesis description

The Norwegian maritime sector is working to reduce its greenhouse gas emissions and become more sustainable. It is expected that global CO_2 emissions from the global maritime fleet will continue to grow strongly and may be as much as 2.5 times higher by 2050, if measures are not taken. Different segments of the sector will need different strategies and measures. Shipping and ferries in coastal waters warrants different solutions than the deep-sea segment. Norway has geared up its efforts to electrify car ferries. Ambitious emission reduction targets for 2030 has accelerated the commissioning of battery electric ferries. While electric ferries provide significant reductions in emissions during operation, insights from life cycle assessments suggests that both production and electricity chains must be assessed to understand the full environmental footprint. Insights from the maritime literature also suggest that the comparative emission footprint of battery vs diesel electric ships is dependent on the load and speed profiles.

The main objective of this thesis is to assess the comparative life cycle environmental footprint of a battery electric vs a diesel electric ferry under real operational and weather conditions. Key tasks include:

- Calibration of a ferry model in the MariTEAM model.
- Development of an LCI model for a ferry.
- Simulation of ferry operation and emissions.
- Integrated assessment applying the LCA and simulation models.

Supervisor: Anders Hammer Strømman.
Co-supervisors: Helene Muri, Diogo Kramel, Lorenzo Usai.
The student will have licensed access to the following for the duration of the work:

- The LCA software ARDA including the Ecoinvent database for the duration of the thesis work.
- The MariTEAM model, including NTNU licensed data on ships, weather data, and AIS data.
- Ship performance and operational data from SIEMENS.

The student has no right to further use or distribution of this software and data. Upon completion of the work, the software and data must be uninstalled from the computer used.

Abstract

The maritime transport sector contributes to emissions of greenhouse gases (GHGs) and global warming. Mitigation strategies are needed to limit the climate changes on Earth. One possible measure is electrification of ferries. To investigate the environmental performance of such a strategy, life cycle assessment (LCA) is a suitable tool because it covers multiple life cycle phases and potential environmental impacts.

This thesis presents a comparative LCA of a diesel electric and a battery electric ferry using real construction, operational and weather data. Indicators assessed comprise global warming, resource depletion, ecotoxicity, human toxicity, eutrophication, ionising radiation, particulate matter and photochemical oxidant formation, terrestrial acidification and land occupation and transformation, as well as total emissions of carbon dioxide, methane, nitrous oxide, nitrogen oxide, particulate matter and sulphur oxide. All activities from raw materials extraction to end of life treatment are included, and the operational phase was modelled using a vessel simulation tool applying automatic identification system (AIS) and weather data.

Results indicate that replacing diesel electric ferries with battery electric ferries may considerably reduce climate change impacts as well as other environmental burdens due to the avoided diesel production and combustion. However, battery electric ferries are disadvantageous compared to diesel electric ferries in terms of certain environmental impacts mainly due to additional construction and electricity production. This thesis contributes to current literature with a detailed inventory and a robust simulation of the ferry operation, and provides an extended understanding of the environmental performance of electric ferries.

Sammendrag

Maritim transport bidrar til utslipp av drivhusgasser og global oppvarming. Klimastrategier er nødvendige for å begrense klimaendringene på jorden. Et mulig tiltak er elektrifisering av ferger. For å undersøke miljøeffekter av å implementere en slik strategi, er livssyklusanalyse (LCA) et passende verktøy fordi det dekker flere livssyklusfaser og mulige miljøpåvirkninger.

Denne avhandlingen presenterer en sammenlignende LCA av en dieselektrisk og en batterielektrisk ferge ved bruk av ekte konstruksjons-, drifts- og værdata. Indikatorer vurdert omfatter global oppvarming, ressursnedbrytning, økotoksisitet, menneskelig toksisitet, eutrofiering, ioniserende stråling, dannelse av partikler og fotokjemiske oksidanter, terrestrisk forsuring, landokkupasjon og -transformasjon, og i tillegg totale utslipp av karbondioksid, metan, dinitrogenoksid, nitrogenoksid, partikler og svoveloksid. Alle aktiviteter fra utvinning av råmaterialer til behandling på slutten av levetiden er inkludert, og driftsfasen er modellert ved å anvende et fartøyssimuleringsverktøy som bruker data fra automatiske identifikasjonssystemer (AIS) og værdata.

Resultatene indikerer at å bytte ut dieselelektriske ferger med batterielektriske ferger kan redusere klimaendringer og flere andre miljøbelastninger betraktelig fordi produksjon og forbrenning av diesel unngås. På den annen side er batterielektriske ferger ufordelaktige sammenlignet med dieselelektriske ferger med tanke på andre miljøpåvirkninger knyttet til hovedsakelig ekstra konstruksjon og elektrisitetsproduksjon. Denne avhandlingen supplerer nåværende litteratur med et detaljert inventar og en robust simulering av fergedriften, og tilbyr en utvidet forståelse av miljøprestasjonen til elektriske ferger.

Preface

This thesis is the conclusion of my master's degree in Energy and Environmental engineering at the Norwegian University of Science and Technology (NTNU). It is a continuation of my project thesis and was written during the spring semester 2020 at the department of Energy and Process engineering (EPT) in cooperation with Siemens.

I would like to express my gratitude towards my supervisor Anders Hammer Strømman, for providing valuable guidance and inspiration throughout the semester, and for always answering the phone with a friendly and positive approach despite his many responsibilities. I would also like to thank my co-supervisors at NTNU, Helene Muri, Diogo Kramel and Lorenzo Usai, for being available for professional discussions and providing feedback, and my co-supervisor at Siemens, Jonas Sjolte, for helping me with data collection and offering comments on my work. Further, I would like to thank the other persons contributing to data collection and answering questions regarding the case ferry. Finally, I would like to thank my boyfriend, mother, father, friends and fellow students for motivation and support throughout the semester.

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Abbreviations

AIS	=	Automatic Identification System
ALOP	=	Agricultural Land Occupation Potential
BC	=	Black Carbon
BE	=	Battery Electric
BIP	=	Battery Insulation and Protection
BOM	=	Bill Of Materials
DD	=	Diesel Direct
DE	=	Diesel Electric
DWT	=	Dead Weight Tonnage
EC	=	Elemental Carbon
EPD	=	Environmental Product Declaration
FDP	=	Fossil Depletion Potential
FEP	=	Freshwater Eutrophication Potential
FETP	=	Freshwater Ecotoxicity Potential
GHG	=	Greenhouse Gas
GWP	=	Global Warming Potential
HFO	=	Heavy Fuel Oil
HTP	=	Human Toxicity Potential
IPCC	=	Intergovernmental Panel on Climate Change
IRP	=	Ionising Radiation Potential
LCA	=	Life Cycle Assessment
LCI	=	Life Cycle Inventory
LCIA	=	Life Cycle Impact Assessment
LDT	=	Light Displacement Tonnage
LIB	=	Lithium Ion Battery
LMO	=	Lithium Nickel Manganese Oxide
LTP	=	Land Transformation Potential
MDP	=	Mineral Depletion Potential
MEP	=	Marine Eutrophication Potential
METP	=	Marine Ecotoxicity Potential
MGO	=	Marine Gas Oil
MMSI	=	Maritime Mobile Service Identity
NMC	=	Lithium Nickel Manganese Cobalt Oxide
NTNU	=	Norwegian University of Science and Technology

OC	=	Organic Carbon
ODP	=	Ozone Depletion Potential
PC	=	Personal Communication
PEP	=	Product Environmental Profile
PKT	=	Passenger Kilometre Travelled
PM	=	Particulate Matter
PMFP	=	Particulate Matter Formation Potential
POFP	=	Photochemical Oxidant Formation Potential
Ro-pax	=	Roll-on/roll-off passenger
SOG	=	Speed Over Ground
SPA	=	Structural Path Analysis
SoC	=	State of Charge
TAP	=	Terrestrial Acidification Potential
TETP	=	Terrestrial Ecotoxicity Potential
ULOP	=	Urban Land Occupation Potential
WDP	=	Water Depletion Potential

Chapter 1

Introduction

In this chapter, an introduction to this thesis regarding a comparative life cycle assessment (LCA) between a diesel electric and a battery electric ferry is given. First, the background and motivation for the topic is presented. Then, a presentation of the state of the art of the relevant subjects is given, and finally the research objective is stated and the report structure outlined.

1.1 Background and motivation

The climate on Earth is changing due to anthropogenic greenhouse gas (GHG) emissions, and the consequences for humans and ecosystems are potentially disastrous. With the aim of strengthening the global response to such consequences, the Paris Agreement was adopted in 2015 with the main objective of limiting the increase in global average temperature to well below 2°C and preferably 1.5°C compared to pre-industrial levels (United Nations Framework Convention on Climate Change, 2015). To reach this goal, substantial measures for mitigation need to be implemented in industries and societies. One sector where climate change mitigation is highly needed is the transport sector.

In 2017, the transport sector was responsible for 8.04 Gt CO_2 equivalents per year, corresponding to 24.5% of global CO_2 emissions (IEA, 2020). The Intergovernmental Panel on Climate Change (IPCC) argued in their latest report that transport emissions could reach 12 Gt CO_2 equivalents per year by 2050 without sufficient mitigation (Sims et al., 2014). Therefore, robust climate change mitigation strategies are needed, and IPCC suggested that a reduction of 15-40% in transport CO_2 emissions compared to a baseline scenario can be reached in 2050 with the correct measures (Sims et al., 2014). One of the mitigation strategies highlighted by the IPCC is reducing the carbon intensity of fuels, for instance by replacing oil-based fuels with low-carbon electricity (Sims et al., 2014). This can also lead to co-benefits like reduced urban air pollution and noise (Sims et al., 2014). Electrification of transport has also been recommended by the European Commission (2017), among others. The world has recently seen a significant increase in electric road transport, but also maritime transport can be subject for electrification.

Shipping was responsible for 2.8% of global GHG emissions in the period between 2007 and 2012, 961 million tonnes CO_2 equivalents of primary GHGs in 2012, and also accounts for 15% of anthropogenic NO_x emissions and 13% of anthropogenic SO_x emissions (International Maritime Organization, 2015). GHG emissions from the maritime sector are expected to increase in the future; the International Maritime Organization (2015) estimated an increase in CO_2 emissions between 50% and 250% by 2050 with business as usual, mainly due to an increased maritime transport demand. Although IPCC argued that full electrification of waterborne transport seems unlikely due to energy storage requirements for long-range transport (Sims et al., 2014), certain short-range maritime transport types have been found suitable for electric solutions (Bellona and Siemens, 2015; Innst. 78 S (2015–2016), 2015; European Commission, 2017; Departementene, 2019). Ferries are particularly convenient for battery electric operation due to their set routes, high regularity and long operation periods (Innst. 78 S (2015–2016), 2015; Departementene, 2019). CO_2 emissions from small ro-pax ferries (roll-on/roll-off passenger ferries) made up 4,308,000 tonnes in 2012 (International Maritime Organization, 2015). Electrification of ferries, which is realised in Norway among other places, can potentially be a way to reduce multiple types of emissions.

Norway is aiming at reducing GHG emissions with 40% by 2030 and 80-95% by 2050, with 1990 as the reference year (Klimaloven, 2017). The transport sector is responsible for approximately 60% of Norwegian emissions not subject to quotas (Meld. St. 33 (2016-2017), 2017), thus it is an important sector for emission reductions. One of the three main objectives of the Norwegian national transport plan 2018-2029 is to reduce GHG emissions towards a low emission society and to reduce other adverse environmental consequences (Meld. St. 33 (2016-2017), 2017). Technology and fuel have the largest potential for reducing emissions (Petersen et al., 2016). Norwegian ferries accounted for 12.7% of domestic shipping emissions in 2017 (Departementene, 2019). Specifically for domestic shipping and fishing, the Norwegian government has ambitions for reducing emissions with 50% by 2030 (Departementene, 2019), and requires low emission technologies in ferry tenders (Meld. St. 33 (2016-2017), 2017). Norway is in front with electric vehicles, and now also electric ferries are emerging. Departementene (2019) argued that by 2022 more than one third of Norwegian car ferries will be electric. Also, the world's first fully electric ferry, MF Ampere, was set into operation in Norway in 2015 (Meld. St. 33 (2016-2017), 2017). Bellona and Siemens (2015) performed a feasibility study and concluded that more than 70% of Norwegian ferries are profitable with electric operation. They also argued that such an electrification of ferries may result in substantial emission reductions, although the study only considered operational emissions and not emissions from construction or end of life treatment.

Although electrification of ferries can contribute significantly to emission reductions, it is essential to analyse a variety of environmental factors in a life cycle perspective in order to obtain an image of how sustainable and environmentally friendly battery electric ferries really are. Direct emissions from the operational phase are reduced with battery electric propulsion in Norway because fossil fuels are replaced with electricity mostly based on renewable energy sources (IEA, 2020). On the other hand, the electricity production as well as the production and the end of life treatment of the additional components in a battery electric ferry can possibly lead to burden shifting. Environmental burdens can shift both between life cycle phases, between sectors, between locations, and between types of environmental impacts (Arvesen, 2019b). Comparative LCAs of conventional diesel electric ferries and battery electric ferries are therefore central both for achieving fair comparisons between the two alternatives and for identifying and preventing burden shifting. Also, the operational phase is a central part of the ferry life cycle influenced by the ship specifics, operational profile, weather, fuel type and power system. It should be assessed using models and simulations based on real operational and weather data. The next section discusses the state of the art regarding these aspects.

1.2 State of the art

The intention of the state of the art section is to present the current knowledge and create a context for the thesis. First, effects of electrification of the maritime sector and diesel electric propulsion technology are discussed. Then, models for ship consumption and emissions are presented as they are relevant for analysing the operational phase of a vessel. Further, Battery electric propulsion technology is explained and LCA studies on battery production are assessed. Finally, the state of the art for LCA of electric ferries is considered, for which all the previously assessed topics are relevant.

1.2.1 Electrification of the maritime sector

Electric propulsion in maritime transport has proven to be more efficient than many other propulsion mechanisms for several vessel types, as emphasised by Hansen and Wendt (2015), among others. Hansen and Wendt (2015) dated the modern electric propulsion back to the 1980s, which introduced a simplification of the mechanical structure and, most importantly, fuel savings. Electric propulsion has been gradually implemented to a larger degree in maritime transport, and is now also used in ferries. Today, electric propulsion is seen in the form of both diesel electric and battery electric systems, among other technologies. Battery electric systems are discussed later in this chapter. In a diesel electric propulsion system, a diesel tank is connected to a diesel engine where the diesel is combusted. The diesel engine is connected to an electric generator that transforms rotational work from the diesel engine to electric energy (Lundby and Æsøy, 2014). The generator delivers electric energy to an electric motor that delivers rotational work to the propeller and thereby forces the propeller to turn and the ship to move (Lundby and Æsøy, 2014). Diesel electric systems do not need auxiliary engines to cover the hotel load[1], and they are advantageous in terms of flexibility and obtaining maximum output at low speeds (Babicz, 2015).

Regarding the move from diesel direct[2] to diesel electric propulsion, some studies have considered the related reduction in fuel consumption. Bastos et al. (2018), Koenhardono and Amiadji (2018) and Łebkowski (2018) found fuel consumption reductions around 86-93% when comparing diesel electric systems to diesel direct systems, based on diesel electric fishing vessels, combination of diesel engine and electric motor offshore patrol vessels and several types of hybrid propulsion systems respectively. Łebkowski also analysed diesel electric propulsion systems in crew transfer vessels for offshore wind farms 2020, and results imply that fuel consumption and emissions to the atmosphere are reduced by approximately 60-70% compared to conventional diesel direct propulsion. From current literature it is evident that the reduction in fuel consumption is among other factors dependent on the model used. Such models are numerous and are continuously being developed and improved, as discussed in the following section.

1.2.2 Models for consumption and emissions

Several studies have considered models for fuel consumption and emissions from ships, and some of these are presented in this section with focus on technologies assessed, data used and emissions calculated. Many studies have assessed only traditional diesel direct propulsion or have not stated anything specific regarding electric propulsion (Jalkanen et al., 2009; Huang et al., 2018; Winebrake et al., 2007; Reis et al., 2019; Moreno-Gutiérrez et al., 2019; Brown and Aldridge, 2019; Tichavska and Tovar, 2015;

[1] Hotel load is the power needed for other purposes than propulsion, e.g. lighting and ventilation.

[2] Diesel direct propulsion involves a diesel engine connected to the propeller, without any generator or electric motor.

Liu et al., 2019; International Maritime Organization, 2015). Hansen et al. (2001), Jalkanen et al. (2012), Gysel et al. (2017) and Simonsen et al. (2018) are though among the studies also analysing diesel electric vessels.

The power consumption, fuel consumption and emissions from a ship are generally determined by the ship speed, which can be derived from automatic identification system (AIS) data regarding ship position and technical vessel data like engine specifications, as described in the background and motivation. Most of the literature has based its models on these types of data; Jalkanen et al. (2009), Jalkanen et al. (2012), Brown and Aldridge (2019), Tichavska and Tovar (2015), Simonsen et al. (2018), Liu et al. (2019), Huang et al. (2018) and International Maritime Organization (2015) used AIS data. Moreno-Gutiérrez et al. (2019) on the other hand argued that AIS data may be uncertain and therefore used daily on-board data sheets instead. Weather also affects ship consumption due to factors like wind and waves creating resistance, but not all studies on consumption and emission models have accounted for weather. Jalkanen et al. (2012), International Maritime Organization (2015) and Huang et al. (2018) are among the studies that did. Jalkanen et al. built on their 2009 model in 2012 and included wave effects, Huang et al. (2018) modelled wind, wave and current influences on ship speed, and the International Maritime Organization (2015) used average values for weather effects on resistance.

Based on the studies considered in this presentation of the state of the art, NO_x, SO_x and CO_2 seem to be the most frequently assessed types of emissions, but also particulate matter (PM) and carbon monoxide (CO) have been considered by some studies (Jalkanen et al., 2012; Tichavska and Tovar, 2015; Gysel et al., 2017; Moreno-Gutiérrez et al., 2019; Winebrake et al., 2007; Huang et al., 2018; International Maritime Organization, 2015). Jalkanen et al. (2012) pointed out the limited data on fuel types in ships in different geographical areas and the lack of experimental data on PM emissions.

The current literature includes several different models for ship consumption and emissions, assessing various vessel types and emissions. Methods have certain parts in common but also several differences. There is a limited amount of studies considering weather data together with AIS and technical vessel data. The field of emission types considered is narrow for certain models, and the amount of studies considering fuel consumption and emissions for diesel electric ferries specifically is rather small. More research is necessary to further develop models for consumption and emissions using real operational and weather data and representing all types of vessels, propulsion systems, fuels and emissions. Such models are essential in comparisons of diesel electric and battery electric ferries.

1.2.3 Life cycle assessment of batteries for electric transport

Another variant of electric maritime transport in addition to diesel electric vessels are battery electric vessels. In a battery electric propulsion system, the diesel engines and generators are replaced with batteries supplying electric energy to the electric motor. The batteries on board the vessel are charged with electricity, replacing diesel as fuel. The battery production is a central factor in determining the environmental efficiency of battery electric propulsion, and is therefore investigated in this section.

The following two paragraphs describing a battery are adapted from the project preceding this thesis (Galaaen, 2019). A battery is an energy storage device using electrochemical reactions to charge and discharge. It is made up of battery cells consisting of a cathode, an anode, an electrolyte, a separator and a cell container. The electrolyte is an ionically conductive substance, and the anode and cathode are electrodes with different chemical potentials (Armand and Tarascon, 2008). The battery charges or discharges when an external device is connected to the electrodes initiating a flow of electrons between the electrodes and a flow of ions through the electrolyte (Armand and Tarascon, 2008).

Different chemistries can be applied in batteries, dependent on the desired characteristics. Typical chemistries include Ni-MH, lead-acid, zinc-air and lithium ion (Armand and Tarascon, 2008). Lithium is favoured in batteries due to its high power and energy density, as well as its light weight which makes it suitable for portable applications, among other factors (Armand and Tarascon, 2008; Nitta et al., 2015). It has been debated whether there may be a risk of shortage of lithium if the use of lithium ion batteries is expanded, but certain studies (Narins, 2017; Speirs et al., 2014) have found this unlikely. Lithium ion batteries (LIBs) are named after the cathode material defining major battery characteristics, and lithium nickel manganese cobalt oxide (NMC) is among the most common types (Zubi et al., 2018). Main characteristics of lithium NMC batteries include high specific capacity and power and long lifetime, among others (Nitta et al., 2015; Cobalt Institute, 2017). While lithium shortage is not necessarily likely, the European Commission listed cobalt as a critical raw material for Europe (COM(2017) 490 final, 2017).

Literature is limited regarding LCA of batteries for maritime use, so literature considering batteries for electric vehicles is considered instead in this presentation of the state of the art. This field of literature is broad, and electric vehicle batteries have many similarities with maritime batteries, making them comparable. First, the system boundaries assessed in literature are considered, before the impacts of the production, operation and end of life phases are discussed. Finally, a closer look is taken on the production phase which generally cause a large share of impacts.

The system boundaries considered vary between the electric vehicle battery studies. Ellingsen et al. (2017) reviewed LCA studies on LIBs for traction considering both production, operation and end of life. They pointed out that few studies have assessed the end of life phase, and that the uncertainty is significant for those that have due to limited data. The same conclusion was drawn by Hawkins et al. (2012), who reviewed environmental impacts of hybrid and electric vehicles in terms of all life cycle phases. Cusenza et al. (2019), Hawkins et al. (2013), Zackrisson et al. (2010), Marques et al. (2019) and Notter et al. (2010) are among the studies analysing both production, operation and end of life treatment.

Most studies agree that the production phase is of high significance (Cusenza et al., 2019; Hawkins et al., 2013; Majeau-Bettez et al., 2011; Zackrisson et al., 2010). Cusenza et al. (2019) included both battery production, operation and recycling at end of life within their system boundaries. They found that the manufacturing phase contributes to more than 60% of impacts in all impact categories, and that recycling contributes less than 11% to most impact categories. The operational phase modelled in current literature typically includes electricity losses due to battery efficiency and extra electricity needed for the car to carry the battery, as in Cusenza et al. (2019). Several studies have discussed that the impact of the operational phase is dependent on operational parameters and electricity (Hawkins et al., 2012; Ellingsen et al., 2017; Marques et al., 2019; Zackrisson et al., 2010; Dunn et al., 2015; Majeau-Bettez et al., 2011). Regarding recycling and reuse at end of life, Cusenza et al. (2019) included the environmental credits for recovery of materials through recycling, and based on the results recommended recycling. The battery was assumed to be dismantled and both pyrometallurgical and hydrometallurgical recycling[3] were included. Marques et al. (2019) assumed that metals were recycled and considered transport and energy consumption. Dunn et al. (2015) also assessed recycling at end of life, and found little benefit from it in contrast to Cusenza et al. (2019).

The following part considering battery production is adapted from the project preceding this thesis

[3]Pyrometallurgical recycling involve thermal treatment, while hydrometallurgical recycling is based on aqueous chemistry.

(Galaaen, 2019). The studies are still relevant. LCA studies regarding electric vehicle battery production vary in terms of the types of data used, as confirmed by Ellingsen et al. (2017) and Hawkins et al. (2012) who reviewed existing studies on the topic. As Peters et al. (2017) and Dai et al. (2019) remarked, only some studies have uses original inventory data and certain inventories have been reused. Reviews have also pointed out a lack of transparency in the inventories of existing studies.

The general opinion in current scientific literature is that electric vehicle battery production creates considerable environmental impacts, although the magnitude of impacts vary between studies. There is an agreement that global warming potential (GWP) is significant, but also other impact categories concerning acidification, toxicity, particulate matter and photochemical ozone have been emphasised (Peters et al., 2017). Several studies (Ellingsen et al., 2014; Kim et al., 2016; Ellingsen et al., 2017; Cusenza et al., 2019; Dai et al., 2019) agree that the battery cell is one of the main contributors to environmental impacts from battery production. Ellingsen et al. (2014) and Dai et al. (2019) both found this result by assessing NMC battery chemistries, but obtained GWP results of quite different sizes; Kim et al. (2016) and Cusenza et al. (2019) on the other hand analysed lithium nickel manganese oxide (LMO)-NMC batteries, and obtained more united GWP results within the range of those of Ellingsen et al. (2014) and Dai et al. (2019). These studies to some degree used primary data, but supplemented with secondary data. Ellingsen et al. (2017) reviewed various LCA studies on LIBs with different battery chemistries and types of data, and based on the findings highlighted the importance of the battery cell. The battery cells are generally similar for electric vehicle batteries and electric ferry batteries, thus the importance of the battery cell can be assumed to be high also for electric ferry batteries.

Zackrisson et al. (2010), Majeau-Bettez et al. (2011), Dunn et al. (2015) and Peters et al. (2017) highlighted the energy consumption during battery production as a central contributor to impacts, based on assessments using different data foundations and battery chemistries. This finding is also relevant for electric ferry batteries as certain production processes are similar. Majeau-Bettez et al. (2011) considered an NMC battery like Ellingsen et al. (2014) and Dai et al. (2019), and compiled an inventory which has ended up being frequently reused in literature. Hawkins et al. (2013) directly reused the inventory and thus obtained similar results for the battery production. Zackrisson et al. (2010) on the other hand came to the same finding by analysing a lithium iron phosphate battery based on secondary data, while Peters and Weil (2018) drew the conclusion based on a thorough literature review of recompiled LIB production LCA studies. Dunn et al. (2015) identified the assembly energy consumption as the most central contributor for low production rates, but emphasised the cathode for high production rates.

The anode and cathode were also highlighted as important components in terms of impacts by Ellingsen et al. (2014), Notter et al. (2010), Dunn et al. (2012), Zackrisson et al. (2010), Ellingsen et al. (2017) and Dai et al. (2019). As the anode and cathode are part of the battery cell, and the battery cell is similar between electric vehicle and electric ferry batteries, their contributions can be considered relevant also for electric ferry batteries. Notter et al. (2010) assessed an LMO LIB using their own estimates for energy calculations, which were noted to be very small by Majeau-Bettez et al. (2011), and led to relatively low impacts compared to other studies. Dunn et al. (2012) and Marques et al. (2019) also assessed LMO LIBs and found results similar to those of Notter et al. (2010), which is especially reasonable for Marques et al. (2019) as they reused the inventory.

To reduce environmental impacts, using cleaner electricity or reducing energy consumption during production have been identified as advantageous measures (Ellingsen et al., 2014, 2017; Cusenza et al., 2019). These suggestions are related to both battery cell and battery manufacture energy, which as discussed are relevant also for electric ferry batteries.

Results are generally similar across different battery chemistries, as Peters and Weil (2018) also remarked after their thorough review. An issue is though the lack of transparency and primary data from industry and thus the reuse of inventories, which possibly have led to a narrow representation of reality. Battery production and electricity mix have generally been found to be essential aspects in terms of environmental impacts for electric vehicle batteries.

1.2.4 Life cycle assessment of electric ferries

The environmental impacts of battery technology discussed in the previous section are an essential part of LCA regarding electric ferries. The literature on LCA of electric ferries is limited, but some studies on the topic are presented in this section. Four of these studies (Faessler and Einberger, 2017; Nordtveit, 2017; Mihaylov, 2014; Kullmann, 2016) are used for results bench-marking in Chapter 6 and for discussion in Chapter 7. Similarly to the literature on electric vehicle battery production, several of the electric ferry studies have used the same data, the operational phase has been modelled in different ways, and the end of life phase has mostly been excluded. To obtain a more comprehensive picture of the state of the art, studies regarding battery technology in other vessel types are briefly assessed towards the end of this section.

Faessler and Einberger (2017), Nordtveit (2017), Mihaylov (2014) and Kullmann (2016) all compared battery electric ferries to conventional diesel ferries, but modelling choices vary between them. All four studies included construction and operation, but only Mihaylov (2014) included end of life. In the study conducted by Faessler and Einberger (2017), the charging power was covered by the grid without any use of batteries on land, while Nordtveit (2017) considered electrical propulsion both with and without batteries on land. Faessler and Einberger (2017) used a functional unit of the ferry lifetime of 30 years, while Nordtveit (2017) and Mihaylov (2014) used functional units of one passenger kilometre travelled (PKT), and Kullmann (2016) used one car equivalent unit transported one kilometre. MF Ampere introduced in the beginning of this chapter was used as a reference by both Faessler and Einberger (2017) and Kullmann (2016). Faessler and Einberger (2017) simulated the drag using geometrical dimensions and weight, and the power was estimated from the drag and further used for calculation of battery capacity and fuel consumption. Mihaylov (2014) used data from the manufacturer for some of the processes, certain data were approximated by the use of models and calculations, and the operational phase was modelled using research data. Kullmann (2016) incorporated some operational data on energy required per trip.

All four studies found significant impact reductions for the battery electric ferry. Faessler and Einberger (2017) found that the battery electric ferry has lower impacts than the diesel electric ferry in all impact categories except agricultural land occupation and water depletion, mostly due to the elimination of fuel combustion during operation. GWP is reduced with 97% when moving from a diesel electric to a battery electric ferry. Nordtveit (2017) found that the diesel propulsion is dominant in terms of GWP, ozone and fossil depletion, acidification, marine eutrophication, photochemcal oxidant and particulate matter formation, ionising radiation, and land occupation and transformation, while the electrical propulsion is dominating freshwater eutrophication, toxicity and water and mineral depletion impacts. The operational phase dominate impacts in all impact categories for the diesel ferry due to the refining and combustion of diesel. Mihaylov (2014) concluded that the diesel power train creates larger impacts in terms of GWP, fossil depletion and various types of ecosystem quality indicators, while the electric power train contributes most to human health indicators as well as some ecosystem quality indicators. Kullmann (2016) found that the all-electric ferry has lower environmental impacts in terms of GWP, photochemical oxidant and particulate matter formation as well as ozone and fossil depletion than the conventional ferry.

The studies also agree that construction impacts are larger for the battery electric ferry than for the conventional case, but that the operational phase also creates impacts for battery electric cases. When Faessler and Einberger (2017) considered only manufacturing, the battery electric ferry was found to have higher impacts than the diesel electric ferry in all impact categories except agricultural land occupation. Impacts for the battery electric ferry are mainly related to manufacturing of electrical equipment like battery, converter and electric motor as well as electricity consumption during operation. Kullmann (2016) found that the all-electric ferry has higher impacts than the conventional ferry in terms of toxicity, to a large extent due to copper extraction. The operational phase has a larger contribution to impacts in most impact categories, but for the electric ferry, the battery also contributes significantly. Nordtveit (2017) found that for the battery production, the energy consumed in manufacturing contributes the most to GWP, followed by the battery cell, similarly to literature regarding electric vehicle batteries as discussed earlier in the state of the art. Regarding the boat production, the drive train is the most significant part in terms of GWP. Within the drive train, the transformers are responsible for the largest share of impacts, mainly related to copper. For electrical propulsion with batteries at ports, battery production impacts increase. Both Kullmann (2016) and Nordtveit (2017) found that results are sensitive to the electricity mix, similarly to studies regarding battery production for electric vehicles as discussed earlier in this chapter.

Henningsgård (2016) and Wang et al. (2018) also conducted LCA of electric ferries. Henningsgård (2016) conducted a simplified LCA to assess a hybrid platform supply vessel and a fully electric ferry compared to their diesel alternatives. The functional unit was 10 years of battery use, the Ecoinvent database was used and the method chosen was ReCiPe with the hierarchist perspective. Only GWP and NO_x emissions were assessed. For the fully electric ferry, the overall emission savings are larger than the additional emissions from the electrification. Wang et al. (2018) conducted a cradle-to-grave LCA of a hybrid ferry operating in Scotland. Diesel direct, diesel electric and hybrid propulsion were considered for a ferry lifetime of 30 years. The actual ferry used as case is hybrid, MV Hallaig. The authors found that the operational phase creates significantly larger impacts than the construction, maintenance and dismantling phases. The hybrid system has the lowest impacts for GWP, acidification and eutrophication, while its photochemical ozone formation impacts are higher than those of the diesel direct case, but still lower than those of the diesel electric case. Wang et al. (2018) concluded that using batteries is preferable from an environmental perspective, but that the electricity source is an important parameter, similarly to Nordtveit (2017) and Kullmann (2016).

Lindstad et al. (2017), Peralta et al. (2019) and Ling-Chin and Roskilly (2016) assessed environmental aspects of batteries in other types of vessels. Lindstad et al. (2017) investigated aspects of pollution, climate impacts and economics for batteries installed in offshore support vessels, and results indicate that the implementation of batteries lead to significant reductions in local pollution and climate change impacts. Peralta et al. (2019) examined the use of LIBs in a platform supply vessel using simulations, and also found emission reductions as a result of battery implementation, due to a more efficient use of the diesel generators. Ling-Chin and Roskilly (2016) conducted an LCA and assessed a new-build hybrid system for cargo ships compared to a conventional diesel direct system. Real time operational data were obtained from the ship owner, and results indicate an overall improvement in environmental performance when switching from the conventional system to the hybrid system. The hybrid system has higher ecotoxicity impacts and significant acidification impacts. The manufacturing phase has little significance compared to operation and end of life.

It can be observed that several of the existing LCA studies on electric ferries based their calculations on the same technologies, e.g. Faessler and Einberger (2017) and Kullmann (2016) both using MF Ampere. This limits the range of real world cases the literature is representative for, and there is therefore a need for more studies on other technology setups. Similarly, other data sources and qualities vary between studies, the same does the solution for modelling the operational phase and which ferry parts are considered in the inventory. This creates deviance. Also, several studies excluded the end of life phase, thus more research should be performed in this area. The studies generally agree that GWP reductions are obtained when moving from diesel electric to battery electric ferries, and that overall, the battery electric ferries achieve larger impact and emission reductions. Though, as the field of literature is limited, more studies are needed to support or challenge these conclusions.

1.3 Research objective and report structure

Considering the aspects discussed in the previous sections, there is a need for more LCA studies on electric ferries. Specifically, studies considering new technologies and detailed operational modelling are needed to broaden the field of literature and cover a variety of real life cases. The objective of this thesis therefore was to conduct a comparative LCA of a diesel electric and a battery electric ferry under real operational and weather conditions. The intended application of the analysis is to support research development and contribute to filling out the literature gap regarding battery electric ferries. By comparing a diesel electric and a battery electric ferry, the consequences of a shift towards fully electrification of ferries and possible burden shifting issues can be analysed. The LCA conducted in this thesis took into account detailed data on a case ferry to make it robust and representative, and a ferry model calibrated in a tool named the MariTEAM model was used to simulate the operational phase based on AIS and weather data. As emphasised in the state of the art presentation, models for vessel consumption and emissions can benefit from further development, therefore the MariTEAM model was modified to represent the specific case in this thesis. The thesis is part of the Smart Maritime centre for research based innovation (Smart Maritime, n.d.) and was carried out in cooperation with Siemens. The LCA was based on real data regarding the ferry construction and operation. 18 types of environmental impacts were analysed together with total emissions within a cradle-to-grave system boundary in order to ensure a comprehensive picture.

The intended audience of the LCA includes ferry owners, operators, shipyards, suppliers, researchers, policymakers and LCA practitioners. Ferry owners, operators and shipyards can use the study when planning new ferries and assessing current ones, and suppliers of technologies analysed in the study can use the results as inspiration when evaluating the environmental performance of their products. Policymakers can use the analysis in decision-making regarding electrification of the maritime sector. Researchers and LCA practitioners can use the study when considering the state of the art and as inspiration and guidance for further research. The audience can learn about environmental impacts of diesel electric and battery electric ferries, and measures for improving the environmental performance of both ferry cases can be identified. This can again be used for guidance and decision making, as well as technology improvements. The study may also provide general guidance on electrification of the maritime transport sector towards obtaining sustainable solutions.

Following this introduction, the report is divided into a methodology overview presenting the LCA methodology, case description and operational modelling, a presentation of the implementation of the MariTEAM model and its results, a life cycle inventory (LCI) description explaining the data foundation for the analysis, LCA results and analysis, a discussion considering robustness, implications and further work and finally a conclusion. Appendices provide additional information. Personal communication (PC) was to a large extent used to collect data during the work with this thesis, and throughout the report such data are labelled.

Chapter 2

Methodology and case description

As introduced in the previous chapter, a comparative LCA of a diesel electric and a battery electric ferry was conducted during the work with this thesis. The general LCA methodology applied is outlined in the first part of this chapter, then the case assessed is described together with its LCA specifics, and the tool used for modelling the operational phase of the LCA, MariTEAM, is then presented. The MariTEAM model was modified to fit the specific cases for this thesis, and then the model outputs were implemented in the remaining LCA calculations. The details of these processes are outlined in Chapters 3 and 5.

2.1 Life cycle assessment

Certain parts of this section are adapted from the project preceding this thesis (Galaaen, 2019). Only the parts of the LCA methodology used in this thesis are described. For further explanation of the LCA methodology, International Organization for Standardization (2006a) and International Organization for Standardization (2006b) should be accessed. LCA is a tool for identifying potential direct and indirect environmental impacts of a product or a service throughout its life cycle. It can be used for comparing different alternatives with regard to environmental performance, identifying ways of improving environmental performance, informing decision-makers and producing environmental product declarations (EPDs), among other purposes (International Organization for Standardization, 2006b). LCA is an iterative technique with four phases called goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation, as illustrated in Figure 2.1 on the following page. As the International Organization for Standardization (2006b) establishes, the four phases should be thoroughly planned and coordinated, and phases often need to be revised as the analysis is carried out and unforeseen aspects emerge. In the following paragraphs, the different LCA phases are explained separately, before the mathematics behind the LCA methodology are presented.

2.1.1 Goal and Scope

The goal and scope definition is the first phase of the LCA methodology, and creates the foundation for the analysis. The goal definition should present the objective of the LCA and include the reasons for carrying out the study as well as the intended application and audience (International Organization for Standardization, 2006b). The scope definition should consider relevant aspects of the product or service, the functional unit, the system boundaries, allocation procedures, LCIA methodology, interpretation, data

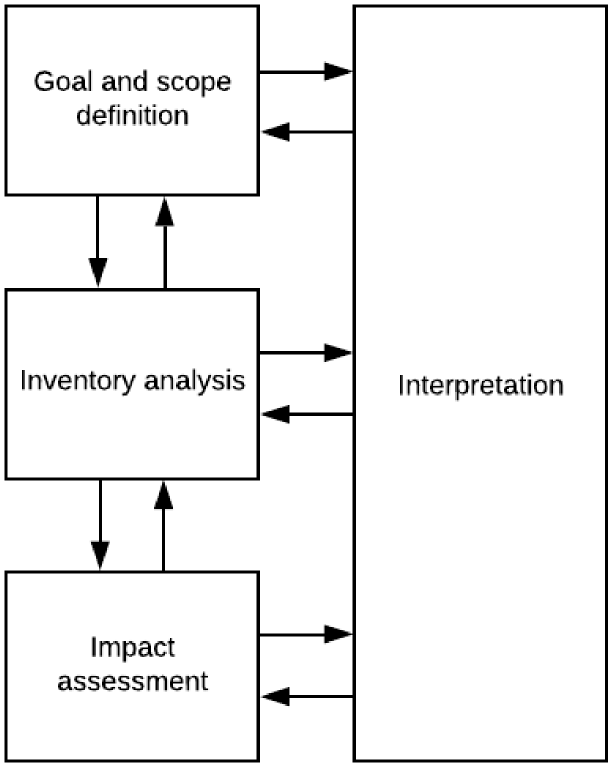


Figure 2.1: The phases of the LCA methodology

requirements, assumptions, value choices, limitations and type and format of the study report, according to International Organization for Standardization (2006b). The functional unit and the system boundaries are two of the most important aspects of the scope, and these are therefore outlined in more detail in the following paragraphs.

Functional unit

The functional unit of an LCA should reflect the function of the product or service under study in a precise and quantitative way, and works as the reference for the LCA as all environmental impacts are related to it (International Organization for Standardization, 2006b). The functional unit can be based on distance, time, size or other parameters, dependent on the function of the product or service, and should also fit the objective of the desired analysis. When performing comparisons based on LCA, the functional unit is also the basis for comparison. Different systems need to have similar functional units in order to be comparable in a fair and productive way. A reference flow is also often defined in addition to the functional unit, describing the measure of process outputs necessary to fulfil the product function established in the functional unit (International Organization for Standardization, 2006b).

System boundaries

The system boundaries of an LCA describe which processes and flows that are included in the analysis, and can be related to life cycle phases, geographical borders, technical systems, time or other measures

(Arvesen, 2019b). The system boundaries should reflect the rest of the goal and scope and be carefully identified, since they affect the calculations and results of the study (International Organization for Standardization, 2006a). LCA researchers often label system boundaries as cradle-to-gate or cradle-to-grave, based on which life cycle phases are assessed. The word *cradle* symbolises resource extraction, and *grave* symbolises end of life treatment. A cradle-to-gate system boundary considers everything from resource extraction up until the final delivery of the product ready for use, while a cradle-to-grave system boundary in addition includes the end of life treatment.

The system boundaries can also be defined based on other parameters than life cycle phases. They can be dependent on time in the form of the system being analysed for a given time period, and they can be dependent on geographical borders for instance when analysing production in a specific country. Other system boundaries can also be defined, and the specifics of the system boundaries are unique for each LCA, which is essential when comparing different LCAs. Generally, the system boundaries should be consistent with the established goal of the analysis (Graedel and Allenby, 2015).

2.1.2 Life Cycle Inventory Analysis

In the LCI phase, quantitative data are used to identify resources consumed throughout the life cycle of the product or service under study, and an inventory is constructed (Graedel and Allenby, 2015). The quantitative data can include input and output materials, energy, emissions, resources and wastes, and need to be identified and systematised (Arvesen, 2019d; International Organization for Standardization, 2006b). Such data can either be measured directly, calculated, or estimated based on literature and databases (Strømman, 2010). Transport is a central part of the LCI. According to Strømman (2010), transport in LCA can be modelled as receiver aggregated, which aggregates transport of products and the end process into a new process, or receiver input, which considers the transport and outputs necessary for the end process separately. Data collected by the practitioner concerning the specific case analysed are called primary data, while data collected by others not necessarily specific for the case analysed are called secondary data. Data used in LCA should preferably be reliable, relevant and accessible (Arvesen, 2019d). The LCI analysis is an iterative procedure as new aspects arising during data collection may lead to changes or adjustments (International Organization for Standardization, 2006a). The LCI phase normally results in a flowchart of the system and a list of resources consumed and emissions to air, water and soil with information on mass flows and chemical specifications (Graedel and Allenby, 2015). Both foreground data and background data are needed in order to obtain a robust inventory. Foreground data concern processes and flows defined in the study, while background data cover upstream processes and flows linked to these, obtained from a generic database (Arvesen, 2019a).

The Ecoinvent database

Background data from databases are needed to compile the LCI. Strømman (2010) emphasised that the data quality is dependent on how well the data represent the processes under study and link with other relevant processes to create a robust image. A database is created by compiling various individual studies, and different LCA databases are available. One of the most commonly used databases is Ecoinvent containing more than 10,000 data sets including various process categories (Arvesen, 2019d). The Ecoinvent 3 database includes different system models, among others the cut-off system model (Ecoinvent, n.d.a). The cut-off system model allocates the burdens of waste treatment to the producer, but does not grant the producer the impacts or benefits of recycling at end of life (Ecoinvent, n.d.a). The Ecoinvent 3.2

database includes both market processes and transforming processes. Transforming processes transform inputs to outputs and consider a specific activity in a specific geographical area (Ecoinvent, n.d.b). Market processes represent consumption mixes and include both raw materials extraction, production, average transport and losses (Wernet et al., 2016). They are intended to be used when specific supply chain information is missing.

2.1.3 Life Cycle Impact Assessment

The LCIA phase relates the results from the LCI phase to environmental impacts (Graedel and Allenby, 2015). It should include selection of impact categories, indicators and characterisation models, classification, i.e. assignment of LCI results to environmental impact categories, and characterisation, i.e. calculation of indicator results (International Organization for Standardization, 2006b). Transparency is important in LCIA because its characteristics affect the results of the LCA (International Organization for Standardization, 2006a). Environmental stressors, e.g. emissions, wastes and resource use, are converted to environmental impacts using a characterisation model with factors characterising the relation between stressors and impacts based on physical and chemical properties (Arvesen, 2019c). Impact assessment can be performed at the *midpoint* or the *endpoint* level; midpoint indicators reflect environmental phenomena like global warming, while endpoint indicators reflect environmental damage like damage to human health (Arvesen, 2019b). Various cultural perspectives can be used in LCIA, representing different viewpoints and positions regarding time and technology. The hierarchist perspective represents a controlling consensus model and is the most frequently used cultural perspective (PRé, n.d.; Goedkoop et al., 2013). Several LCIA methodologies exist, varying regarding calculations, characterisation factors, definitions of impact categories and whether impacts are assessed at the midpoint level or the endpoint level (Woods, 2019). ReCiPe is a commonly used impact assessment method applied by the Ecoinvent database. Structural path analysis (SPA) is a technique that investigates the production or value chain of a final product or service, and identifies where specific environmental impacts occur (Peters and Hertwich, 2006). It can be performed after or as part of the LCIA phase in order to better understand the environmental performance of the system, obtaining valuable information for the interpretation. The LCIA phase also includes optional elements, among others data quality analysis (International Organization for Standardization, 2006b). Data quality analysis covers techniques for improving the understanding of the results, including sensitivity analysis (International Organization for Standardization, 2006b). Sensitivity analysis is a method for identifying how changes in data and methodological choices affect results (International Organization for Standardization, 2006b), and can be valuable in the interpretation phase.

2.1.4 Life Cycle Interpretation

In the interpretation phase, the results from the previous LCA phases are interpreted, and conclusions and recommendations are made (Graedel and Allenby, 2015). The phase also concerns identifying significant issues, evaluating the completeness, sensitivity and consistency of the study, and discussing limitations (International Organization for Standardization, 2006b).

2.1.5 The mathematics behind LCA

The LCA technique is based on vector and matrix calculations for moving from data input to environmental impacts. These mathematical aspects are described in the following paragraphs, based on Strømman

(2010).

The y vector expressed in Equation (2.1) describes the external demand of the processes in the system, typically representing the functional unit of the study.

$$y = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \end{bmatrix} \tag{2.1}$$

The total production output, including both the external demand and the additional requirements for producing the external demand, i.e. the intermediate demand, is described in the x vector expressed in Equation (2.2).

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \end{bmatrix} \tag{2.2}$$

To address the interdependencies between the different system processes in the LCI and describe the intermediate demand per unit output, the A matrix is used. The A matrix is called the requirements matrix, and can be divided into four sub-matrices: A_{ff}, A_{fb}, A_{bf} and A_{bb}. A_{ff} considers the demands between foreground processes, and A_{bb} similarly considers the demands between background processes. A_{bf} represents flows from the background system to the foreground system, while A_{fb} similarly describes flows from the foreground system to the background system. A_{fb} is generally set equal to zero in most LCAs because these flows are neglected as the flows between the foreground system and the background system are assumed to be unidirectional from the background to the foreground. Equation (2.3) illustrates the A matrix.

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1,pro} \\ \vdots & \ddots & \vdots \\ a_{pro,1} & \cdots & a_{pro,pro} \end{bmatrix} = \begin{bmatrix} A_{ff} & A_{fb} \\ A_{bf} & A_{bb} \end{bmatrix} \tag{2.3}$$

A coefficient of requirement, a_{ij}, represents the amount of process i needed per unit output of process j, as shown in Equation (2.4).

$$a_{ij} = \frac{\text{amount of i required}}{\text{output of j}} \tag{2.4}$$

The total production is equal to the sum of the intermediate demand and the external demand of the system. This is called the production balance in LCA. Equation (2.5) illustrates the production balance and how it can be rearranged as a function of L, expressed in Equation (2.6).

$$x = Ax + y = Ly \tag{2.5}$$

$$L = (I - A)^{-1} \tag{2.6}$$

L is the Leontief inverse matrix. Each coefficient in L, l_{ij}, represents the amount of process i necessary to obtain one unit external demand of process j. I is the identity matrix, i.e. a square matrix the same size of the A matrix with ones along the diagonal and zeros elsewhere.

Contribution analysis is carried out to calculate stressors and environmental impacts. As described earlier in this chapter, environmental stressors are identified in the LCI phase. The S matrix, modelled in Equation (2.7), is a matrix describing the stressor intensities of the different processes, meaning how much of a stressor is resulting from a certain amount of a process. The stressor matrix can also be split into foreground and background sub-matrices like the requirements matrix. The foreground stressor intensity matrix S_f concerns stressors created by the foreground system while the background stressor intensity matrix S_b concerns stressors created by the background system.

$$S = \begin{bmatrix} s_{11} & \cdots & s_{1,pro} \\ \vdots & \ddots & \vdots \\ s_{1,str} & \cdots & s_{str,pro} \end{bmatrix} = \begin{bmatrix} S_f & S_b \end{bmatrix} \tag{2.7}$$

The e vector represents the total stressors calculated in the LCI phase. It equals the product of the stressor intensities and the total production output, as expressed in Equation (2.8).

$$e = Sx \tag{2.8}$$

To analyse which processes the total stressors of different types are caused by, the E matrix is created, as shown in Equation (2.9). $\hat{x}$ is a diagonalised form of the x vector in the form of a square matrix.

$$E = S\hat{x} \tag{2.9}$$

In order to convert environmental stressors to environmental impacts in the LCIA phase, the characterisation matrix C is applied. The characterisation matrix contains characterisation factors describing relations between stressors and impacts as introduced earlier in this chapter. Equation (2.10) illustrates the C matrix.

$$C = \begin{bmatrix} c_{11} & \cdots & c_{1,str} \\ \vdots & \ddots & \vdots \\ c_{imp,1} & \cdots & c_{imp,str} \end{bmatrix} \tag{2.10}$$

The total impacts equal the product of the characterisation matrix and the total stressors. The d vector represents the total impacts, and it is presented in Equation (2.11).

$$d = Ce \tag{2.11}$$

To investigate how different processes contribute to various impacts, the D_{pro} matrix is used. It is equal to the product of the C matrix and the E matrix, as illustrated in Equation (2.12).

$$D_{pro} = \begin{bmatrix} d_{11} & \cdots & d_{1,pro} \\ \vdots & \ddots & \vdots \\ d_{imp,1} & \cdots & d_{imp,pro} \end{bmatrix} = CE \tag{2.12}$$

To analyse how different stressors contribute to various impacts, the D_{str} matrix is used. It is the product of the C matrix and the e vector, as illustrated in Equation (2.13). $\hat{e}$ is a diagonalised version of the e vector in the form of a square matrix.

$$D_{str} = \begin{bmatrix} d_{11} & \dots & d_{1,str} \\ \vdots & \ddots & \vdots \\ d_{imp,1} & \dots & d_{imp,str} \end{bmatrix} = C\hat{e} \tag{2.13}$$

D_{pro} represents the total impacts from the separate processes. To further explore how impacts are linked to foreground and background processes, advanced contribution analysis needs to be carried out. If the output of the foreground system is defined as in Equation (2.14), and the demand placed upon the background system from the foreground system expressed as in Equation (2.15), the output of the background processes by each foreground process is illustrated in Equation (2.16).

$$x_f = (I - A_{ff})^{-1} y_f \tag{2.14}$$

$$M_{bf} = A_{bf}\hat{x_f} \tag{2.15}$$

$$X_{bf} = (I - A_{bb})^{-1} M_{bf} \tag{2.16}$$

Using these equations, the direct impacts of each foreground process are modelled in $D_{pro,ff}$, the impacts of the background processes associated with each foreground system in $D_{pro,bf}$, and the total impacts of each foreground process in $D_{pro,f}$, as illustrated in Equations (2.17)-(2.19).

$$D_{pro,ff} = CS_f\hat{x_f} \tag{2.17}$$

$$D_{pro,bf} = CS_b X_{bf} \tag{2.18}$$

$$D_{pro,f} = D_{pro,ff} + D_{pro,bf} \tag{2.19}$$

The calculations described above results in values that can be interpreted. The aspects of the LCA methodology presented in this section are used throughout this thesis, and the mathematics are used during the LCI and LCIA phases to obtain the desired results. The following section presents the characteristics of the case analysed and the LCA conducted in this thesis.

2.2 Case description

The objective of this LCA was stated and explained as part of the research objective in Chapter 1. The scope of the LCA in line with the LCA methodology presented in the previous section is described in the following sections in terms of the product system, the functional unit, the system boundaries and the LCIA methodology. Limitations, assumptions and data are described in the following chapters.

2.2.1 Product system

The product system analysed is a ro-pax ferry including its necessary systems on land. The ferry used as a basis for the analysis is MF Lagatun operating the route Flakk-Rørvik in Trøndelag, Norway. Figure

2.2 illustrates the crossing with the associated distance and travel time. MF Lagatun is actually a hybrid battery electric ferry, but for the purpose of this thesis, the ferry was used to model one diesel electric ferry and one fully battery electric ferry. The diesel electric ferry is the conventional case and the battery electric ferry is the new technology to be examined in a comparison with the conventional case.

The two ferries operating the route, MF Lagatun and MF Munken, are identified as circles. The mooring system machines are identified as squares.

Figure 2.2: Ferry crossing studied including distance and travel time

The ferry battery system on board MF Lagatun is made up of four individual batteries, and it is charged from the electricity grid and batteries on land at each side of the fjord. The ferry was built in 2018 and has been in operation since 2019 (Vadset, 2019), and was assumed to have a lifetime of 30 years (PC). FosenNamsos Sjø is the ferry owner, Myklebust Verft is the shipyard that built the ferry, and Siemens is the supplier of batteries and other electric equipment. The ferry MF Munken operates the route together with MF Lagatun, evenly switching between operating as A and B ferries[1]. The two ferries are identical, and the systems on land are shared between them.

A ferry consumes power both for propulsion and for hotel energy, and is generally built up of a hull and structure, cables, a navigation system, a hydraulic system, a ventilation system, a propulsion system, control systems, interior, safety equipment and a fire suppression system. Both diesel electric and battery electric ferries have electric motors linked to thrusters as part of the propulsion system, as described in Chapter 1. A diesel electric ferry in addition consists of diesel tanks and diesel generating sets including

[1] A ferries operate during the night, while B ferries only operate during the day.

diesel engines and electric generators connected to the electric motor. A battery electric ferry has batteries connected to the electric motors and charging stations on land. For the diesel electric ferry, the diesel generating sets deliver the electric power for propulsion, while for the battery electric ferry, the batteries delivers the electric power. The charging stations for the case ferry include batteries charged from the electric grid on land. Additional transformers and other electric equipment and infrastructure are needed both on land and on board the case ferry to perform charging. During non-operating hours, both ferry cases are supplied with shore power[2] to cover the hotel load. A vacuum based mooring system is present for both the diesel electric and the battery electric ferry and used for mooring during charging, boarding and disembarking. There are two mooring machines at each port. Specifics regarding MF Lagatun and its route are outlined in Table 2.1 on the following page, based on FosenNamsos Sjø (n.d.a), Skipsrevyen (2018), Marine Traffic (2020), Myklebust (n.d.) and personal communication. The diesel engines total rated power in the table is the rated power in the diesel electric case where there is an additional diesel engine. The diesel engine rated power for the actual hybrid ferry is 1605 kW. Details on the inventory of the product system in the two ferry cases are presented in Chapter 5.

2.2.2 Function, functional unit and reference flow

The function of the ferry is to transport passengers and cars between Flakk and Rørvik in Trøndelag, Norway according to a set timetable. As described in the LCA methodology earlier in this chapter, the functional unit needs to reflect this function. In Chapter 1, it was observed that various functional units can be used for LCA of transport. The functional unit in this analysis was defined as the ferry lifetime of 30 years, and the reference flow was one diesel electric ferry in the diesel electric case and one battery electric ferry in the battery electric case with corresponding operation and infrastructure. One PKT, one seat kilometre travelled, one vehicle kilometre travelled or one year of operation are other functional units that could have been used. The ferry lifetime was found to be the most suitable because it is straightforward and easy to interpret. Results were also calculated for PKT, and the calculations and results per PKT are presented in Appendix C.

2.2.3 System boundaries

The analysis is a cradle-to-grave LCA, meaning all processes linked to materials extraction, production and manufacturing, operation and end of life were intended to be assessed. Maintenance was not thoroughly modelled due to limited data, but replacements of components due to lifetimes and overhauling of certain components were included. Most of the processes occur within the geographical borders of Norway and Europe, but there were not set any geographical system boundaries excluding other processes. The time system boundaries were set equal to the lifetime of the ferry, and the analysis was based on the current situation without taking into account future changes. The operational data used to model the operational phase cover a time period of two weeks in February 2020. The system boundaries and flowcharts are further elaborated in Chapter 5.

2.2.4 LCIA methodology and impact categories assessed in the analysis

The LCA software used in this thesis was Arda, an Excel- and Matlab-based LCA software developed by the Industrial Ecology programme at NTNU. Arda uses the Ecoinvent 3.2 database with the cut-

[2] Shore power is electrical power provided to the vessel directly from shore.

Table 2.1: Specifics for the ferry MF Lagatun and its route Flakk-Rørvik

Measure	Value
Crossing distance	7.4 km
Crossing time	25 minutes
Charging time	5 minutes
Passenger capacity	399 including crew
Inside seats	390
Outside seats	120
Car capacity	130
Lifetime	30 years
Yearly operating time	7000 hours
Ship type	Passenger
Maritime mobile service identity (MMSI)	257057960
Year of construction	2018
Dead weight tonnage (DWT)	750 ton
Light displacement tonnage (LDT)	1965.2 ton
Draught	4.05 m
Breadth	17.2 m
Length	111.9 m
Length between perpendiculars	108.543
Service speed	12 knots
Diesel engines cylinders (DE)	8
Diesel engines total rated power (DE)	2140 kW
Diesel engines rotational speed (DE)	1500 rpm
Diesel engines stroke (DE)	4
Diesel engines tier	II
Electric motors rated power	2400 kW
Electric motors total rotational speed	1200 rpm
Ferry battery capacity	2138.4 kWh
Ferry battery state of charge (SoC)	20-80%
Hotel power	100 kW

DE = used only for the diesel electric ferry.

off classification system model and the ReCiPe LCIA model with the hierarchist cultural perspective and midpoint indicators. The 18 midpoint impact categories from the ReCiPe model as well as total emissions of CO_2, CH_4, N_2O, NO_x, PM and SO_x, described in Figure 2.3 on the following page, were assessed in this analysis. SPA was used for all indicators to investigate why and where impacts occur.

The main focus in this LCA is on GWP, as one of the main reasons for implementing battery electric ferries is to mitigate climate change, as discussed in Chapter 1. Emissions of NO_x are also central regarding transport and are therefore also in focus. These indicators were prioritised during the results interpretation in addition to other indicators with large differences between the diesel electric and the battery electric case. Still, it is important to assess a range of environmental impact categories to obtain a holistic picture and assess sustainability, and this analysis therefore considers all 18 impact categories and total emissions for the base cases. A central part of the LCA modelling in this thesis is the method used for simulating the operational phase, which is introduced in the following section.

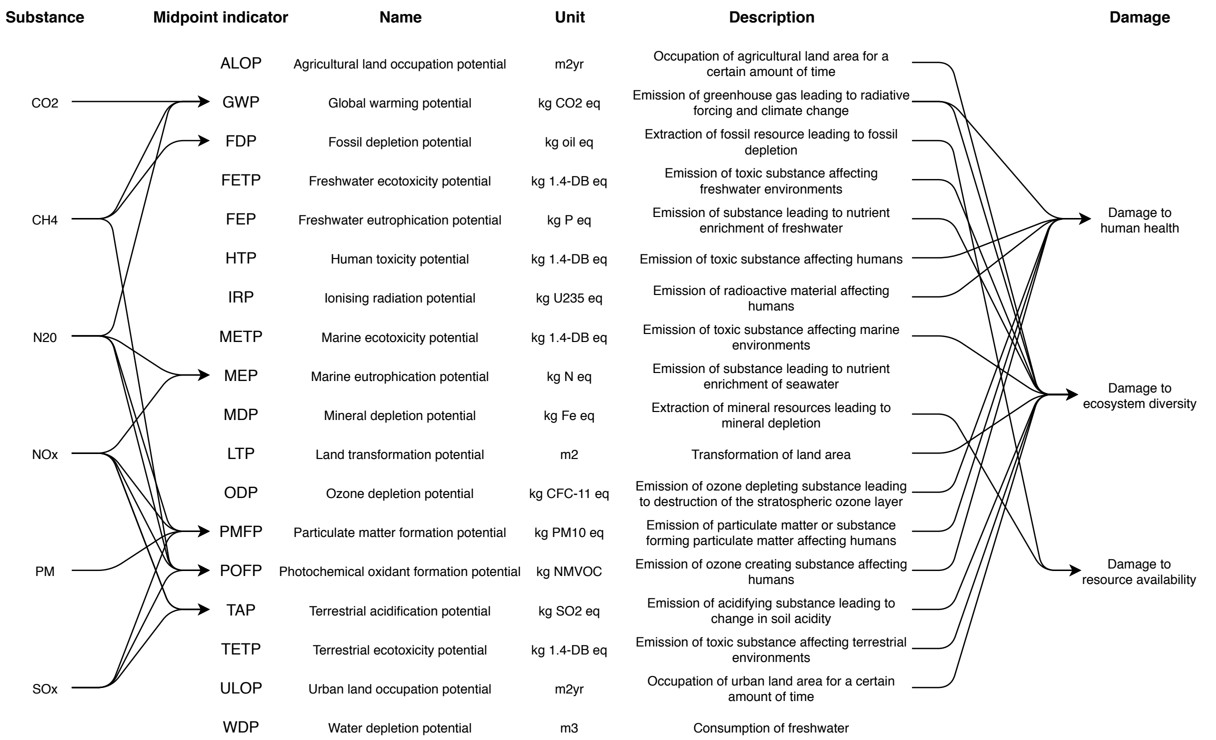


Figure 2.3: Midpoint indicators analysed and relations between substances and midpoint indicators based on Goedkoop et al. (2013)

2.3 The MariTEAM model

The MariTEAM model is the tool used for simulating the operational phase of the LCA in this thesis, developed by NTNU as part of the Smart Maritime project (Smart Maritime, n.d.). It is a Python based tool for calculating fuel consumption and emissions in maritime transport for different ship types, fuels, engines, speeds and weather profiles. It is based on Jalkanen et al. (2012), which was introduced in Chapter 1, and MAN Energy Solutions (2018), Hollenbach (1998), Molland et al. (2011), Schneekluth and Bertram (1998), Lindstad et al. (2011), International Maritime Organization (2020b), Network for Transport Measures (2015), GDV (2020), Trozzi and De Lauretis (2016), Bertram (2012) and Kwon (2008). It uses AIS, weather and ship data input to perform ship-specific calculations and simulate the ship power and emission profile based on the Hollenbach method for diesel direct propulsion (Hollenbach, 1998). The original model was modified to represent electric ferries as part of the work with this thesis, and then the modified version was used to simulate the operational phase of the LCA. In this chapter, the original MariTEAM model is described, and in Chapter 3 the modifications performed and related codes developed are explained.

The code for the MariTEAM model is built up of five main modules: ship, engine, weather adjustment, power profile and emissions. The model uses these modules and their classes and functions to simulate a specified ship with specified engines under stated operational and weather conditions as illustrated in Figure 2.4 on the following page.

Input to the model includes ship specifics, operational data, fuel data, emission data and weather data. The user specifies ship and engine parameters and imports an operational profile before the model is run. Weather calculations are optional, but if they are to be executed, the user also needs to load weather data

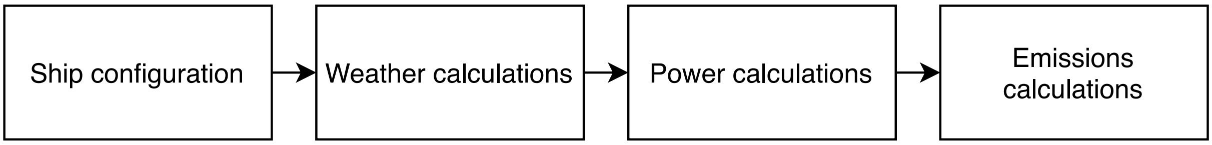


Figure 2.4: Overall methodology of the original MariTEAM model

including ship bearing, wind speed, wind direction, Beaufort number and wave direction. Ship specifics for ship configuration include:

- Ship type and MMSI number
- Breadth, length, draught and length between perpendiculars
- Year of construction and service speed
- Dead weight tonnage (DWT)
- Light displacement tonnage (LDT)
- Main engine cylinders, rated power, rotational speed [rpm] and stroke
- Auxiliary engine rated power
- Number of reefer[3] points

The operational profile includes the following elements:

- Position in longitude and latitude
- Speed over ground (SOG)
- Change in distance from one timestamp to the next
- Change in time from one timestamp to the next
- ECA status: whether the ship is inside an emission control area (ECA)
- AIS status: whether there are original AIS and port call messages

Fuel and emission data can also be loaded by the user, if not default values are used. Fuel data include fuels with related CO_2 factors and sulphur percentages. Emission data contain functions for fuel consumption and emission curves based on the type of engine, stroke, tier, fuel and load. The default emission data account for engine efficiency and are based on literature and International Maritime Organization (2020b). The model input is used in calculations that result in an emission profile describing the fuel consumption and emissions of the ship under study for the given time period. Emissions included in the model are CO_2, SO_x, NO_x, CO, OC, elemental carbon (EC) and black carbon (BC), and the MariTEAM model assumes that SO_x emissions are 97% SO_2 and 3% SO_4. These emissions are related to midpoint indicators in the ReCiPe model as outlined in Figure 2.5 on the following page.

Initially, the ship and engine parameters and modules are used to create a ship with engines. A ship class within the ship module is used to create a ship object with the parameters specified by the user,

[3] A reefer is a refrigerated container.

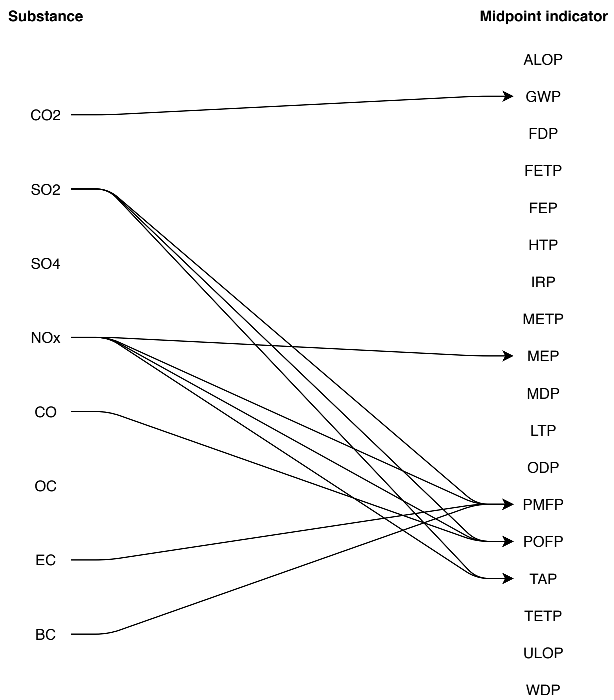


Figure 2.5: Substances from the MariTEAM model related to midpoint indicators based on Goedkoop et al. (2013)

and additional parameters required for subsequent calculations are created. The ship tier is calculated based on the year of construction, the length at waterline is calculated based on the length between perpendiculars, and the displacement tonnage is calculated based on the LDT and DWT. The wetted area is calculated based on the length between perpendiculars, the draught and the displacement, and the block coefficient is calculated based on the displacement, the breadth, the length and the draught. The propeller diameter is calculated based on the main engine rated power and rpm, and the reefer use is calculated based on the number of reefer points. The ship class calls the engine module to create the ship engines. The engine module has three classes: a base engine class and main and auxiliary engine classes inheriting[4] from the base engine class. When creating an engine, the respective engine class is called, and the engine object is created based on the engine parameters specified by the user. The main engine speed category is calculated based on the tier and rpm.

After the ship object is created with its respective main and auxiliary engine objects, the SOG in the operational profile is adjusted and if the weather option is chosen, the operational profile is adjusted based on the weather data. The model accounts for tailwind and headwind and the effect of waves on the ship power profile. The weather adjustments include calculations of the Froude number based on the speed and length at waterline, and calculations of a weather reduction coefficient used for finding the actual speed of the ship. The weather reduction coefficient is the product of coefficients for direction reduction, speed reduction and ship form reduction. The direction reduction coefficient is calculated based on the bearing, wind direction, wave direction, Beaufort number and distance, finding the angle from which the weather hits the ship. The speed reduction coefficient is calculated based on the block coefficient and the Froude number, and the form reduction coefficient is calculated based on the displacement, ship type and Beaufort number. The weather adjustment calculations result in an updated operational profile

[4]Inheritance in programming is a technique for basing an object or a class on another object or class.

accounting for weather effects.

After the weather adjustments, the ship power profile is calculated based on the ship and the operational profile in the power profile module. The Hollenbach method is used to calculate the power. It is based on diesel direct propulsion vessels and involves calculations of resistance curves to predict the power requirements (Schneekluth and Bertram, 1998; Molland et al., 2011; Hollenbach, 1998). The propulsion efficiency, still water power requirement and residual power requirement are calculated and used to obtain the total power requirement. The propulsion efficiency is calculated based on the ship design efficiency, design speed and current speed. The still water power requirement is calculated based on the wetted area, the SOG and the still water resistance coefficient calculated based on the length between perpendiculars and the SOG. The residual power requirement is calculated based on the ship breadth, draught, SOG and calculations of the minimum residual resistance coefficient for single-screw ships based on the length, length between perpendiculars, block coefficient, draught, breadth, length at waterline and SOG. After the initial power profile calculations, reefers are added and the power profile is adjusted to obtain loads at design speed between 80% and 95%. The power profile is also adjusted so that the maximum propulsion power cannot exceed the rated power of the main engine. Then, the final power profile is obtained presenting power for each timestamp in the operational profile, and the model moves on to calculate the emissions.

The emission calculations in the emission module are based on the ship, the operational profile, emission data and fuel data. Auxiliary engine use and load are calculated using the engine module and based on the main engine rating and reefer use, ensuring that the auxiliary engine power consumption does not exceed the rated power of the auxiliary engine. The number of auxiliary engines in use is calculated and the power demand is distributed evenly between them. After the auxiliary engine calculations, the emission calculations proceed to define the type of fuel used based on the engine size and ECA status. Then, emission curves are identified for the main and auxiliary engine based on the engine type, emission data, ship tier and fuel data. CO_2 and SO_x emissions are calculated directly based on fuel consumption, while the fuel consumption and the other emissions are calculated using the emission data. The emission calculations result in an emission profile with emissions for each timestamp in the operational profile. This is the final step in the original MariTEAM model.

The MariTEAM model was modified to represent a diesel electric and a battery electric ferry, and codes were developed for preparing data and analysing the model outputs before implementation in the LCA. These implementations are described in Chapter 3, and the implementation of the LCA methodology is elaborated in Chapter 5.

Chapter 3

Implementation part 1: MariTEAM

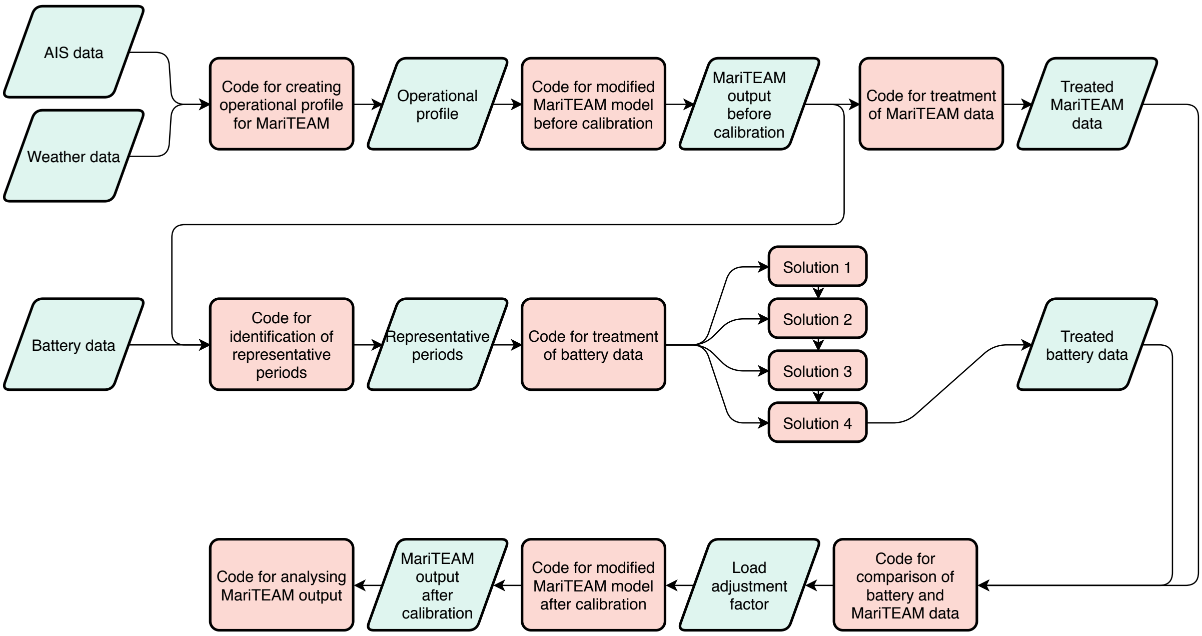
The first part of the methodology implementation presented is the work with the MariTEAM model. Four main codes were developed for simulating the operational phase of the LCA based on real battery data, AIS data and weather data:

- A code for creating the operational profile for the MariTEAM model based on AIS and weather data
- A code for a modified MariTEAM model used for diesel electric and battery electric ferries
- A code for calibrating the modified MariTEAM model
- A code for analysing the MariTEAM output

The codes can be found in Appendix A, and are further described in Figure 3.1 on the following page and in the following sections. The programming language used was Python 3.8, and the integrated development environment used was PyCharm.

3.1 Code for creating operational profile for MariTEAM

The basis for the operational profile used in the MariTEAM simulation is AIS and weather data for the case ferry. AIS data include position in longitude and latitude, SOG and Unix timestamps, and are given on a minute basis. The weather was found at Meteorologisk insitutt (n.d.), considering the weather station at Trondheim - Høvringen, as this is the one closest to the Flakk ferry pier measuring wind. Data were downloaded on an hourly basis and include wind speed and wind direction. The wave direction was assumed to be the same as the wind direction. A code was created for treating these data after extraction from the database, before implementation in the MariTEAM model. The code calculates time, distance, bearing and Beaufort number. Duplicate values for the same timestamp are initially removed leaving only the last value, as the other measurements for the same timestamp were assumed to be sensor errors. The amount of time between each timestamp is calculated directly, and the distances between each timestamp are calculated based on coordinates. The ship bearing is calculated based on the formula from Igismap (2020). The ECA status is set equal to true despite the ferry not actually operating inside an ECA (International Maritime Organization, 2020a), because it is operating in a Norwegian fjord and thus has emission restrictions. The AIS status is set equal to true, and the Beaufort number is calculated. The weather data are assigned to the Unix timestamps of the operational data by finding the weather data



Green represents data, red represents code.

Figure 3.1: System of codes developed during the work with this thesis

timestamp closest to each AIS data timestamp. The calculated data are then added to a file, and the final operational profile for the MariTEAM model is created.

3.2 The modified MariTEAM model

As established in Chapter 2, the original MariTEAM model is designed for shipping using diesel direct propulsion, and a modified MariTEAM model was therefore created to represent diesel electric and battery electric ferries operating inland waterways. The modified MariTEAM model was later calibrated with the battery data, and the corresponding code is described in the next section. The descriptions of the modifications in this section are based on the initial description of the MariTEAM model from Chapter 2, describing only the modifications in detail.

The first step of the MariTEAM model is to configure the ship and import the operational profile. The original ship configuration was modified so that electric motor rated power and rpm can be entered in addition to the ship specifics in the original MariTEAM model. In this way, both battery electric, diesel electric and diesel direct propulsion systems can be modelled. New ship parameters in the ship class were created for the modified model:

- A float parameter regarding the rated power of an electric motor
- A float parameter regarding the rpm of an electric motor
- A Boolean parameter[1] regarding whether the ship is diesel direct (DD)
- A Boolean parameter regarding whether the ship is diesel electric (DE)
- A Boolean parameter regarding whether the ship is battery electric (BE)

[1] A Boolean parameter is a parameter that can obtain either the value *true* or the value *false*.

The Boolean parameters are central for which parts of the code are accessed during execution. The DD ship parameter is set equal to true if the user specifies a rated power for only the main engine, the DE ship parameter is set equal to true if the user specifies a rated power for both the main engine and the electric motor, while the BE ship parameter is set equal to true if the user specifies a rated power for only the electric motor. The calculation of the propeller diameter was modified so that it is based on the electric motor in the BE case, while it is based on the main engine for the DE case as for the DD case in the original model. The code was modified so that initiation of the main and auxiliary engine and the electric motor only is executed if the user specifies a rated power for them. The DE case does not have auxiliary engines, but uses the diesel generating set to cover the hotel load. The BE case covers the hotel load using the batteries. The diesel engine used in the case ferry is tier II, but because the ferry was built in 2018 the original code models the engine as tier III. The code was therefore modified so that the tier is hard-coded equal to II.

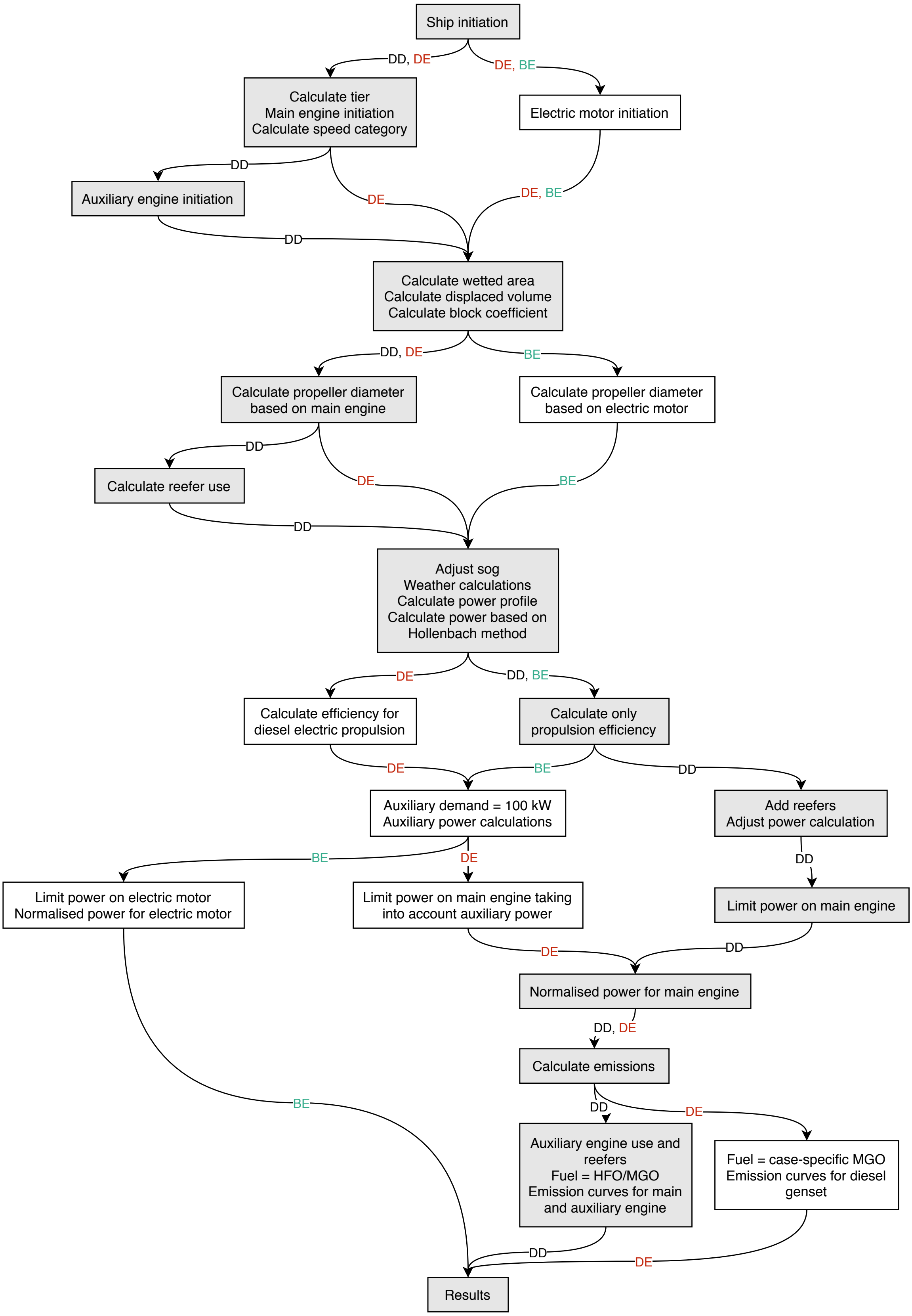
A new class was created in the modified MariTEAM model, representing an electric motor. This class is similar to the engine class, and includes rated power and rpm for the electric motor. Generally throughout the code, similar functions to the ones existing for the main engine were created for the electric motor. In the engine class of the modified model, a diesel generating set was added as a possible engine type, in addition to main and auxiliary engines. The diesel generating set represents the diesel engine and generator together, and is only used when accessing the emission data, as described later in this section. The main engine is used for DE power calculations including both propulsion and hotel power.

The power profile is calculated based on the ship and its operational profile using the Hollenbach method, as described in Chapter 2. Even though this method is intended for ships with diesel direct propulsion, it is assumed to be fairly representative for electric ferries and is therefore also used in the modified MariTEAM model. The calibration is intended to adjust for related inconsistencies. The Hollenbach method calculates the power in the last step prior to the propeller: the electric motor in the BE and DE cases, and the main engine in the DD case. In the modified model, the power in the power profile is intended to represent the point of output from the electric motor in the BE case, and the point of output from the main engine in the DE and DD cases to be able to calculate emissions correctly. The efficiency calculations part of the Hollenbach method were adjusted in the modified model based on the type of propulsion system. For DE cases, the power in the engine is assumed to vary linearly with the power in the electric motor calculated using Hollenbach. Thus, the total efficiency is obtained by including both the propeller efficiency from the original code, the generator efficiency and the electric motor efficiency. For BE cases, only the propeller efficiency is included, and calculations regarding other efficiencies in the propulsion system are carried out separately. Reefer use is assumed to only be relevant for DD cases in the modified model. The parts of the original MariTEAM model considering reefer use are therefore only executed if the ship is DD in the modified model, and the code was modified accordingly. For DE cases, the hotel power in the power profile calculations was set equal to 100 kW as for the case ferry and multiplied with a factor for the losses from the engine to the point of hotel load in the modified model. Hotel consumption and emissions, which are calculated in the emission module in the original model, are calculated separately in the power profile module for DE cases. For BE cases, the hotel power and energy are calculated separately in the code for analysing the MariTEAM output. The load and maximum power in the modified model are calculated based on the rated power of the electric motor for BE cases, and on the rated power of the main engine for DE and DD cases, as in the original model. For the DE case, a function was created so that the sum of the propulsion power and the hotel power cannot exceed the rated power of the main engine. For the BE case, the battery covers both the hotel load and the propulsion load, and has a capacity well above the maximum total load, implying that such a function is not necessary.

The code was modified so that after the power profile calculations, the emission calculations are only accessed for DE or DD cases. The emission data were updated to represent the DE case in the modified model. The load curves for engine loads higher than 20% were set equal to 1 to reflect the improved performance of a diesel electric propulsion system compared to a diesel direct one. The load curves for engine loads lower than or equal to 20% remain as in the original model. The SFOC is modelled as a function of power per cylinder based on data regarding Wärtsilä diesel generating sets (Wärtsilä, 2020). A power regression was used on the data, and the regression function was implemented in the emission data, creating a functionality for the fuel consumption with a diesel generating set. The calculated values were assigned to the diesel generating set engine type in the emission data. The MariTEAM code was modified so that if the ship is characterised as DE it enters the fuel consumption functionality for a diesel generating set in the emission data. NO_x, CO, OC, EC and BC emissions are calculated using the functionality of the original model with marine gas oil (MGO) as a simplification. A case-specific MGO was added as a fuel in the modified model. In order to ensure consistency, the same procedure as already used for obtaining the CO_2 factors of heavy fuel oil (HFO) and MGO in the original MariTEAM model was used. The CO_2 factor for the case-specific MGO was set equal to the factor for diesel/gasoil from MEPC/Circ.471 (2005), 3206.0 kg CO_2 per tonne fuel. The sulphur percentage was set equal the sulphur content in the fuel used by the case ferry, 0.05% (PC).

In the emission calculations, auxiliary engine values are only calculated for DD cases in the modified model. For DE cases, the fuel is set equal to the case-specific MGO in the modified model, while for DD cases, the original code defining fuel type is executed. For DD cases, emission curves are calculated as in the original model, while for DE cases, they are calculated using the diesel generating set engine for both hotel and propulsion emission curves. When calculating the emission curves for DE cases, the parameters for the engine in the case ferry are hard-coded and the diesel generating set emission data are accessed.

Before simulations with the MariTEAM model as part of this work, the ship specifics of the case ferry from Chapter 2 were implemented for the ship configuration. The output of the modified MariTEAM model is the power profile for BE cases and both the power profile and the emission profile for DE and DD cases. The profiles present power, fuel consumption and emissions as a function of time as in the original model. The power profile for the BE case ferry analysed was used in the following calibration. The differences in the modified MariTEAM model from the original MariTEAM model are summarised in Figure 3.2 on the following page.



DD = diesel direct, DE = diesel electric, BE = battery electric. Grey represents original code, white represents new code.

Figure 3.2: Modifications to the original MariTEAM model resulting in the modified MariTEAM model

3.3 Codes for calibration of the modified MariTEAM model

The objective of developing the calibration codes was to treat the battery data and the output of the modified MariTEAM model, compare them and based on that calibrate the modified MariTEAM model. First, minor adjustments to the modified MariTEAM model described in the previous section were made to prepare it for calibration. Then, robust time periods without significant error measurements were identified due to the inconsistencies of the data. The battery data and the pre-calibration modified MariTEAM output were treated before calibration. The calibration was performed by comparing a robust time period for the battery data and the pre-calibration modified MariTEAM output, identifying an adjustment factor and implementing it into the modified MariTEAM model, and then comparing another robust time period for the battery data and the output from the adjusted modified MariTEAM model. Ultimately, a final adjustment factor was established. It was essential that the MariTEAM model created a representative operational profile of the real case since it was used to model the operational phase of the LCA for both the diesel electric and the battery electric case. The procedure for developing the codes for this process was iterative because each time a code was created, flaws or inaccuracies in the data set leading to errors or inaccuracies in the code were discovered, and a new one needed to be developed. The codes developed are presented in the following sections.

3.3.1 Pre-calibration modified MariTEAM model

The modified MariTEAM model was prepared for calibration with the battery data by removing adjusting functions for load and maximum power in the power profile so that the raw power calculations were used for calibration. This code is referred to as the pre-calibration modified MariTEAM model, and is not the final version of the modified MariTEAM model used in the LCA simulation. The pre-calibration modified MariTEAM model was run and its output was compared to the battery data as a basis for calibration.

3.3.2 Identification of representative periods

The pre-calibration modified MariTEAM model was to be compared to the battery data on a consistent and representative basis. The battery data include energy values in each of the four ferry batteries for different timestamps on a minute basis, and are divided into two files for each battery, one for each week of the considered time period. The energy values are given at different timestamps for the separate batteries, and the time period considered vary somewhat between the batteries. The most robust and representative periods in the battery data were identified and used for calibration. The identification was done by comparing power profiles of the battery data and the pre-calibration modified MariTEAM output for the same periods. The battery data are confidential and are therefore not included in this report.

In the code for identification of representative periods, the battery data are imported and duplicate values for the same timestamp are removed leaving only the last. This decision was made because it is assumed that when multiple energy values are measured within the same time stamp, it is due to corrections in the measurement, and the last value is correct. No further cleaning of the data is performed in the code. The separate files for the weeks are merged into one data structure for each battery. A collection of all the timestamps within the period from the first to the last is created. The data structures for the batteries are merged with this collection so that the energy values of each battery are listed for their respective timestamps. Then, this merged data structure is linearly interpolated so that missing energy values for each battery are estimated based on the existing values for the respective battery. This is done to be able to summarise values across all batteries despite the values being measured at different timestamps. Only the timestamps for which there exist data for all batteries are considered. The energy levels in each battery are summarised across the batteries to obtain the total energy level for the ferry. Then, the power P in each timestamp is calculated based on the change in energy ΔE and time ΔT to the next timestamp as described in Equation 3.1.

$$P = \frac{\Delta E}{\Delta T} \tag{3.1}$$

The power profile created from the battery data and the power profile from the pre-calibration modified MariTEAM model output were compared for different time periods manually based on outputs from a code creating power profiles for various periods. First, the whole period was considered to obtain an overview, and then the first and last week of the period were investigated separately. Periods where the power profiles for the battery data and the MariTEAM output seemed to be considerably similar were identified from the code output. Then, these periods were investigated on a two-day-basis, and the same procedure was followed, identifying robust periods. These periods were investigated on an hourly basis where crossings and charging periods were clearly visible. A period was defined as representative if the ferry was operating, the same number of crossings and charging periods could be observed for both the battery data and the MariTEAM output, if the curves were fairly consistent, and if there were few or no clear outliers. A representative crossing has a quite sharp curve for acceleration and deceleration, and a fairly constant power during the rest of the crossing. The charging power was not emphasised because this was not to be accounted for in the following energy calculations. The representative periods identified were further used for treatment of battery and MariTEAM data and ultimately comparison and calibration, as described in the following paragraphs.

3.3.3 Treatment of battery data

Working with raw data is a time consuming process involving a need for significant amounts of data pre-processing. Different solutions for treatment of the battery data were developed, and the process of establishing one final feasible and robust solution was iterative. Only the final solution is described in this section. In the same way as for the identification of representative periods, the code imports the battery data, duplicate values are removed, the different weeks are merged for each battery and the data are prepared for further treatment. The energy consumption during a time period is calculated as the sum of negative energy changes between one timestamp and the next for all timestamps. One battery is considered at a time, but the negative energy changes are added to the same sum.

The MariTEAM output reflects the power consumption delivered to the propeller, i.e. the power out of the electric motor in the battery electric case. In order to make the battery data comparable to the MariTEAM output, the energy delivered to the propeller (E_p) needs to be found from the energy in the battery (E_b). To account for losses in electrical components, the discharge energy from the batteries is multiplied with the efficiencies of the battery discharging (η_d), the switchboard between the battery and the electric motor (η_s) as well as the electric motor (η_e), as described in Equation (3.2).

$$E_p = E_b * \eta_d * \eta_s * \eta_e \tag{3.2}$$

The batteries and diesel engines operate at the same time when extra diesel propulsion is needed in the hybrid case ferry (PC). The data obtained only describe the batteries, meaning that extra power from the diesel engines needs to be added manually in the code before comparison with the MariTEAM output. Rates of hybridisation[2] for each week of operation were provided by the ferry owner (PC). Based on the these, additional energy is added to the battery data in the code to reflect the actual total energy consumption including the diesel energy consumption. The total energy is found by using Equation (3.3), where E_{tot} is the total energy consumed by the ferry, $E_{battery}$ is the energy consumed in the battery, and $r_{hybridisation}$ is the rate of hybridisation.

$$E_{tot} = \frac{E_{battery}}{r_{hybridisation}} \tag{3.3}$$

This energy sum is multiplied with -1 in order to obtain a positive value for easier comparison with the MariTEAM model. The hotel energy consumption is included in the battery data, and the hotel energy is calculated as the constant hotel power demand of 100 kW multiplied with the amount of time in the period considered and subtracted from the energy sum to find the propulsion energy. The periods identified as representative as described above were analysed using this code when calibrating the MariTEAM model.

3.3.4 Treatment of MariTEAM output

The pre-calibration modified MariTEAM output also needed to be treated before the comparison with the battery data. A code was developed importing the MariTEAM output. The same energy and time calculations as performed for the battery data are performed for the MariTEAM output, but as the MariTEAM output only include power, the energy needs to be calculated from the power applied over a time period. The change in energy from the previous timestamp to the current timestamp is defined as the power in the previous timestamp multiplied with the time since the previous timestamp, as described in Equation (3.4). In the MariTEAM model, the power is equal to zero when the ferry is charging at port.

$$\Delta E = P * \Delta T \tag{3.4}$$

3.3.5 Comparison of battery data and MariTEAM output

After the battery data and the pre-calibration modified MariTEAM output were treated, they could be compared and used to calibrate the modified MariTEAM model. The energy sum for a representative period for the battery data was manually compared to the energy sum for the same period for the MariTEAM output. An adjustment factor, load_adjust, was defined based on the energy sum for the battery data, $E_{tot,battery}$ and the energy sum for the MariTEAM data, $E_{tot,MariTEAM}$ as described in Equation (3.5). This factor was then applied to the modified MariTEAM model, adjusting the power profile to create a more precise representation of the real operation. The modified MariTEAM model was run with the adjustment factor. Then, the energy sum for another representative period was calculated for both the battery data and the adjusted MariTEAM output, and the same ratio as in Equation (3.5) was calculated for these energy sums. This was defined as one test case. A ratio close to 1 implies agreement between the battery data and the MariTEAM output, and the aim was to obtain a ratio as close to 1 as possible after calibration. It was investigated whether the ratio was improved after the adjustment with load_adjust

[2]The rate of hybridisation is the share of total energy consumption covered by electricity and not diesel.

or not to determine if the adjustment factor was appropriate. A final adjustment factor to be used in the calibrated modified MariTEAM model was determined based on these calculations.

$$\text{load\_adjust} = E_{tot,battery}/E_{tot,MariTEAM} \tag{3.5}$$

Values outside the SoC were removed to investigate the respective effects, as these values were assumed to be error measurements, and the calibration was executed again. A control was also executed after calibration to investigate if the re-implementation of the power limiting based on the rated power of the electric motor for the battery electric case would have significant effects on the energy sum. Finally, the functions for limiting the power were implemented back into the code, and the calibrated modified MariTEAM model was obtained. Calculation results for the different test cases can be found in Appendix A.

3.4 Model simulation and code for analysing MariTEAM output

The ferry specifics from Chapter 2 were implemented in the modified MariTEAM model. For both the electric cases, the auxiliary engine rated power and number of reefer points were set equal to zero. For the battery electric case, the main engine parameters were also set equal to zero. The calibrated modified MariTEAM model was run with the case-specific AIS and weather data one time simulating the diesel electric ferry and one time simulating the battery electric ferry.

The codes for analysing the results import the MariTEAM output. Because the ferry switches between operating as A and B ferry as described in Chapter 2, there are periods for which it is out of operation. The codes need a continuous operational profile, thus a functionality was implemented for removing non-operating periods. The code detects periods where the ferry is out of operation as periods where the propulsion power load is less than 0.5% for longer than 10 minutes. These periods are removed and a charging period of 5 minutes is inserted instead. The remaining parts of the codes differ, and are therefore explained separately in the following sections.

3.4.1 Analysis of MariTEAM output for battery electric case

For the battery electric case, energy is summarised for the time period considered and scaled up with the 7000 hours of operation during a year to find yearly propulsion energy consumption according to Equation (3.6). $R_{year,o,p}$ are the total results for one year of operation, $R_{sim,o,p}$ are the results from the simulation of the limited time period, $T_{year,o,p}$ is the yearly operating time of the ferry, and $T_{sim,o,p}$ is the time period considered in the simulation.

$$R_{year,o,p} = R_{sim,o,p} * \frac{T_{year,o,p}}{T_{sim,o,p}} \tag{3.6}$$

The yearly hotel load consumption covered by the batteries is found by multiplying the constant hotel load of 100 kW with the 7000 hours of operating. The yearly hotel load consumption covered by shore power is found by multiplying the hotel load with the 1760 hours of non-operation. The lifetime propulsion energy, hotel energy from shore power and hotel energy from battery are found by multiplying the yearly energy with the ferry lifetime of 30 years. The sums are adjusted with a factor for the losses in the different electricity chains, further described in Chapter 5.

3.4.2 Analysis of MariTEAM output for diesel electric case

The diesel electric case uses the same time period calculations as the battery electric case. For each fuel consumption or emission calculated by the MariTEAM model, the total amounts for the time period considered are calculated. These totals include the hotel energy during the non-operating hours, which needs to be removed because this energy is covered by shore power. The actual amounts of fuel consumption and emissions are found by subtracting the share of the fuel consumption and emissions that are caused by the hotel demand during non-operating hours, using factors for the share of hotel results compared to total results and the share of non-operating time compared to total time considered. Equation (3.7) illustrates the calculation of final fuel consumption or emission where $S_{1,x,tot}$ and $S_{2,x,tot}$ are total sums for fuel consumption or emission x before and after removing hotel energy during non-operation respectively, F_{hotel} is the hotel factor, and $F_{non-operation}$ is the non-operation factor. The hotel factor is calculated as described in Equation (3.8), where $S_{1,FC,hot}$ and $S_{1,FC,tot}$ are total sums for fuel consumption due to hotel energy and total energy demand respectively. The non-operation factor is calculated as described in Equation (3.9), where T_{tot} is the total time period analysed before removing periods where the ferry is out of operation.

$$S_{2,x,tot} = S_{1,x,tot} - S_{1,x,tot} * F_{hotel} * F_{non-operation} \tag{3.7}$$

$$F_{hotel} = \frac{S_{1,FC,hot}}{S_{1,FC,tot}} \tag{3.8}$$

$$F_{non-operation} = 1 - \frac{T_{operation}}{T_{tot}} \tag{3.9}$$

CO_2 and SO_x emissions are calculated based on fuel consumption using factors, thus these are also adjusted based on fuel consumption. The yearly fuel consumption and emissions are found using Equation (3.6), and the lifetime fuel consumption and emissions are found by multiplying this with the ferry lifetime of 30 years. The hotel energy from shore power is found in the same way as for the battery electric ferry.

The results were implemented in the remaining LCA according to Figure 3.3 on the following page. The results from the work with the MariTEAM model are presented in the following chapter, before the LCI including the MariTEAM results for the operational phase is described in Chapter 5.

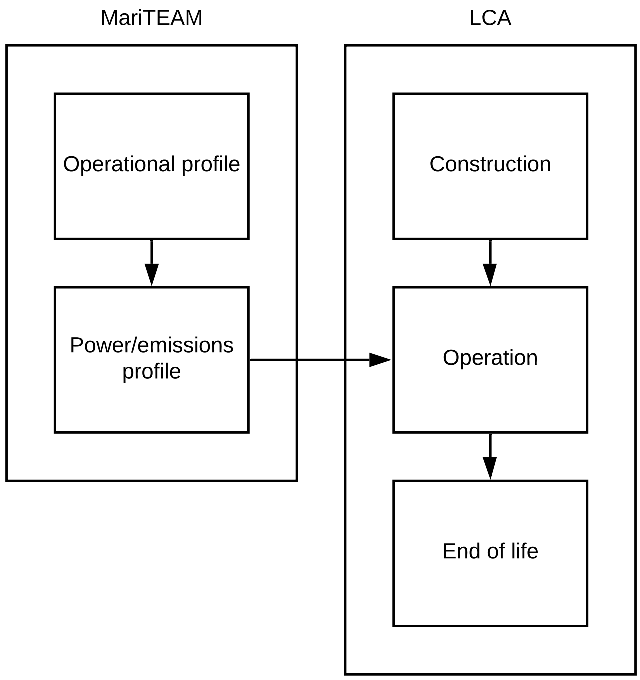


Figure 3.3: Implementation of MariTEAM results in the LCA

Chapter 4

Application part 1: MariTEAM results

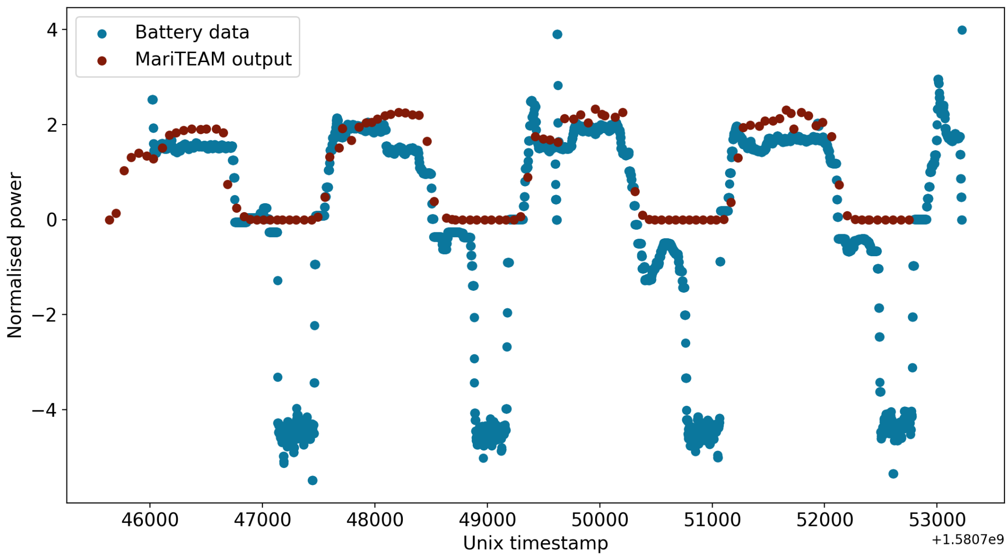
In this chapter, the MariTEAM results from the implementation described in the previous chapter are presented. First, the stepwise results used to calibrate the modified MariTEAM model are outlined, before the results from the final model simulation and the analysis of the MariTEAM output to be used in the LCI in the following chapter are assessed.

4.1 Results from calibration of the modified MariTEAM model

As described in the previous chapter, different steps were taken to calibrate the modified MariTEAM model: first, representative periods were defined, then the data were treated before they were compared and the MariTEAM model calibrated. The relevant results from this process are presented in this section.

Several representative periods are identified. The battery data and the MariTEAM output are found to be out of sync with a time delay, which is further discussed in Appendix C. This is assumed not to affect the total energy consumption significantly, and a representative period where the time delay is adjusted is illustrated in Figure 4.1 on the following page. In the figure, the power is normalised on average power during the period due to confidentiality. The representative periods identified were used to compare battery data and MariTEAM output as explained in the previous chapter.

As evident from Figure 4.2 on the following page, all ratios found through the comparison of battery data and MariTEAM output are around 1, and for both the ratios with adjustment and the ratios without adjustment, values both lower and higher than 1 are observed. The values do not indicate a specific unified ratio other than 1. When considering one test case at a time, it is evident that for some test cases the ratio is closer to 1 and thus the results improved with adjustment, while for other test cases the results are more accurate without adjustment.



Positive power in the figure represents discharging of the battery while negative power represents charging of the battery.

Figure 4.1: Battery data and MariTEAM data normalised on average power and adjusted for time delay during a representative period

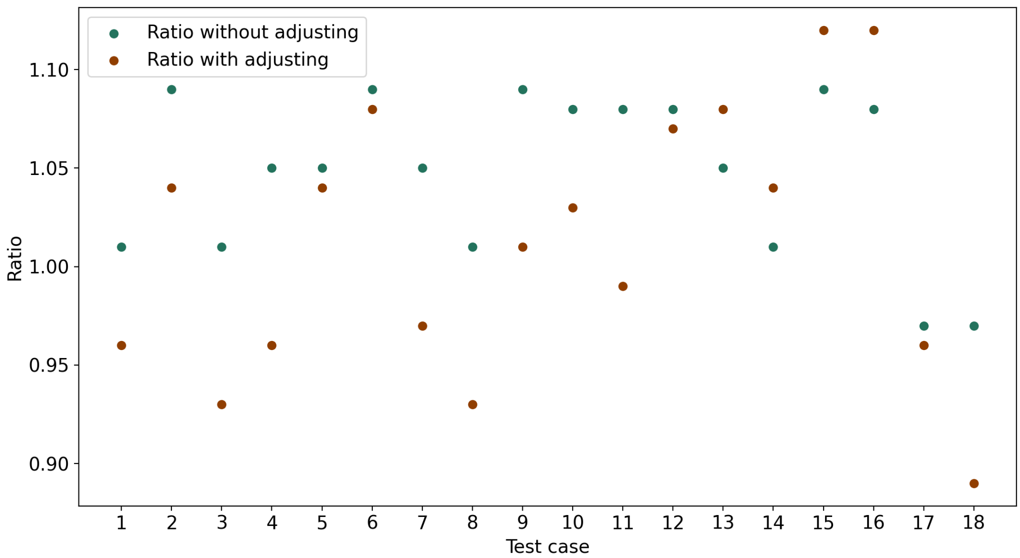


Figure 4.2: Ratios for battery data and MariTEAM output with and without adjustment for all test cases

Based on these results, it is concluded that the battery data and the MariTEAM output do not vary significantly for the representative time periods. Also, as these results are based on only short time periods and hybridisation ratios on a weekly basis used on a minute basis, a scaling factor of high precision is not considered meaningful. Therefore, the battery data are found to validate that the modified MariTEAM model can be used to simulate the diesel electric and battery electric ferries, and it was decided to use the modified MariTEAM model as it is without using any adjustment factor.

The cleaning of the values outside the SoC did not lead to changes in the results due to the uncleaned data being relatively free of error measurements for the representative periods considered. The other periods not found representative initially are still not representative, even though the size of the errors are smaller. The results do not vary significantly when implementing the power limiting function, and the computed load adjustment factors for each period are the same on a two decimal basis. The conclusion therefore remains after the controls, and the modified MariTEAM model was calibrated and ready for simulating the operational phase of the LCA.

4.2 Results from model simulation and analysis of MariTEAM output

The modified MariTEAM model produced a power profile for the battery electric case and power and emission profiles for the diesel electric case. A figure of the power profile for the entire period can be found in Appendix C. From Figure 4.3, it can be seen that the ferry accelerates and decelerates quickly and spends most of the time either cruising or charging. The length of the crossing time periods and charging time periods are similar for the different crossings and time periods.

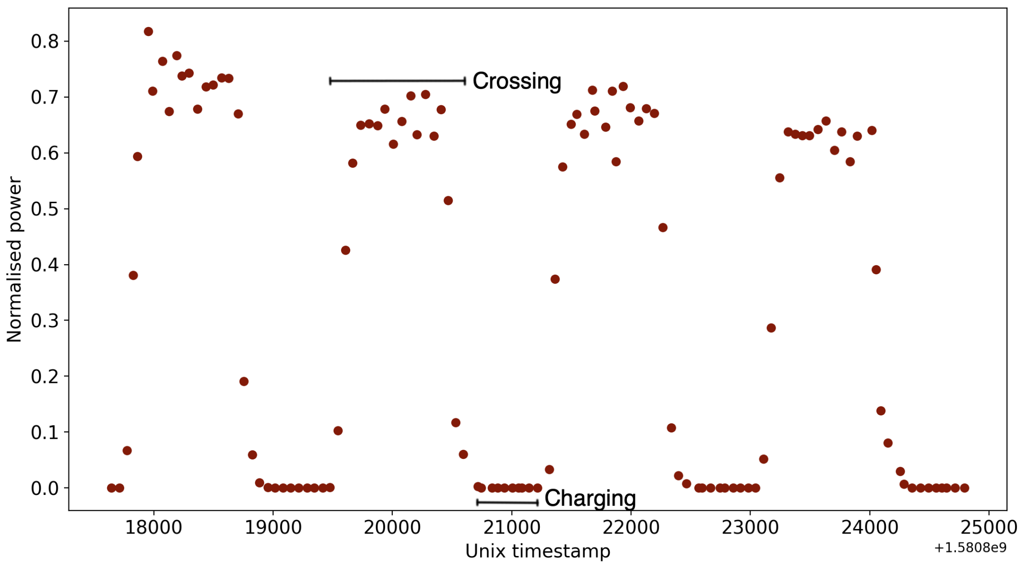


Figure 4.3: Load power profile of four sample crossings from the MariTEAM simulation for the battery electric case

According to the weather data, the weather during the time period considered was fairly mild without any extreme wind speeds. Therefore, the weather adjustment did not result in major changes to the power profile. Figure 4.4 on the following page illustrates a period where the ferry had tailwind one way and headwind the other way. Where the ferry had tailwind, the SOG was reduced to represent what would have been the SOG with the power consumed without wind effects, and where the ferry had headwind, the SOG was increased. It can be observed that the power profile is more affected by the headwind than by the tailwind. It should be noted that the ferry was moving with higher speed in the direction that had tailwind also after the weather calculations, which is due to the operational pattern of the ferry and not underestimated weather effects.

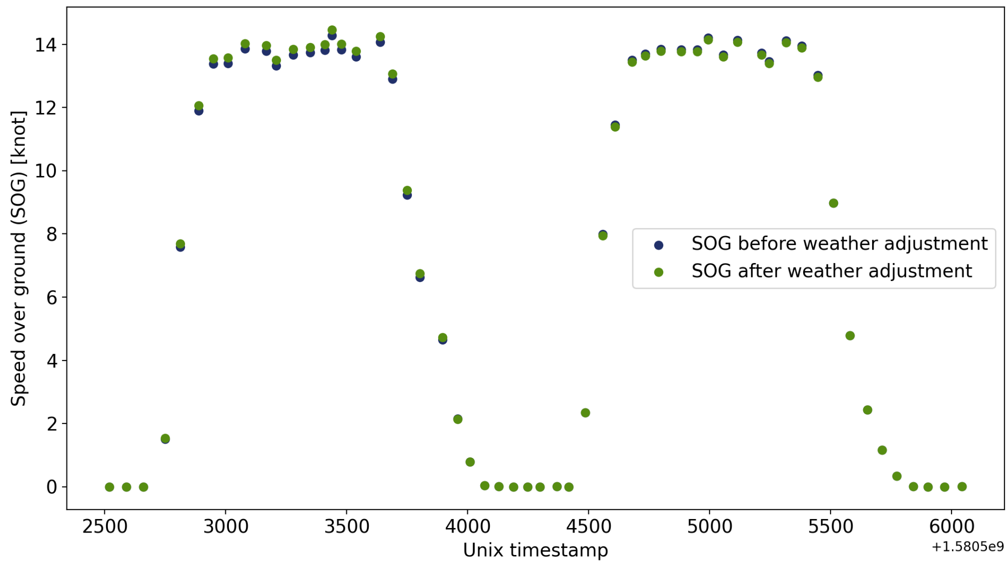
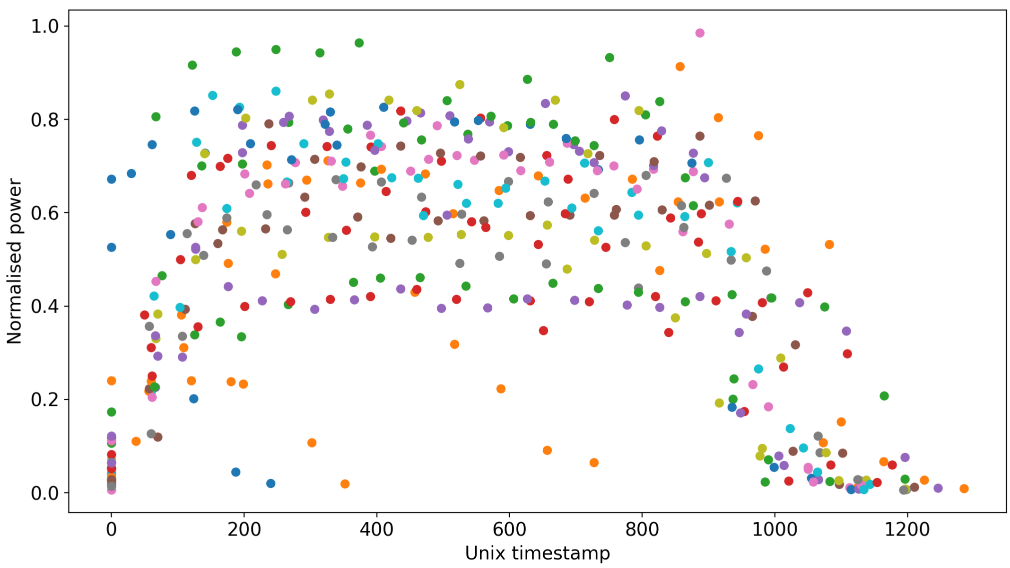


Figure 4.4: SOG for two crossings from the MariTEAM simulation with weather adjustments

From Figure 4.5, it can be observed that the crossings have similar profiles counting the same amount of time for a crossing, although varying in load during cruising.



Each colour represents a crossing.

Figure 4.5: Load power profiles for all crossings from the MariTEAM simulation for the battery electric case

Regarding CO_2 emissions illustrated in Figure 4.6 on the following page, it is evident that the CO_2

emissions are dependent on the power. The same is found for the other emission profiles, which can be found in Appendix C.

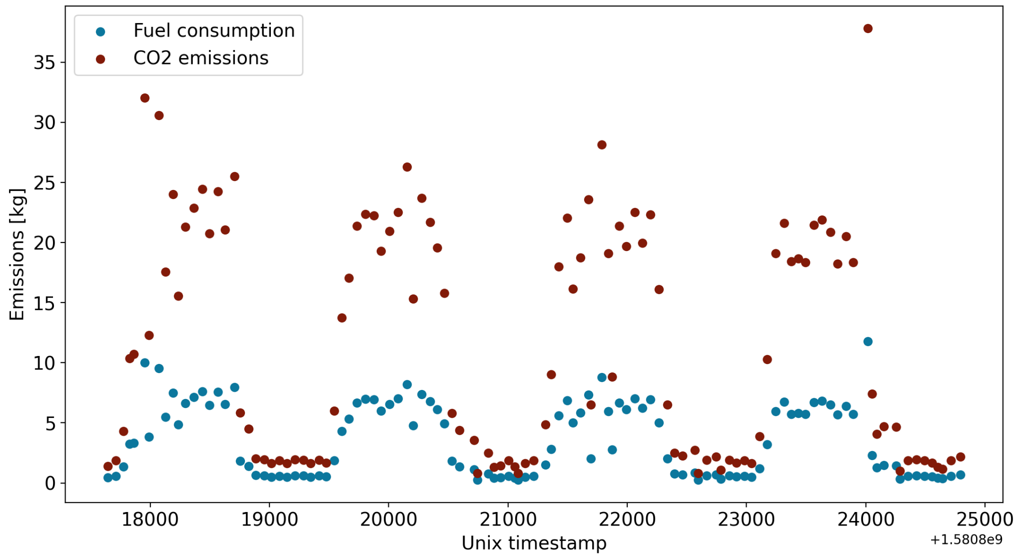


Figure 4.6: CO_2 emission profile for four sample crossings from the MariTEAM simulation for the diesel electric case

The lifetime results from the modified MariTEAM model are presented in Table 4.1 and Table 4.2 on the following page. The hotel electricity from shore power is similar for the two cases. CO_2 and NO_x emissions, which are in focus in this analysis, are the largest in quantity, as also observed from the emission profile. These results were implemented into the LCI, as further described in the next chapter.

Table 4.1: Lifetime electricity and fuel consumption from the modified MariTEAM model for the battery electric and diesel electric case

Result	Battery electric	Diesel electric
Hotel electricity from shore power [kWh]	5.39E+06	5.39E+06
Hotel electricity/fuel from battery/engine [kWh]/[tonne]	2.58E+07	9.19E+03
Propulsion electricity/fuel from battery/engine [kWh]/[tonne]	2.06E+08	2.95E+04
Total electricity consumption [kWh]	2.37E+08	5.39E+06
Total fuel consumption [tonne]	0	3.87E+04

Table 4.2: Lifetime emissions from the modified MariTEAM model for diesel electric case

Emission [kg]	Diesel electric
CO_2	1.24E+08
NO_x	1.70E+06
SO_x	3.87E+02
SO_2	3.76E+02
SO_4	1.16E+01
BC	6.74E+03
EC	3.33E+03
CO	1.62E+05
OC	2.10E+04

Chapter 5

Implementation part 2: Life cycle assessment model

The case description in Chapter 2 creates the foundation for the LCI, and the results from Chapter 4 were used to create inputs to the LCI for the operational phase. The details of the LCA model including the LCI are presented. Then, the overall LCI modelling comprising identification of data sources, the procedure for collecting data, calculation procedures and descriptions of data used in the analysis is described. Then, the LCI is divided into the different life cycle phases of the two ferry cases included in the analysis: construction, operation and end of life. The construction phase is further divided into ferry construction, propulsion system construction, battery production and shore system construction. More details regarding modelling choices and data can be found in Appendix B, and the full LCI models can be found in the attachment to this thesis.

5.1 Foreground system and flowcharts

For both ferry cases, the ferry construction, pier construction, mooring system construction, ferry operation, mooring system operation, ferry end of life treatment and mooring system end of life treatment were assessed. The pier and mooring system are identical for the two cases, while the other parts vary in their processes and flows. Certain components part of the ferry and shore system are specific only for the diesel electric ferry, and some are specific only for the battery electric ferry. Both electricity for mooring and shore power as well as operational diesel for propulsion were included in the operational phase for the diesel electric system, as well as direct emissions from diesel combustion. For the battery electric ferry, the operational phase comprised electricity for mooring and shore power as well as operational electricity for propulsion. The flowcharts for the diesel electric and the battery electric ferry are presented in Figures 5.1 and 5.2 on the following pages, and illustrate the components and processes part of the foreground system. The weight of components in the two ferry cases vary between the cases as illustrated in Figures 5.3 and 5.4 following the flowcharts. Transport, electricity, infrastructure, diesel, liquefied petroleum gas, heat energy, materials, metal working processes and process-specific burdens for waste treatment were also assessed in the LCI in addition to materials and components. Such processes were applied to several of the components and life cycle phases and are thus not included in the flowcharts.

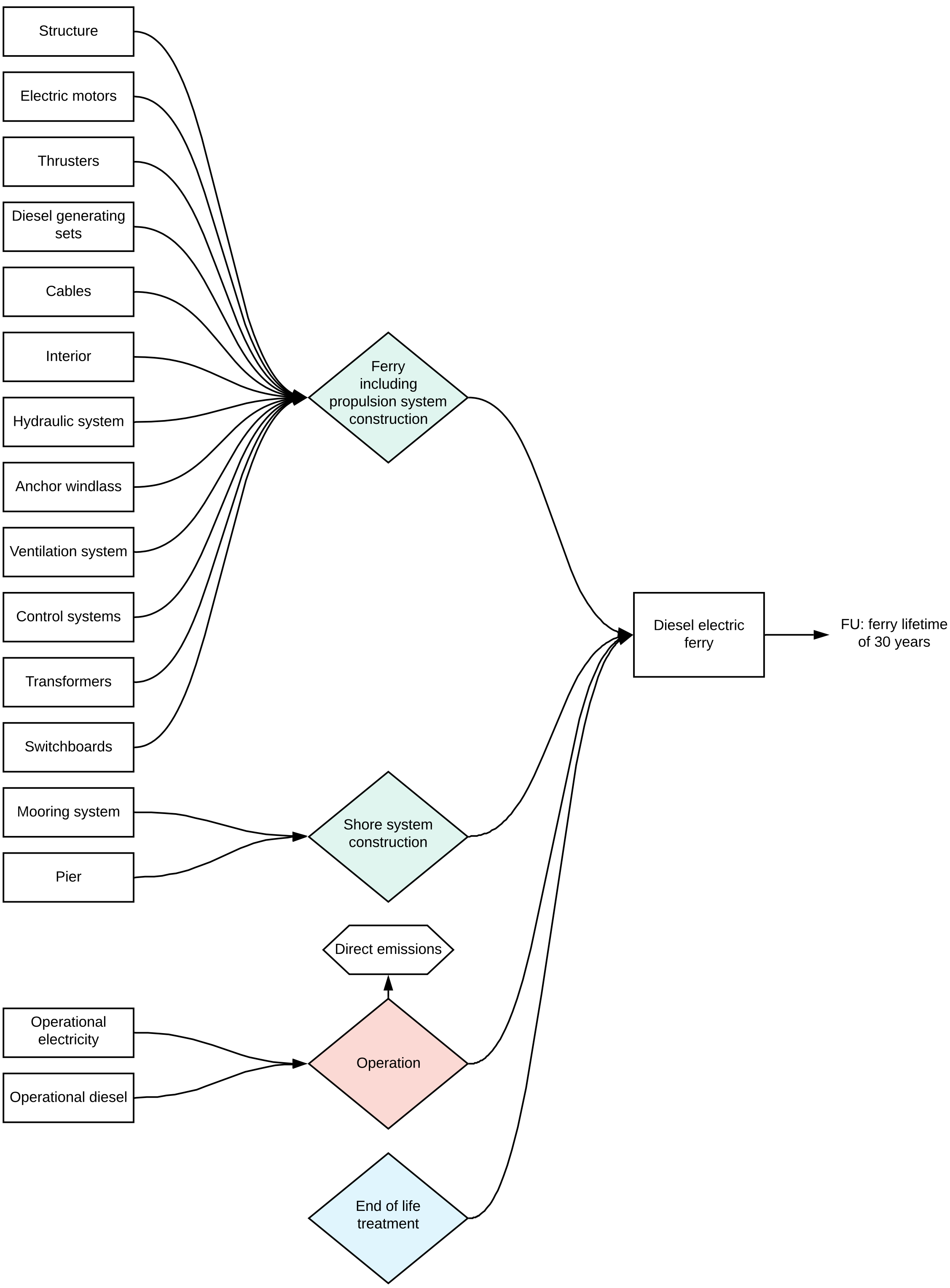


Figure 5.1: Flowchart for the diesel electric ferry

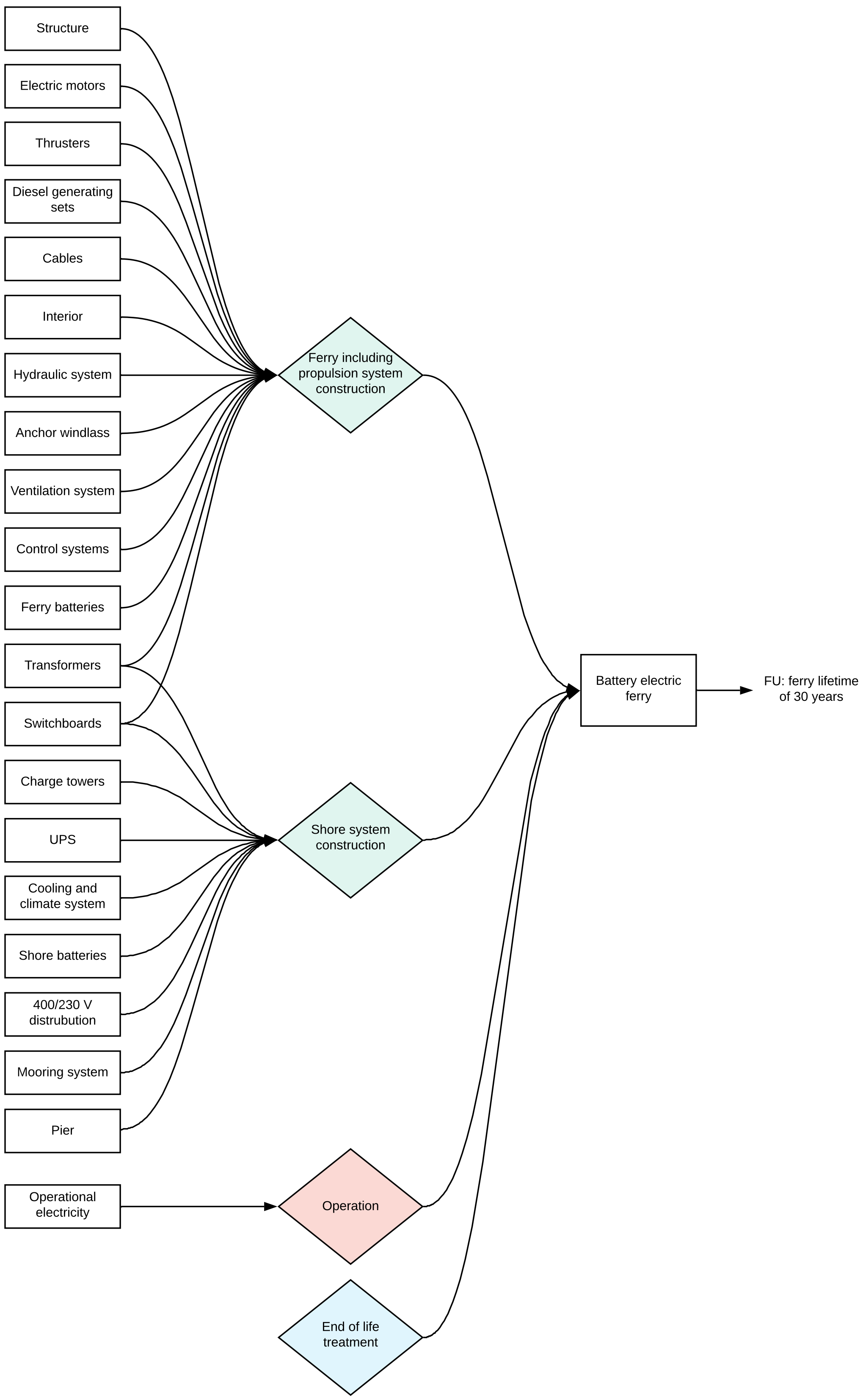


Figure 5.2: Flowchart for the battery electric ferry

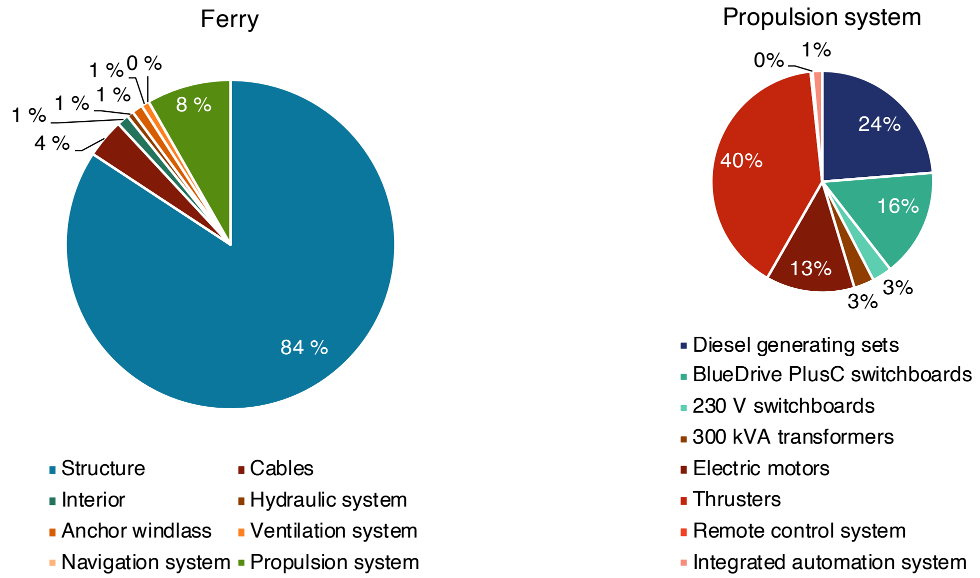


Figure 5.3: Weight of components in the diesel electric ferry and in the diesel electric propulsion system

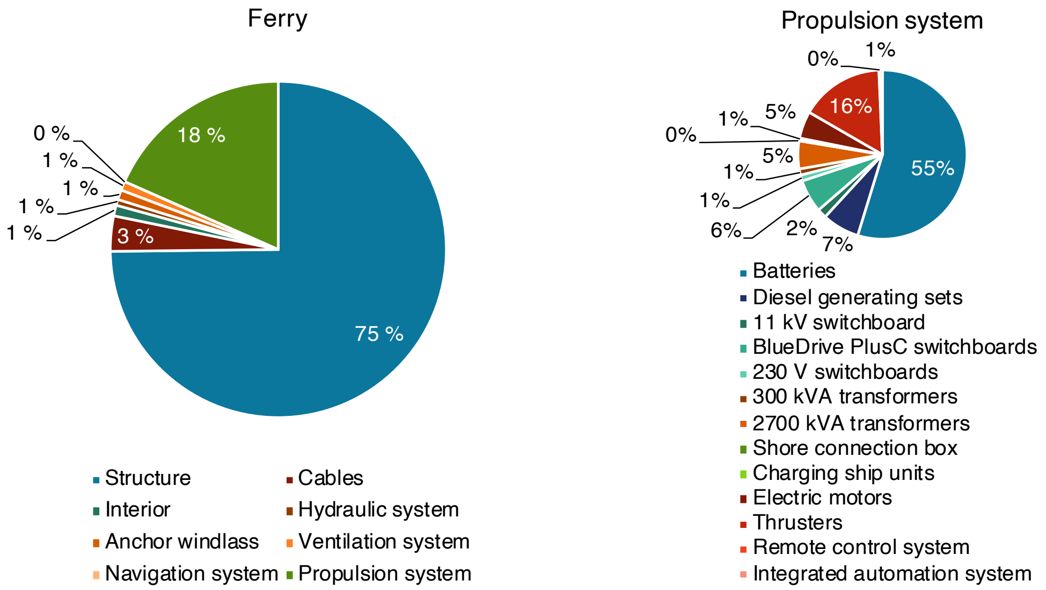


Figure 5.4: Weight of components in the battery electric ferry and in the battery electric propulsion system

5.2 Data sources and collection procedure

Data were as far as possible collected for the specific ferry instead of approximated, and data used are meant to be up to date, relevant for the case and reliable. It was initially assumed that the hybrid electric ferry used as a reference is capable of fully battery electric operation, and that the two week time period used for modelling the operational phase could represent average operation of the ferry throughout the lifetime.

The process of building up the LCI started with identifying which data were needed by studying the different propulsion systems and the ferry setup. Several sources were used to collect data. First, communication with Siemens, the supplier of the batteries and other electric equipment (from here on, only *the supplier*), was initiated in order to obtain data on the products delivered by them. Visits to the battery production facility were taken. Later, also FosenNamsos Sjø (the ferry owner), Myklebust Verft (the Norwegian shipyard, from here on, only *the shipyard*) and certain subcontractors were contacted and agreed to collaborate. These parties were contacted because they hold different types of necessary information and data. Communication was in the form of meetings, e-mails, phone calls, and web meetings. Some data were provided directly through these channels, and some were contained in data sheets and drawings transmitted. Certain data were found in public data sheets. A visit was also taken to the ferry to visualise the equipment and ask questions directly. The ferry crew gave a tour of the battery rooms, the motor rooms, the high voltage room, the bridge, the saloon and the control room, and answered questions regarding the ferry and its operation. Pictures and notes from this tour were used to confirm and support the data in the LCI modelling. Generally, primary data were obtained for types of components, component weights, electric specifications, production countries and lifetimes, while secondary data were used for the materials compositions of the components and energy consumed during component production.

For the ferry components or processes where actual data could not be obtained during the data collection period, literature, Product Environmental Profiles (PEPs) or EPDs were used in the cases where the processes were considered essential for the analysis. Literature sources were found through searches in Elsevier (n.d.) and Google (n.d.), PEPs were found at Schneider Electric (2020), and EPDs were found at The Norwegian EPD Foundation (n.d.) and ABB (2020). For the ABB EPDs used, it was assumed that the materials used for the product include the shares that become manufacturing waste, and the weight of the product was calculated as the materials used for the product minus manufacturing waste and packaging. The waste was scaled based on the power and calculated weight of the ABB product. The materials from the EPDs were matched with the most representative Ecoinvent 3.2 processes, and all material, waste and energy inputs were included and scaled based on weight if not stated otherwise. The hazardous waste from manufacturing was assumed incinerated, and the regular waste to landfills was modelled as residual materials to landfills. When using PEPs, materials were also scaled based on weight. Where EPDs or PEPs were used, the input materials and energy were modelled using Ecoinvent 3.2 processes instead of using the impact assessment results from the EPDs or PEPs directly in order to obtain a consistent analysis. Processes not considered to be essential for the analysis were excluded if data were missing and no relevant source for modelling was found. Assumptions and simplifications made were generally discussed with the supplier and the shipyard to ensure representative modelling.

5.3 Transport

Transport was included in the respective life cycle phases to which it was linked, and was added as input to the foreground process for the component that was transported. For instance, the transport of a transformer from the production location to the shipyard was assigned to the transformer process. The transport was modelled as receiver aggregated where Ecoinvent 3.2 market processes were used, and as receiver input otherwise.

No primary data were obtained on transport, but production locations were identified for most ferry components. Transport processes were assumed based on production locations: road transport was applied where possible and reasonable, and sea transport was assumed otherwise, for instance for products produced in England and transported to Norway. Freight Euro VI lorry transport was assumed for road transport as Forskrift om energi- og miljøkrav ved anskaffelse av kjøretøy til veitransport (2018) demands minimum Euro V for lorries, and freight sea transport with a transoceanic ship was assumed for sea transport. Road transport distances were identified using Google (2020) and sea transport distances were estimated using Sea-distances.org (2020). Where transport was neglected, it was due to missing data and an assumed short transport distance. Transport is included in the market processes and not added separately for components modelled using these. The freight ships and road vehicles were assumed to have full loads also on their returns, thus only their contribution in one direction and not on the return were accounted for in this analysis.

5.4 Materials, energy and other resources

Raw materials extraction and production, energy production and diesel extraction and refining are among the processes in the background system, and no primary data were obtained on these processes. Therefore, such processes as input to the foreground processes were modelled using market processes in Ecoinvent 3.2. Transport and metal working were modelled as transforming activities in Ecoinvent 3.2 using European geography. Where the exact type of material was uncertain, alternatives were examined and compared before choosing a process. In the base cases, all input materials were assumed to be primary materials.

Where the type of energy is not specified in the data, electricity was assumed. Medium voltage was assumed to be representative for the different production facilities, thus the market process for medium voltage electricity in the geographical area was used for production electricity. Heat energy was modelled using the market process for district or industrial heat in Ecoinvent 3.2. The geography used for the heat processes was Europe without Switzerland for all cases as processes for the specific countries do not exist. The heat energy was divided into heat energy from natural gas and heat energy from other sources than natural gas due to the nature of the Ecoinvent 3.2 heat energy processes. The share of heat from natural gas in a specific country was found using statistics from IEA (2020) considering *electricity and heat* and *heat generation by source* in 2018. The Ecoinvent 3.2 market process for district or industrial heat from natural gas was used for the calculated share of heat demand for natural gas, while the market process for district or industrial heat from other sources than natural gas was used for the remaining heat energy in a process. Processes for metal working in the geographical area of production were used for products without any data regarding manufacturing energy consumption in order to represent the resources consumption during production. The metal working processes in Ecoinvent 3.2 consider various metals like steel and copper and include energy and auxiliary inputs, machines, factory infrastructure and additional material inputs for manufacturing of final products for various materials like steel and copper. The manufacturing resources consumption is included in the market processes.

5.5 Lifetimes and number of components

Lifetimes of the equipment delivered by the supplier were provided by the supplier. Lifetimes for other components were based on PEPs or EPDs or estimated. The lifetimes were used to calculate the total number of each ferry component needed during the ferry lifetime using Equation (5.1), where f_i is the number of component i needed based on lifetime, l_f is the lifetime of the ferry, and l_i is the lifetime of component i:

$$f_i = \frac{l_f}{l_i} \tag{5.1}$$

The shore systems are shared between the ferries, as mentioned in Chapter 2. There are two charging systems, one at each port, two mooring systems at each port resulting in four mooring systems in total, and one pier. Because the shore system equipment is shared between the two ferries, half of it was assigned to the ferry analysed in this thesis.

The coefficients of requirement introduced in Chapter 2 were in this analysis based on the amount of process i needed per process j, the number of component i needed during the lifetime, and the number of ferries sharing component i in order to model the system over the ferry lifetime. These parameters are represented by n_{ij}, f_i and $n_{f,i}$ respectively, and the calculation of a_{ij} is presented in Equation (5.2). For situations where a foreground process was part of another foreground process, this calculation was only performed for one of the processes to avoid double-counting.

$$a_{ij} = \frac{n_{ij} * f_i}{n_{f,i}} \tag{5.2}$$

For instance, the coefficient of requirement for the mooring system part of the shore system construction was calculated as $a_{\text{mooring system, shore system construction}} = \frac{4*1}{2} = 2$ because in total four mooring systems are part of the shore system, two ferries share the mooring systems, and the lifetime was assumed to be equal to the ferry lifetime.

5.6 Construction

The construction phase was divided into ferry construction, battery construction, propulsion system construction and shore system construction in the LCI model. The propulsion system construction and the battery production were separated from the rest of the ferry because they are central in the comparative analysis, and because the rest of the ferry is similar for the diesel electric and battery electric ferry. Construction facilities were generally not included, except for the battery production facility. Packaging of components was excluded where data were missing.

5.6.1 Ferry construction

The ferry construction life cycle phase covered everything that is part of the ferry itself, except the propulsion system. For both the battery electric case and the diesel electric case, this includes the structure, cables, interior, hydraulic system, anchor windlass and ventilation system. The only difference between the two cases is the ventilation system, which includes additional components for the battery electric case. Safety equipment, water tanks, toilets, kitchen, beds, playroom for children, the fire suppression system and other smaller components were excluded because of lacking data and because they were assumed to have negligible contributions to the environmental impacts of the ferry. Primary data regarding the ferry construction were provided by the shipyard. The lifetimes of all components included in the ferry construction phase were assumed to be equal to the ferry lifetime of 30 years, except the interior which was modelled with a lifetime of 15 years based on EPDs.

Components in the foreground system were modelled based on their compositions and production location and transport to the shipyard was included. Then, the assembly of the different components into a ferry was assessed with the related energy and diesel consumption, and finally the transport of the ferry from the construction site to the operation site was included in the calculations.

The hull with tubes and superstructure was constructed in Gdansk, Poland, and was then towed to the shipyard in Norway (PC). Data regarding weight and types of materials were primary data obtained from the shipyard. The hull and tubes are mostly made of NVA steel and were thus modelled as low-alloyed steel, while the superstructure was modelled as chromium steel (PC). The hull was constructed at various shipyards using various suppliers in Gdansk (PC), and the resource consumption during hull construction was estimated using processes for metal working on steel and chromium steel products. The towing was modelled using the process for freight transport at sea with a transoceanic ship, and the weight transported was set equal to the sum of the weights of the hull, tubes and superstructure.

The cables were modelled using the market process for unspecified cable in Ecoinvent 3.2 based on primary estimates regarding weight from the cable supplier (PC). The navigation system was modelled as 5 computers without screen as an estimate, using the Ecoinvent 3.2 market process. Market processes were used, as data on the production process were not obtained.

The ferry has interior in the form of chairs, sofas, benches and tables, which is partially pictured in Figure 5.5 on the following page. The interior was modelled based on EPDs of similar products as outlined in Table 5.1 on the following page, obtained from EPD Norge (The Norwegian EPD Foundation, n.d.). Based on the tour taken on the ferry and pictures of the inside of the ferry, the number of each interior element in the ferry was estimated. The number of elements modelled using the EPDs was found based on the functional unit of the EPD; for instance, the functional unit of the Nordia 3-seater was one 3-seater, equivalent to 3 wood chairs in the ferry, resulting in 1 Nordia 3-seater for every wood chair in the ferry. It was assumed that each sitting bench covers four seats. It was assumed that all the energy consumed during manufacturing was electricity. The interior was delivered by a Norwegian company (PC), thus the Norwegian electricity mix was used. The materials in the EPDs were matched with Ecoinvent 3.2 processes as precisely as possible. Packaging was assumed to be kraft paper. Acetaldehyde was used as an approximation for polyoxymethylene, and the unclassified material in the EPDs was assumed to be nylon 6. Transport was neglected.

The hydraulic system was modelled based on primary data in the form of case-specific estimated weights and material types provided by the shipyard (PC). It consists of cylinders and a power pack made of steel and containing oil, and was produced in Norway (Vadset, 2019). Metal working was used to model manufacturing, and the transport was neglected. The anchor windlass was also modelled based on estimated data from the shipyard, using cast iron (PC), and metal working was used to model manufacturing. The anchor windlass was produced in Croatia (PC) and road transport was included.

The ventilation system was modelled based on primary data obtained from the shipyard (PC). A data sheet describing the ventilation system components for the battery electric case was used, and the ventilation system components for the diesel electric case were identified by removing the battery electric specific components, e.g. fans in the battery room. The ventilation system was divided into ducts, heat pumps, fans and control panels, and these components were modelled separately. Two of the heat pumps in the ventilation system have power ratings close to 10 kW, so the Ecoinvent 3.2 process for a brine-water 10 kW heat pump was used to model these. One of the heat pumps has a higher power rating and was

Figure 5.5: A part of the interior inside MF Lagatun

Table 5.1: Number of each interior element in the ferry and specifics of the EPDs used to model them

Interior element	Number in ferry	Name of EPD	Number in EPD	Reference
Wood chairs	282	Nordia 3-seater	94	Helland Møbler AS (2019)
Metal chairs	30	Clint Conference - high back	30	Fora Form AS (2016)
Sofa seats	78	Pivot 3-seater without armrest	26	VAD AS (2018)
Bench seats	120	Sitting bench 240 cm	30	Aarsland Møbelfabrikk AS (2016)
Tables	30	Clip table 1200 x 450	30	Fora Form AS (2017)

Number in EPD represents the number of components defined as the functional unit in the EPD needed to cover the number of components in the ferry.

modelled with the 30 kW heat pump process from Ecoinvent 3.2. The steel ducts in the ventilation system are circular and were assumed to have a diameter of 30-50 cm and be of 300 m length. The Ecoinvent 3.2 process for a DN 400 spiral-seam duct was therefore used. Four ventilation control panels were also included, using the process for ventilation control and wiring, central unit. The ventilation system was delivered by a Norwegian company, but it was unclear whether all the components were produced in Norway. Therefore, market processes were used for the heat pumps, ducts and control panels. The components using electric motors[1] were modelled based on a low voltage electric motor from ABB (ABB, 2002) assumed to be representative. The total power for the motors summarised was used to scale the materials, waste and energy from the EPD. This may have resulted in a different modelled weight than the actual weight. Transport was excluded. The electricity and heat energy were modelled using Norwegian values. The share of heat from natural gas was found to be 3% in Norway and applied to

[1]Fans, humidifiers and air curtains.

the heat demand in the EPD. The weight of the full ventilation system was calculated based on the data sheet (PC), by summarising the individual weights of the components. This weight was not used in the modelling of the ventilation system, but later in the transport of the ferry from the shipyard to the port.

The energy and diesel consumption during ferry assembly at the shipyard were modelled based on primary estimated numbers provided by the shipyard (PC). The diesel was modelled as diesel burned in a building machine, and the amount of diesel was converted from litres to MJ using the average EN 590 diesel density of 832.5 kg/m^3. Transport of the ferry from the shipyard to the port was modelled as sea transport and assigned to the assembly. The weight transported from the shipyard to the ferry port was set equal to the total lifetime weight of the ferry construction components, excluding packaging and the propulsion system. The transported weight was somewhat larger for the battery electric case than the diesel electric case due to the additional components in the ventilation system.

5.6.2 Battery electric propulsion system construction

The construction of the propulsion system was modelled for each ferry separately. The diesel electric propulsion system was modelled based on the battery electric propulsion system in the actual ferry. Therefore, the battery electric propulsion construction is described first, and then the differences in the diesel electric propulsion are presented. The battery electric propulsion construction together with the ferry construction, the battery production and the shore system construction made up the construction phase for the battery electric ferry.

Data regarding the products delivered by the supplier were provided. The remaining equipment for the battery electric propulsion system was identified using Vadset (2019) and Skipsrevyen (2018) and with help from the shipyard. The components making up the battery electric propulsion system are presented in Table 5.2. The battery is described separately in the next section. Transport of the propulsion system to the port was included.

Table 5.2: Components in the battery electric propulsion system

Name	Amount	Production location
Battery	4	Norway
Electric motor	2	Germany
300 kVA transformer	2	Finland
2700 kVA transformer	2	Finland
Thruster	2	-
Diesel engine	3	-
Generator	3	England
11 kV switchboard	1	Germany
BlueDrive PlusC switchboard FWD	1	Norway
BlueDrive PlusC switchboard AFT	1	Norway
230 V FWD switchboard	1	Latvia
230 V AFT switchboard	1	Latvia
Shore connection box	1	Norway
Remote control system	1	-
Integrated automation system	1	-
Charging ship unit	2	Germany

The electric motors pictured in Figure 5.6 on the following page are 1200 kW, 630 V thruster motors weighing 5050 kg each according to primary data provided by the supplier (PC). These were modelled based on ABB's EPD for a 1278 kW, 660 V AC machine used for ship thrusters among other purposes (ABB, n.d.a), which was found representative for the power and voltage for the electric motors. Materials included were electrical steel, other steel, copper, aluminium, cast iron, insulation material, impregnation resin, paint and wooden packing material. The electrical steel was modelled as low-alloyed steel. The other steel was assumed to be low-alloyed and hot rolled. The impregnation resin was modelled as phenolic resin, and the insulation material was assumed to be glass fibre. The road transport from Germany was included, and the share of heat energy from natural gas in Germany was found to be 49%. The transport weight was set equal to the weight of the electric motors including packaging. The lifetime of the electric motors was equal to the ferry lifetime (PC).

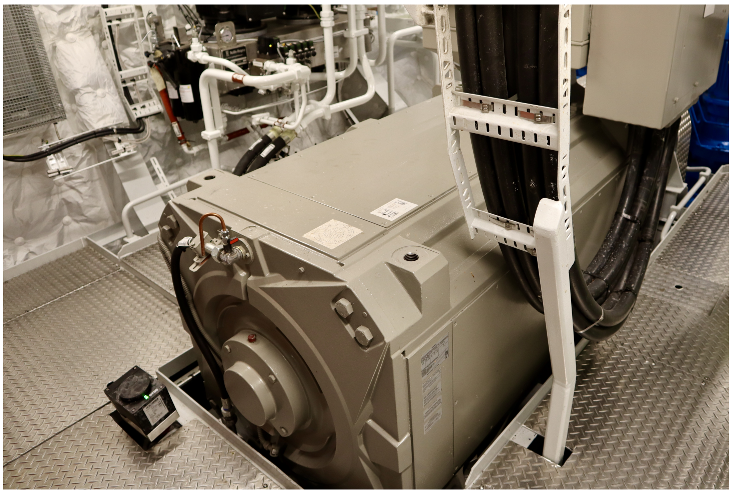


Figure 5.6: One of the two electric motors on board MF Lagatun

The battery electric ferry contains diesel generating sets for backup, pictured in Figure 5.7 on the following page. These consist of 550 kVA generators, 535 kW diesel engines and base frames (PC). ABB's EPD on a 1278 kW, 660 V AC machine (ABB, n.d.a) also representing AC generators was used to model the generators, as it was found representative for the generator power and voltage. The same processes were included as for the electric motors. The generators were produced in England (PC), and the share of natural gas in heat sources was found to be 92%. The transport from England to Norway was assumed to be freight sea transport, and the transport weight was set equal to the weight of the generator including packaging. The lifetime of the generators was set equal to the ferry lifetime (PC).

The generators are connected to low-emission Scania DI16 090M diesel engines delivered by Nogva motorfabrikk (Vadset, 2019; Skipsrevyen, 2018; FosenNamsos Sjø, n.d.b). The data of the diesel engines were obtained from Nogva (n.d.). The engines were modelled using the market process for an internal combustion engine from Ecoinvent 3.2, as no case-specific data were obtained. The base frame was modelled as steel based on primary data (PC), and the process for metal working for steel products was used to model the manufacturing of the base frame. The generators, diesel engines and base frames together make up the diesel generating set. The generators have the same lifetime as the ferry and the diesel engine and base frames were assumed to have the same lifetime (PC).

The thrusters are Azipull 085 thrusters from Rolls-Royce with FF propellers, including steering gear (Rolls-Royce, 2014). The shipyard provided primary estimates for shares of different materials making up the total weight of the thrusters (PC). The thruster house was modelled as cast iron, the gear steel,

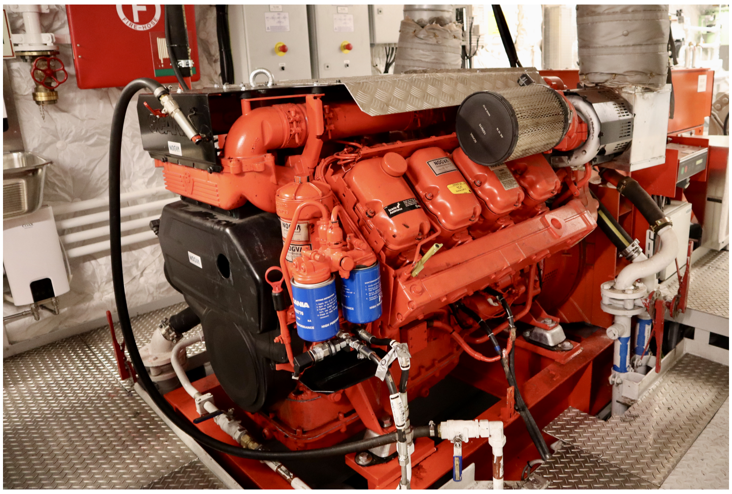


Figure 5.7: One of the three diesel generating sets on board MF Lagatun

and the propeller bronze. Metal working for steel and metal was used to model the manufacturing of the thruster. The transport of the thruster to the shipyard was neglected. The thrusters are overhauled every tenth year, where some components are replaced (PC). This was modelled by replacing an assumed share equal to 10% of the thruster weight every tenth year. This resulted in 2.4 thrusters in total needed during the ferry lifetime.

The switchboards have different weights and electrical specifications but were modelled in a similar way. The switchboard cabinets were modelled as steel, and the busbars were modelled as copper, based on primary data from the supplier (PC). The 11 kV switchboard and the 230 V switchboards have 4 cabinets and busbars each, and the BlueDrive PlusC switchboards have 13 cabinets and busbars each. The remaining weight was estimated to be 80% drive and 20% electronics (PC). The ABB EPD for a 3200 kW drive (ABB, n.d.b) was chosen for modelling the drive in the switchboards and assumed to be representative. Materials included were aluminium, copper, plastic, steel, iron, cardboard and unclassified material. The unclassified material in the EPD was assumed to be zinc based on material inputs in other EPDs regarding drives from ABB (2020). The plastic was assumed to be 50% nylon 6 and 50% nylon 66. The 11 kV switchboard was produced in Germany (PC) and road transport was included. The 230 V switchboards were produced in Latvia (PC) and the transport was assumed to be by sea from Latvia to Sweden and then by road from Sweden to Norway. The BlueDrive PlusC switchboards were produced in Norway (PC) and transport was neglected. Metal working processes for steel and copper were used to model the manufacturing of the steel cabinets and copper busbars. The drives in the switchboards have lifetimes of 15 years and thus two are needed during the ferry lifetime (PC). The rest of the switchboard has a lifetime equal to that of the ferry (PC).

The shore connection box and charging ship units were also modelled based on primary data from the supplier. The shore connection box is used for connecting the ferry to shore supply and was estimated to be 33% copper and 66% (PC). Metal working for steel and copper was added as manufacturing. It was produced in Norway (PC), and thus transport was neglected. The shore connection box was assumed to have a lifetime equal to the ferry lifetime. The charging ship units were produced in Germany and modelled as pure steel as simplified by the supplier (PC). Transport was modelled as road transport. Metal working for steel was added for manufacturing, and the charging ship units were assumed to have a lifetime equal to that of the ferry.

The remote control system controls propulsion, charging and mooring, and consists of different components, the heaviest one being a medium controller cabinet according to primary data obtained from the supplier (PC). The remote control system was modelled as electronics for control units using the weight of the controller cabinet as a simplification. The remote control system has an approximate lifetime of 15 years and thus two are needed during the ferry lifetime. The integrated automation system is also made up of several cabinets and different equipment. The heaviest parts were summarised based on primary data provided by the supplier (PC). This sum was used to model the integrated automation system using the process for electronics for control units. The integrated automation system has an approximate lifetime of 15 years and two are needed during the ferry lifetime.

The 300 kVA transformer is a vacuum pressure impregnated dry type transformer used for hotel load, and the 2700 kVA transformer is a dry type cast resin transformer. The inventory for the dry type transformers was created based on Schneider Electric's PEP for a Trihal cast resin transformer (Schneider Electric, 2016b). Both the dry type transformers were found to be within the power, voltage and weight ranges of the PEP. Materials included were aluminium, steel, epoxy resin, copper, glass fiber, polyethylene terphtalate, ferrous alloys and unsaturated polyester. The aluminium was modelled as wrought alloy. The ferrous alloys were modelled as cast iron, and the unsaturated polyester was modelled as polyester resin. The unclassified material in the PEP was set equal to copper as copper is frequently used in the products of the supplier (PC). It was assumed that the steel used in the transformers is electrical steel, which is assigned to the process for low-alloyed steel in Ecoinvent 3.2. The energy required for manufacturing was estimated from ABB's EPD on a Large Distribution Transformer 10 MVA (ONAN) (ABB, 2003) because the Trihal PEP did not include energy consumption. The transformers were produced in Finland and the related share of natural gas in the heating was calculated as 13%. Transport was modelled as road transport. The transformers have lifetimes equal to the ferry lifetime (PC).

5.6.3 Battery production

The production of the batteries pictured in Figure 5.8 on the following page was separated from the other construction because it is a central part of the inventory that was modelled in a similar way for the ferry batteries and the shore batteries. The ferry and shore batteries are modelled in the same way. They are lithium NMC batteries optimised on power density, produced by the supplier at their battery factory in Trondheim. The battery factory has one part producing the modules and another part producing the remaining equipment. The batteries consist of battery cells assembled into battery modules packed into battery packs as described in Table 5.3 on the following page. The battery has an estimated lifetime of 10 years, implying that 3 batteries are needed of each type during the ferry lifetime. All values in the inventory dependent on the number of battery packs in the ferry and shore batteries were scaled to fit the case ferry and shore batteries and to represent the total of 3 batteries of each kind needed during the ferry lifetime.

Figure 5.8: One of the four batteries on board MF Lagatun

Table 5.3: Characteristics of ferry and shore batteries

Parameter	Value
Cells in module	28 pc
Modules in pack	9 pc
Packs in a ferry battery	9 pc
Ferry batteries in ferry	4 pc
Packs in a shore battery	2*7, 2*8 pc
Shore batteries on land	4 pc
Energy capacity module	6.6 kWh
Energy capacity ferry batteries	2138.4 kWh
Energy capacity shore batteries	1782 kWh

The following description of the battery and its inventory is adapted from the project preceding this thesis (Galaaen, 2019) and updated with the modifications performed during the work with this thesis.

The battery cell was produced in Taiwan[2] by LG Chem, and imported to the facility in Trondheim. Here, battery modules were produced employing the cells, and these were later assembled with the separately manufactured remaining parts of the battery into complete ferry and shore batteries. The battery factory has an anticipated lifetime of 5 years with the current production process (PC). The battery factory is operating with shifts of 8 hours length, two times a day, five days a week, all year. 55 modules are produced per shift. These values were used as a basis for inventory calculations.

Data sources obtained or accessed from the supplier and used in the analysis included a bill of materials (BOM) for the battery module, an overview of material types and weights of the remaining battery packaging, control system and cooling system, e-mails, pictures and meetings. Data were only obtained on the materials in the final battery, therefore additional requirements during production were excluded from the analysis. All data are primary except the composition of the cell.

The battery was divided into five main parts in the inventory: the battery pack, the battery packaging, the control system, the cooling system, and the battery cells. These battery parts have a weight distribution as illustrated in Figure 5.9 on the following page. The battery packaging was further divided into the battery pack frame, the battery insulation and protection (BIP), and the module packaging. The battery cell was divided into electrolyte, cathode, anode, cell container and separator, each of these further divided into sub-components, and battery cell production. The battery pack activity assembled the other battery parts and only consisted of battery cell transport, energy consumption during assembly and infrastructure. All stressors and impacts were linked to one of the battery parts, thus the total impacts for each battery part included impacts of all processes contributing to its production. Transport, infrastructure and energy consumption necessary for components and materials were linked to the respective components and materials as in the rest of the inventory. The battery packaging, control system and cooling system were produced at the battery factory in Trondheim and transport was thus not included for them. Transport of the battery cell from Taiwan to Norway specifically was linked to the production of the battery pack, as this transport was not part of the cell production process, but a necessary activity in order to produce the final battery. Robots were used in the production of the battery modules and these were linked to the production of the module packaging. The construction of the battery factory and the electricity consumed for the final assembly were linked to the battery pack, as these were generic activities needed for the production.

The average transport distances used in the modelling were found in Frischknecht et al. (2007) for Europe, specific overseas distances were found at Ports.com (2018), and specific road transport distances were calculated on Locatienet (2020). All transport, infrastructure, energy and processes were implemented per battery. Transport, infrastructure and location for certain materials and processes were based on generic European values for the battery except the battery cell. Transforming Ecoinvent processes were used for the battery packaging, control system and cooling system as these used locally produced materials (PC), while market processes were used for the cell as the origin of materials used was missing.

The BOM provided by the supplier lists masses of materials in the cell and module packaging. The materials composition of the cell is confidential and is thus not further discussed. Materials part of the module include plastic, copper and iron. Aggregated values for one module were used in the BOM, not specifying the various components making up the total weight of each material. The plastic is nylon 6 and nylon 66, and the specific amounts of each were updated as part of the work with this thesis based on primary data (PC). Iron listed in the BOM was assumed to be steel. The weight of the electronics board

[2]The battery cell is currently produced in China, but was produced in Taiwan when the LCI model was built.

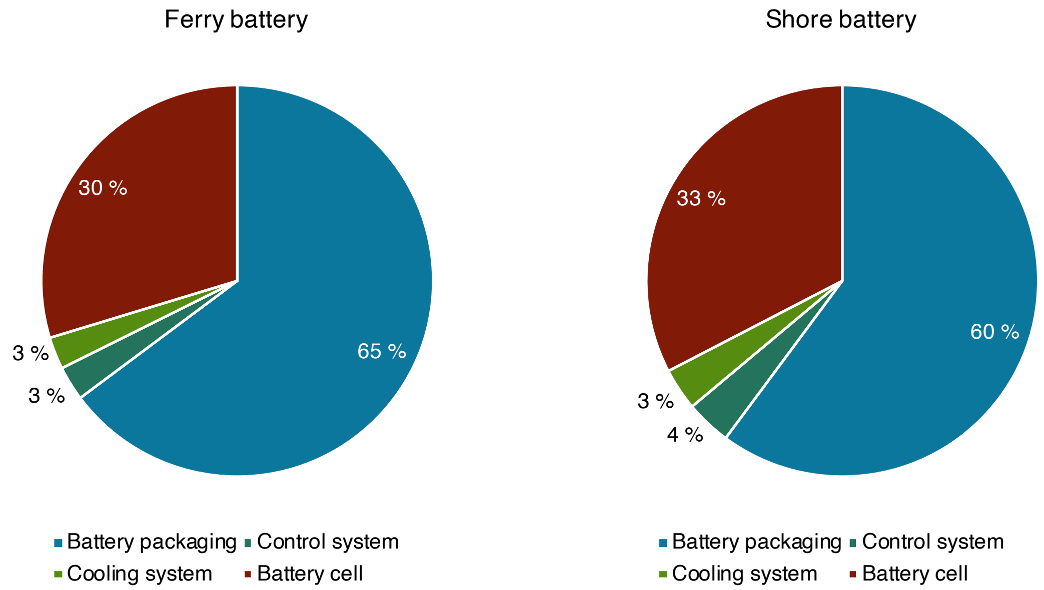


Figure 5.9: Weight of components in the ferry and shore batteries

in the module was aggregated with other materials in the BOM (PC), so this was subtracted from the total weight of the module, and the remaining materials were scaled linearly accordingly. The difference between the total weight of the module and the sum of weights in the BOM was equal to the weight of the coolant (PC). The coolant is 30% Antifrogen N and 70% water (PC). Antifrogen N contains more than 90% ethylene glycol (Clariant, 2014), thus the process for ethylene glycol in Ecoinvent 3.2 was used to model Antifrogen N.

The overview of the remaining battery packaging includes figures and total weights of the battery pack frame, BIP, cooling system and control system. The overview also presents weights of the main components or materials making up the different battery parts. The battery cabinet is made up of galvanised steel, copper, aluminium, glass fibre, packaging and electronics. The control cabinet consists of galvanised steel, copper, glass fibre, fuses, polycarbonate and electronics. Galvanised steel, copper, polycarbonate and electronics make up the BIP. Panels, doors, cooling pipes and bottom frames are made of steel. For galvanised steel included in the overview, a weight increase of 1% during galvanising was assumed. The weight of steel was set equal to the total weight of galvanised steel divided by the factor 1.01 representing the 1% weight increase. The weight of zinc was then set equal to the total weight of the galvanised steel minus the weight of steel. Smaller packaging and electronics were assumed to be 50% packaging and 50% electronics. It was assumed that both the battery packs and the control systems are 0.5 m wide per unit (PC) in order to calculate the total amount of cooling pipes and bottom frame based on the data per meter.

During the work with this thesis, the battery packaging inventory was updated with cables consisting of 50% plastic and 50% copper and additional steel based on an estimate made by the supplier (PC). The weight of cables per battery was set equal to the same value for both the ferry and shore batteries, and the weight of additional steel was calculated as the difference between the weight given in the data sheets provided minus the additional cables, and the weight provided from the supplier for the project (PC). The transport of the additional materials was also included. The transport of the batteries from the production location in Trondheim to the shipyard and back to the ferry port was neglected.

Weight data on the robots were collected from public data sheets after the specific robot models were identified during visits to the facility. The robots are Kuka KR 3 R540, KR 20-3, KR 90 R3100 extra, KR 210 R2700 extra, LBR iiwa 14 R820, KR 30-2 and MiR100 (KUKA, 2019a,b,c,d; RobotWorx, 2019; KUKA, n.d.; Mobile Industrial Robots, 2020). It was assumed that all the robots used in the module production are made of pure steel, even though they also consist of other materials and components. This simplification was made because no specific information regarding the materials and components making up the robots was obtained, and because steel clearly makes up the major share of weight. The weights of the robots were summarised and distributed between the number of modules produced by the robots during the factory lifetime. The construction of the battery facility was also divided between all batteries produced during its lifetime in the same way.

The monthly energy consumption for the battery module factory and for the rest of the battery production was provided by the supplier and assumed to be average values representative for the energy consumption throughout the year (PC). This energy consumption covered heat energy for the battery module factory and heat energy for other parts of the facility as well as soldering, testing and initial charge for the rest of the battery production. Aggregates used for welding in the module production were examined during a visit to the battery factory to calculate their energy consumption, which was excluded from the monthly energy consumption data. The yearly heat and aggregate energy consumption for the battery module factory was calculated and divided by the yearly module production in order to obtain the energy consumption per module. The yearly energy consumption for the rest of the battery production was calculated and divided by the yearly amount of produced batteries to find the energy consumption for the production of one battery. All energy consumption was assumed to be electricity, and the Norwegian electricity mix was applied.

The battery cell input processes and direct emissions were modelled based on Ellingsen et al. (2014) using the LCI template created by NTNU. When tuning the battery cell LCI template based on the mass based BOM from the supplier, a linear scaling was assumed where specific data were missing. The import of the battery cell was assumed to use freight ship transport from Kaohsiung, Taiwan to Rotterdam, Netherlands, and then freight road transport from Rotterdam to Trondheim. The electricity mix used for the electricity consumption during the battery cell production was based on data for Chinese Taipei from 2017 obtained through IEA (2020). Since the only information obtained on the battery cell was its final form and that it was produced in Taiwan, and nothing was known about the process of or inputs to the production there, Ecoinvent 3.2 processes regarding markets for products were assumed to be representative enough and used for the battery cell. Facilities and electricity are not included in these processes and were therefore added for the battery cell and left as in the LCI template, only changing the geographies so that they were more relevant for Taiwan where possible. As no specific information on direct emissions from the battery cell was obtained, these were assumed to be similar to the ones in the LCI template and adjusted in line with adjustments made to the battery cell. The supplier reported no direct emissions from their production.

5.6.4 Diesel electric propulsion system construction

The diesel electric propulsion system construction was modelled by modifying the battery electric propulsion system construction. The 11 kV switchboard, the 2700 kVA transformers and the ferry batteries are not part of the diesel electric propulsion system (PC), while a fourth diesel engine and generator were added in the diesel electric case to cover the total power demand. The components making up the diesel electric propulsion system are listed in Table 5.4. They were modelled in the same way as for the battery electric propulsion system construction.

Table 5.4: Components in the diesel electric propulsion system

Name	Amount	Production location
Electric motor	2	Germany
300 kVA transformer	1	Finland
Thruster	2	-
Diesel engine	4	-
Generator	4	-
BlueDrive PlusC switchboard FWD	1	Norway
BlueDrive PlusC switchboard AFT	1	Norway
230 V FWD switchboard	1	Latvia
230 V AFT switchboard	1	Latvia
Remote control system	1	-
Integrated automation system	1	-

5.6.5 Shore system construction

The shore system construction included the pier and mooring system for both ferry cases and the charging infrastructure for the battery electric ferry. As mentioned earlier, all elements in the shore system construction are shared between the two ferries operating the route, and their inputs and thus environmental impacts were therefore divided by the two ferries in the model.

The area of the pier that was built when the new ferries were implemented was obtained from Statens vegvesen (n.d.a). The height was assumed to be 1.5 m, resulting in a volume of 1980 m^3. The pier was assumed to be made of concrete. 3 light columns were also modelled at the new pier, with a length of 7 m and an assumed diameter of 15 cm (Statens vegvesen, 2017). These were modelled as steel, and a density of 7850 kg/m3 was used. There are 2 mooring machines and 0.5 pier for each ferry, thus the amount of pier for each mooring machine in the aggregated inventory was set equal to 0.25.

The vacuum mooring system is the MM400E delivered by Cavotec and produced near Milano, Italy (PC). There are two mooring systems at each port, one system located at each side of a pier, so two vessels can be automatically moored; resulting in four mooring systems in total. Total weight of one mooring system as well as approximate percentages of different materials and electric motors making up the weight were provided by Cavotec. These data were used to model the material inputs, while metal working processes for the metals present were used to model the manufacturing. The mooring systems consist of inox steel, plastic, rubber, lubricants, mild steel, electrical components, electrical cabling, paint and electric motors. It was assumed that the plastic used in the mooring system is 50% nylon 6 and 50% nylon 66. Lubricating oil was used to model the oils and lubricants. For the electrical components, it was assumed that 50% of these are active and 50% are passive. Unalloyed steel was used to model the mild steel. Electrostatic paint was used for the paint. The electric motor was modelled in the same way as the electric motor in the ferry using the ABB EPD (ABB, n.d.a), assumed to be representative also for the mooring system electric motor. The share of natural gas used in heating in Italy was found to be 63%, and transport from Italy to the port was modelled. The lifetime of the mooring system was assumed to be the same as the lifetime of the electric motors, and thus equal the ferry lifetime.

There are two charging stations in the system, one at each port. The charging stations consist of the components presented in Table 5.5.

Table 5.5: Components in one charging station

Name	Amount	Production location
Battery	2	Norway
1600 kVA transformer	2	Norway
930 kVA transformer	1	Finland
BlueDrive PlusC switchboard	1	Norway
11 kV switchboard	1	Germany
Charge tower	2	Germany
Uninterruptable power supply	1	Italy
400/230 V distribution	1	Norway
Cooling and climate system	1	-

The 930 kVA transformer is a 2237 V/690 V dry type cast resin transformer, and the 1600 kVA transformers are oil transformers. The inventory of the 930 kVA transformer was created in the same way as the inventory of the dry type transformers in the battery electric propulsion system, and this transformer was also produced in Finland and within the range for the PEP used. The function of the 930 kVA transformer is to compensate for reactive power[3] in the grid, in contrast to the other components whose function is to directly contribute to ferry operation. The inventory of the oil transformers was created based on Schneider Electric's PEP for a Minera transformer (Schneider Electric, 2016a), which is an oil filled transformer. Both transformers were found to be within the power, voltage and weight range of the PEP. Materials included were copper, steel, epoxy resin, unsaturated polyester, mineral oil, aluminium, paper, cardboard and wood. Also for these transformers, the unclassified material in the PEP was set equal to copper. The cardboard was modelled as kraft paper. The oil used is NYTRO 10XN based on primary data provided by the supplier (PC), which was modelled as lubricating oil. The energy required for manufacturing was estimated from ABB's EPD on their Large Distribution Transformer 10 MVA (ONAN) (ABB, 2003). The 1600 kVA transformers were made in Norway, thus the share of natural gas used was 3%. Transport was excluded for the transformers produced in Norway but included for the 930 kVA transformer. The transformer lifetimes are equal to the ferry lifetime (PC).

The charge towers pictured in Figure 5.10 on the following page were modelled as steel based on primary data from the supplier (PC), and metal working for steel was used to model the manufacturing. The charge towers were assumed to have a lifetime equal to the ferry lifetime. There are two charge towers at each port and two ports, resulting in four charge towers in total for the system. The charge towers were produced in Germany and transport was modelled as road transport.

An UPS is a tool for ensuring power for critical equipment in situations where the power in the socket is out (PC). The UPS was modelled using the PEP for Schneider's Smart-UPS (Schneider Electric, 2012), assumed to be representative. Materials included copper, steel, acrylonitrile butadiene styrene, polyvinyl chloride, other thermoplastics, lead-acid batteries, an electronic circuit, connectors, cables, paper and a fan. As no process exists for lead-acid batteries in Ecoinvent 3.2, a NaCl battery was used as an approximation in this analysis. Electronics for control units was used to model the electronic circuit.

[3]Reactive power is power not producing directly useful effects in contrast to active power, but often production of useful effects is not feasible without reactive power (Tabatabaei et al., 2017). Reactive power is always present in alternating voltage systems like electricity grids, and reactive power consumption leads to increased active power losses in passive elements and increased voltage losses (Tabatabaei et al., 2017). Therefore, it is ideal to compensate for reactive power in the electricity grid.

Figure 5.10: MF Lagatun charging next to one of the charge towers

It was assumed that 50% of the weight of cables and connectors is cables and that 50% is connectors. The fan was modelled using the process for a power supply fan unit in a desktop computer. Other thermoplastics were grouped with polyvinyl chloride. The sum of material inputs in the PEP equals only 94% of the total weight, therefore additional steel and electronics were added in this model to reach 100%. Metal working processes for steel and copper were used to model manufacturing. The UPS was produced in Italy and has a lifetime of 10 years (PC), resulting in three UPSs needed during the ferry lifetime.

The switchboards on land were modelled in a similar way to the switchboards part of the propulsion system, only scaled on different weights. The producing countries, transport, materials compositions and lifetimes were modelled as the same as their equivalents in the propulsion systems. The 400/230 V distribution is a cabinet with fuses, and it was estimated as 33% copper and 66% steel by the supplier (PC). The 400/230 V distribution was assumed to have a lifetime equal to that of the ferry.

The cooling and climate system was modelled based on primary data sheets provided by the supplier (PC). It consists of many smaller components and was simplified as tubes, a dry cooler, a cooling machine and 6 pumps. The steel tubes have a size of DN125 and were assumed to be 25 m long. They were modelled using the market process for spiral-seam ducts of steel in Ecoinvent 3.2. The coolers were modelled using the market process for absorption chillers and scaled based on effect. The pumps were modelled using the market process for a 40 W pump, scaled based on effect. The cooling and climate system was assumed to have a lifetime equal to the ferry lifetime.

5.7 Operation

The operational phase included energy needed for ferry propulsion, ferry operational hotel load, mooring and shore power. For the battery electric ferry, the propulsion energy is in the form of electricity, and all processes from electricity production from energy source up until the energy is consumed by the propeller were accounted for. For the diesel electric ferry, the propulsion energy is in the form of diesel, and all processes from extraction up until the energy is consumed by the propeller were accounted for. During the operating hours, energy is needed for both the ferry propulsion, hotel load and mooring. During the non-operating hours only the constant hotel load is demanded. The simulation of the operational phase using the MariTEAM model was described in Chapter 3, and the results were presented in Chapter 4. In this chapter, the implementation of the MariTEAM results in the inventory is considered.

5.7.1 Operational diesel and emissions

All emissions from the diesel electric operation were assumed to be emitted to air, and the stressors for unspecified emissions to air in ReCiPe were used in the LCI. No specific stressors exist for EC and BC in ReCiPe, so these were modelled using stressors for particulates less than 2.5 um. In addition to the foreground emissions released during operation, the diesel fuel value chain needed to be included in the analysis. The total amount of diesel consumed during the ferry lifetime established in Chapter 4 was implemented in the inventory using the market process for low-sulfur diesel with geography Europe without Switzerland to model the diesel fuel value chain. Engine oil was added as lubricating oil, and the amount was set equal to 0.2% of the fuel consumption (PC).

5.7.2 Operational electricity

Both ferry cases consume electricity during the operational phase; the battery electric ferry both for propulsion, mooring and hotel load at all times, and the diesel electric ferry for hotel load during non-operating hours and mooring. An estimate of the electricity consumed by the mooring system per machine per day was provided by Cavotec (PC). This estimate was based on an average time the ferry is moored of 5 minutes (PC). Based on the assumption that the ferry operates every day a year, the lifetime electricity consumption $E_{\text{tot, lifetime, mooring}}$ was found using Equation (5.3). $E_{\text{day, mooring}}$ is the electricity consumption per machine per day, D_{year} is the number of days in a year, Y_{lifetime} is the number of years in the ferry lifetime, and N_{machine} is the number of machines per ferry.

$$E_{\text{tot, life, moor}} = E_{\text{day, moor}} * D_{\text{year}} * Y_{\text{life}} * N_{\text{machine}} = E_{\text{day, moor}} * 365 * 30 * 2 \tag{5.3}$$

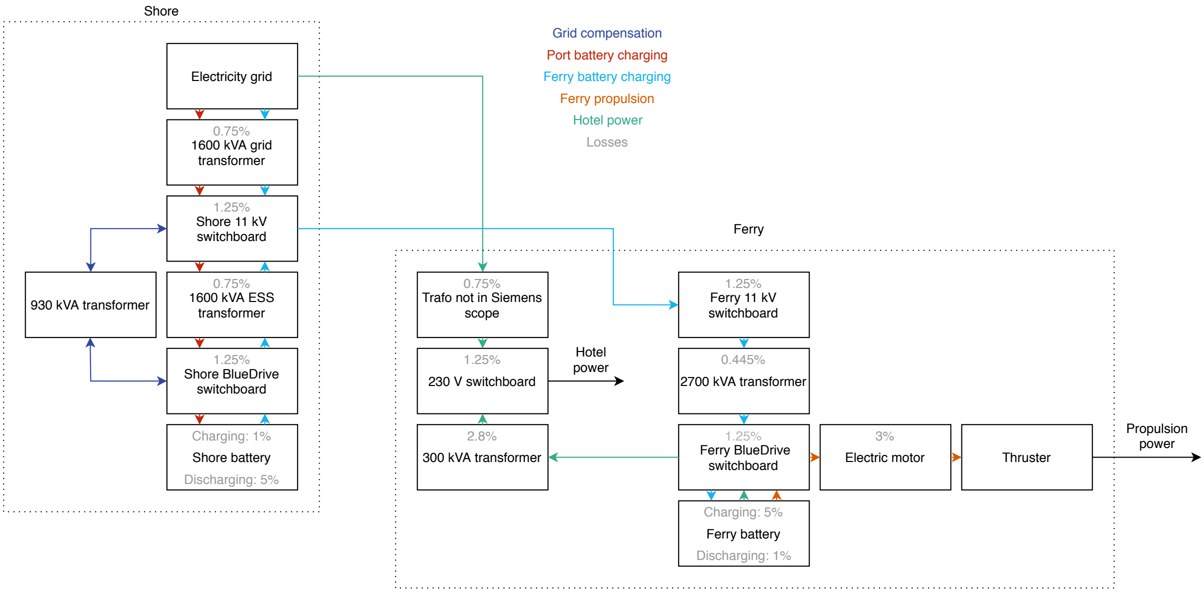
The electricity consumed in the operational phase was modelled in a more detailed and updated way than the electricity consumed during construction due to its significance. Modelling of electricity can be performed in various ways in LCA and is a debated aspect. As the electricity grid is connected between countries and regions and electricity floats in various directions based on production, demand and economics, it can be hard to model an accurate electricity consumption mix being certain of the energy sources the electricity originate from. Norges vassdrags- og energidirektorat (NVE) every year publishes an electricity disclosure of the Norwegian electricity purchased (NVE, 2020b). This is based on the Norwegian production mix, guarantees of origin[4] and European trade. In the most recent disclosure, they stated that the Norwegian electricity consumption mix for consumers not buying guarantees of origin consisted of 58% electricity from fossil sources, even though 98% of Norwegian electricity production is based on hydro power. In one way, one could argue that this type of electricity mix should be used to model Norwegian electricity consumption because it is the electricity mix assigned based on guarantees of origin. At the same time, one could also argue that the electricity that is actually consumed, which is not necessarily the same as the guarantees of origin mix, should be used. Norway imports electricity

[4]Guarantees of origin are a debated tool for guaranteeing the consumer of electricity that the electricity consumed comes from a specific energy source, for instance a renewable one (NVE, 2020a). The purpose is to contribute to an increased production of renewable energy (Rosvold, 2019), but the electricity actually consumed by the customer is not necessarily the specific electricity bought.

from other countries and whether the Norwegian hydro power or imported power is consumed is based on economic parameters. Another aspect is to consider the electricity production mix of the consuming country. One could also argue that if an amount of renewable electricity is consumed in Norway, that prevents that electricity from being consumed in another country. Thus, that amount of electricity may need to be produced from non-renewable energy sources to fulfil the demand in the other country. In this way, electricity can be seen as an international value and the electricity mix of the wider geographical area should be considered. Due to these different aspects of electricity mix modelling in LCA, sensitivity analyses are useful for assessing the effects of the choices made by the LCA practitioner on the results.

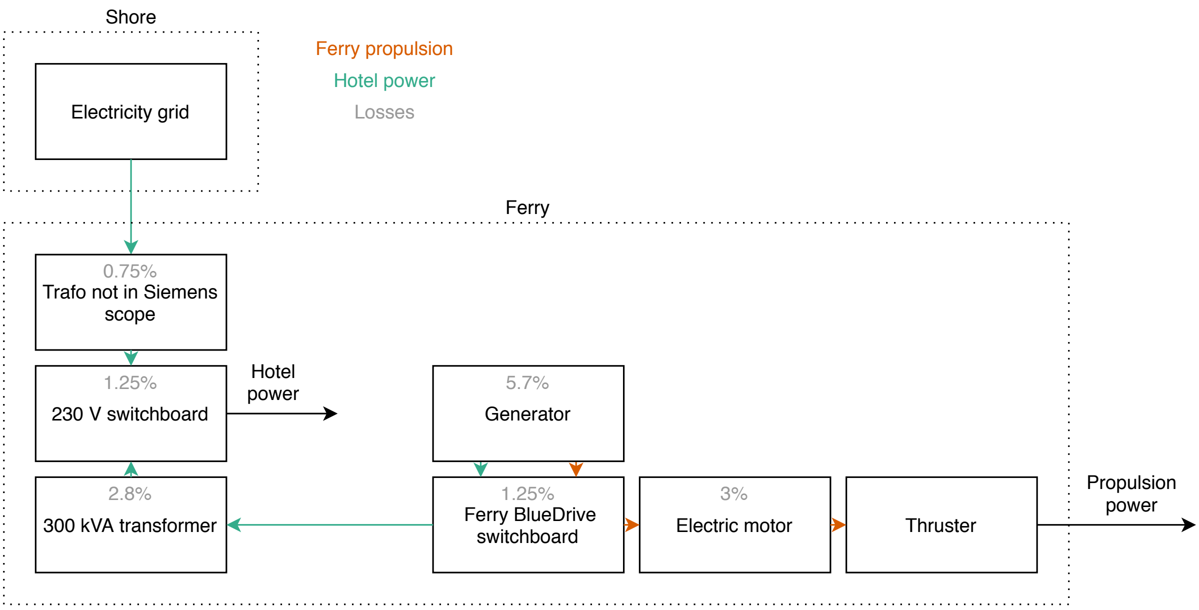
A consumption based approach including imports and exports was used in this analysis. The electricity produced from various energy sources in Norway in 2018 was obtained from IEA (2020), as well as amounts of imports and exports. The imports were assumed to come from different European countries due to the increasing connections and the aspects regarding electricity consumption mix discussed in Chapter 1 and in order to create a model towards worst-case to ensure safety margins. Therefore, the share of the consumption mix originating from Norwegian production was modelled based on Norwegian data and the imports were modelled based on European data. The electricity produced from various energy sources in Europe was also obtained from IEA (2020). The amounts of electricity from different energy sources in the Norwegian production data were divided by the total Norwegian production minus Norwegian exports, while the amounts in the European production data were divided by Norwegian imports. Biofuels and waste were grouped together under the Ecoinvent 3.2 process for electricity production from heat and power co-generation using biogas. Nuclear and solar power were modelled using Sweden as geography as these processes do not exist for Norway in Ecoinvent 3.2. Electricity from geothermal, tide and other sources were modelled as the NORDEL production mix as a generalisation. The shares of electricity production from different sources making up the import from Europe were modelled with Norwegian or other Nordic geographies as processes with generic European geographies do not exist in the database. The amount of high voltage electricity produced was increased with 0.77% to account for transformation losses from high to medium voltage, based on the Ecoinvent 3.2 process for electricity transformation from high to medium voltage. The amount of sulphur hexafluoride was calculated based on the one used in the process for medium voltage electricity market in Norway per kWh. The solar power production process has low voltage, so 1% was added to the produced electricity in order to account for losses in the transformation from low voltage to medium voltage. No long-distance transmission network was included for the imported electricity because there were no specific data regarding where the electricity is imported from.

The lifetime electricity consumption calculations described in Chapter 3 included factors for losses from the electric grid to the point of consumption in the ferry. The background for these factors is efficiencies of components the electricity is transmitted through, and is described in Figures 5.11 and 5.12 on the following page and in the following paragraphs. The electricity for grid compensation illustrated in the figures was not included in the inventory because it does not contribute directly to the function of the ferry, and because data were not obtained. Several of the electrical components in the product system has efficiencies stated in their data sheets (PC). Some of these efficiencies are given for different loads, and in these cases the average efficiency over all the load alternatives without weighing was used. This means that it was assumed that the electrical components operate with an equal share of each load. The supplier provided the losses in the remaining electrical components, and the average values were used also here. For the electricity that goes through the batteries at port, equivalent losses were used for the electric system at port, except that the battery charging and discharging had opposite values (PC).



Losses are written in grey colour.

Figure 5.11: Electricity chain for battery electric ferry including losses



Losses are written in grey colour.

Figure 5.12: Electricity chain for diesel electric ferry including losses

The ferry is divided into two similar parts with similar equipment on each side. For the components for which there are more than one, e.g. the 230 V switchboards and the 300 kVA transformers, it was assumed that the electricity only flows through one of these, thus the losses of the component were only accounted for once.

For the battery electric case, 2 MW of a total of 4.5 MW ferry charging power is provided by the batteries on land (PC), while the rest is provided directly from the electricity grid. The amounts of operational energy transmitted directly from the grid and via the shore batteries were calculated based on the power ratio, which resulted in approximately 56% of the energy coming directly from the grid and 44% via the battery. This modelling was assumed to be representative because the power was assumed to be equal over time, so that the power ratio is similar to the energy ratio. One kWh consumed by the propeller in the battery electric case was thus modelled as 0.56 kWh directly from the grid and 0.44 kWh via the shore batteries. The amount of electricity extracted from the electric grid to deliver this kWh to the propeller was found using the efficiencies of the components in the electricity fuel chain, based on Equation (5.4). E_{out} is the electricity going out of a component, E_{in} is the electricity going in to the component, and η is the efficiency of the component. Calculations regarding the operational electricity can be found in the attachment to this thesis.

$$E_{out} = E_{in} * \eta \tag{5.4}$$

5.8 End of life

The end of life phase included treatment of the ferry and related components after they go out of use, and was modelled in a simplified way in this thesis because no data were obtained on the end of life treatment of the case ferry. The processes included were the resources used for ferry dismantling, transport of batteries as well as wastes and energy consumption from the disposal phase of the major electrical components. These are listed for the battery electric and diesel electric cases separately in Table 5.6.

Table 5.6: Components assessed in the end of life phase

Name	Ferry/shore	Amount BE	Amount DE
Electric motor	Ferry	2	2
300 kVA transformer	Ferry	2	2
2700 kVA transformer	Ferry	2	0
Generator	Ferry	3	4
11 kV switchboard	Ferry	1	0
Drive BlueDrive PlusC switchboard FWD	Ferry	1	1
Drive BlueDrive PlusC switchboard AFT	Ferry	1	1
Drive 230 V FWD switchboard	Ferry	1	1
Drive 230 V AFT switchboard	Ferry	1	1
Battery	Ferry	4	0
Electric motor in mooring system	Shore	2	2
1600 kVA transformer	Shore	2	0
930 kVA transformer	Shore	1	0
Drive BlueDrive PlusC switchboard	Shore	1	0
Drive 11 kV switchboard	Shore	1	0
Battery	Shore	2	0

BE = battery electric, DE = diesel electric

A typical ferry is often sold to instances other places in the world, most commonly Africa (PC). Here it is probably used for a period before it is dismantled. Due to the lack of data and an increasing focus on sustainability, a possible future scenario based on circular economy principles was considered in this analysis. Such a scenario may include increased producer responsibility leading to dismantling, recycling and other end of life treatment occurring in proximity to the producer. Therefore, the ferry dismantling was modelled taking place in Norway after the 30 years of use, using Norwegian or European processes in Ecoinvent 3.2. The ferry dismantling was modelled based on Mathesh and Satheesh Babu (2016) which presented energy consumption per tonne dismantled ship based on data collection from a shipyard. The DWT of the case ferry was used to scale these numbers. The combustion of diesel was modelled as diesel burned in a building machine. Oxygen was excluded.

No case-specific data were obtained regarding disposal of the major electrical components, thus the values from the EPDs and PEPs used to model the construction phase were used for all components assessed except the batteries. The disposal data from these sources included energy consumption and waste amounts, so other processes like transport were excluded from the end of life phase. All hazardous waste was assumed to be incinerated, and all regular waste was assumed to be sent to landfills as also stated in the EPDs. Processes for process-specific burdens, which represents burdens independent of waste composition, were used to model incineration and landfills. Electricity consumption during the disposal phase was assumed to be medium voltage. The EPDs, PEPs and information from the supplier (PC) stated that a large share of the materials in the electrical components can be recycled at end of life. Though, as the cut-off system model was used in this analysis, the recycling was not included.

In the EPDs, waste and energy for the disposal phase were included, but not in the PEPs. The end of life for the transformers was therefore modelled using the EPD from ABB regarding a 10 MVA transformer (ABB, 2003), which was also used to model the energy consumption in the construction phase. Hazardous, recycled and landfill waste were listed, but only hazardous and landfill were included in this analysis as the cut-off system model was used. Similarly to the manufacturing waste in the construction phase, the waste was scaled based on the power and calculated weight of the ABB product.

The batteries will be collected by Batteriretur (Batteriretur, n.d.) when they reach their end of life. The following end of life procedure described is used by Batteriretur (PC) and based on primary data. After collection, the batteries will be transported to Sandefjord, Norway where they will be analysed and demolished to module level. From there, an analysis and thorough testing of the modules will be carried out in order to identify whether they can be reused or if they need to be recycled. If a module needs to be recycled, 75% of the cell materials will be transported to France or Germany and recycled there, while materials from outer battery components like copper, steel and aluminium will be recycled in Norway. In this analysis, it was assumed that cell materials will be recycled in Germany and the transport of the batteries to Sandefjord and of the 75% of the cell materials that can be recycled to Germany were included. The analysis, demolition and testing were assumed to be performed manually and thus no energy consumption was included. The recycling itself was out of scope as previously described, due to the use of the cut-off system model. It should be mentioned that Batteriretur assumes that the recycling of cell materials also can be performed in Norway in the future, which probably will lower the environmental impacts related to recycling.

5.9 Sensitivity analysis

The sensitivity analysis focuses on the battery electric ferry, and explores how changes to the product system and LCI model may affect the results of the LCA. Aspects covered were losses in electrical components, electricity mix for operation, shore power, battery cell production, use of secondary materials in the battery and a future scenario, as presented in Figure 5.13. The modifications in the LCI modelling for each sensitivity case are described in the following paragraphs.

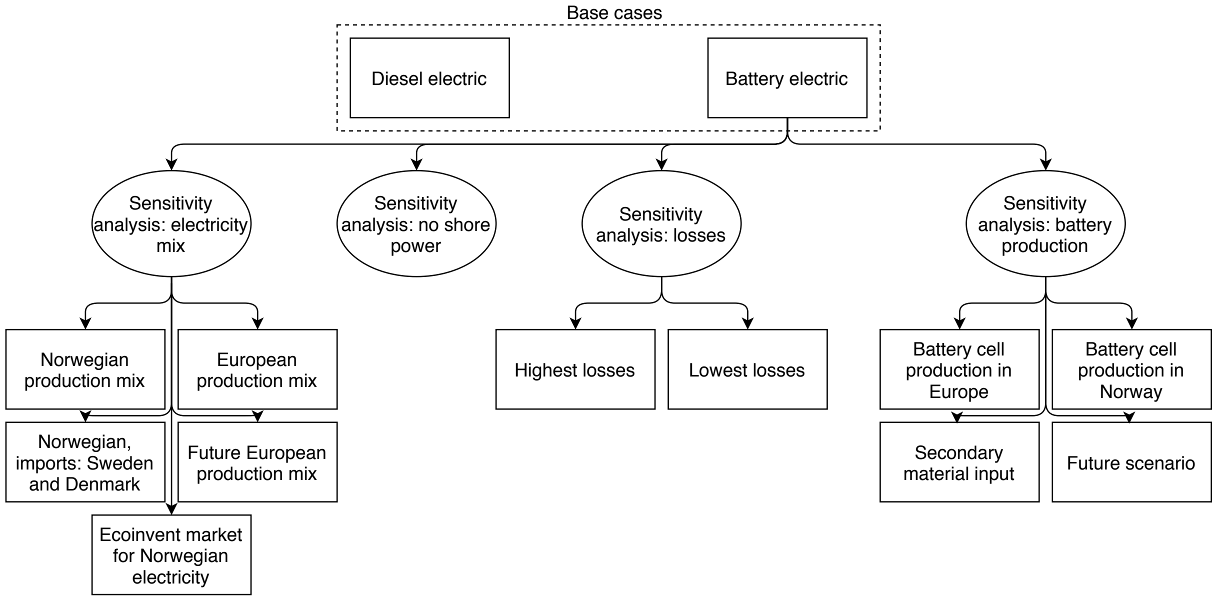


Figure 5.13: Overview of base cases and sensitivity cases analysed

5.9.1 Losses

The losses in the electrical components part of the electric systems vary based on load, and approximate values were used in the base cases. With a large amount of electricity consumed during the ferry lifetime, the values used for these losses had an impact on the results of the LCA. Therefore, a sensitivity analysis was carried out, varying the losses and investigating their effects on the results. The construction and end of life phases were identical to the base case. The only change in this sensitivity case was the amount of electricity extracted from the grid as described in Table 5.7, which is dependent on the losses in the electricity chains of the product system. One sensitivity case was created setting all losses in electrical components equal to the lowest value provided by the supplier. A new factor for the losses was found and multiplied with the energy calculated by the MariTEAM model instead of the average factor used in the base case. The same was done using the highest value for losses.

Table 5.7: Total ferry electricity consumption obtained using the MariTEAM model for the sensitivity analysis regarding losses in electrical components

Sensitivity case	Total ferry electricity [kWh]
Highest losses	2.45E+08
Base case	2.37E+08
Lowest losses	2.30E+08

5.9.2 Electricity mix

A sensitivity analysis was performed to analyse the effects of the electricity characteristics on the results. Both the geography, imports and exports and whether the production or consumption mix is used affect the modelling of the electricity mix. The reason for creating this sensitivity case was to investigate the effects of uncertainty around electricity consumption mix modelling, and to explore how operation in another location or in the future with a different electricity mix could affect the results. The construction and end of life phases were identical to the base case. The only change in this sensitivity case was the electricity mix. One case was modelled for the current European production mix, one for the current Norwegian production mix, one for the current Norwegian consumption mix assuming imports only from Sweden and Denmark, and one for a projected future European production mix. The two latter were created during the work with the project preceding this thesis and are adapted here (Galaaen, 2019). The three electricity mixes considering the current situation were based on data from IEA (2020), the production mixes based on 2018 data and the Norwegian consumption mix with imports from Sweden and Denmark based on 2017 data. The same geographies as for the base case electricity mix were used, also for the European production mix, as generic production processes for Europe do not exist and no specific country was found to be more representative. The projected future European production mix was modelled using the EUCO27 scenario for 2030 (Banja and Jégard, 2017), which is the least ambitious of the EUCO scenarios but still more ambitious than the reference and INDC scenarios. For this electricity mix, electricity from solids was modelled as electricity from hard coal, and electricity from unspecified renewable energy sources was modelled as electricity from wind.

5.9.3 No shore power

A sensitivity case was created to investigate how results change if the battery electric ferry does not use shore power for covering the hotel load during non-operating hours, but instead uses the battery. The construction and end of life phases were identical to the base case. The only change in this sensitivity case was which source that covers the hotel energy during non-operating hours. Instead of applying shore power, the battery is used, but the shore system construction remained. The factor accounting for efficiencies and losses was changed from the one for shore power to the one for battery power for hotel energy during non-operating hours, which resulted in changes to the total ferry electricity consumption as described in Table 5.8.

Table 5.8: Total ferry electricity consumption obtained using the MariTEAM model for the sensitivity analysis regarding no shore power

Sensitivity case	Total ferry electricity [kWh]
No shore power	2.38E+08
Base case	2.37E+08

5.9.4 Battery production

From the state of the art in Chapter 1 it is evident that battery production is central for battery electric ferries environmental impacts. Therefore, a sensitivity analysis was conducted focusing on battery production, more specifically battery cell production location, use of secondary material input and a future scenario.

Battery cell production location

A sensitivity analysis was performed to investigate how the location of the battery cell production affected the total results. This part of the sensitivity analysis was adapted from the project preceding this thesis (Galaaen, 2019). One case representing battery cell production in Europe was created. Salzgitter in Germany was chosen as a hypothetical location for the battery cell production because battery cells are already being produced there (Halvorson, 2019), and Germany is centrally localised in Europe and a typical industrialised European country. The electricity mix used in the battery cell production was changed to from the Taiwanese to the European production mix used in the electricity mix sensitivity analysis, and the transport distances for the battery cell were changed to only road transport from Salzgitter to Trondheim. The rest remained as in the base case.

As an ideal scenario, another case representing battery cell production in Norway was also created. Mo i Rana was chosen as a hypothetical location for battery cell production because the supplier is supporting the FREYR battery cell production there (Cision, 2019). The transport distances for the battery cell were changed to only road transport from Mo i Rana to Trondheim. The electricity mix for the cell production was changed to the Norwegian consumption mix used for operation in the base cases. The rest remained as in the base case.

Secondary material input

A sensitivity case was created to investigate the effect of using secondary steel, aluminium and copper materials in the production process at the battery factory in Trondheim, as these materials create significant impacts. The battery cell modelling and the other processes in the battery production as well as the remaining part of the ferry model were unchanged. 50% of steel, copper and aluminium inputs in the battery production occurring in Trondheim was modelled as secondary material. Secondary steel was modelled using the process for European secondary steel production using an electric furnace, and secondary copper was modelled using the process for European treatment of copper scrap through electrolytic refining. Secondary aluminium was assumed to be recycled new aluminium scrap[5], and the process for European treatment of new aluminium scrap at the remelter was therefore used. These processes include transport of scrap to the recycling facility and recycling. No burdens were assigned to the primary material production for the scrap, and the processes are consistent with the cut-off system model.

Future scenario

A sensitivity case was created to represent a possible future scenario in Europe, in order to investigate the potential environmental impacts of future battery production and electrification of ferries in other parts of Europe. Germany was used as the location for both battery cell production and remaining battery production for the same reason as in the battery cell location sensitivity case. The electricity consumed during cell production was changed to the projected future European electricity mix, as in the sensitivity analysis for cell production in Germany. The electricity consumed during module production was changed to the German market electricity from Ecoinvent 3.2. The production locations were adapted from the project preceding this thesis (Galaaen, 2019). It was assumed that the battery cell production

[5] New scrap is scrap obtained directly after the production phase.

takes place in Salzgitter as for the sensitivity case regarding battery cell location, and the remaining production in Regensburg as battery production is already taking place there (Hampel, 2019). The distance for transporting the cell to the battery production facility was then equal to the distance from Salzgitter to Regensburg. 50% of steel, copper and aluminium inputs were modelled as secondary material in the same way as for the secondary material input sensitivity case, but also including the cell materials in this case. The operational phase for the battery electric ferry was modelled using the future European electricity mix.

The contents of this chapter creates the basis for the LCA model. The inventory thoroughly described in the above sections was implemented into the LCA software and used to perform the impact assessment. In the next chapter, the results from the LCA are presented.

Chapter 6

Application part 2: LCA results

This chapter presents the results from the LCA built up as described in the previous chapters. Environmental impacts are presented according to the indicator definitions in Figure 2.3 in Chapter 2. First, total results for both base cases are presented separately and then compared. Further, the construction, operational and end of life phases respectively are examined for both base cases individually and in a comparative manner. Finally, the results from the sensitivity analysis are presented, comparing the sensitivity cases to each other and to the base cases. Additional results are presented in Appendix C.

6.1 Total base case results

This section first considers the total impacts of both the diesel electric case and the battery electric case and compare them to each other, before the impacts for each life cycle phase and base case are examined in more detail to investigate which processes and components that create the various impacts.

6.1.1 Total results for diesel electric case

Figure 6.1 on the following page illustrates that for the diesel electric ferry, the only indicators having foreground impacts originating from the operation are GWP, marine eutrophication potential (MEP), particulate matter formation potential (PMFP), photochemical oxidant formation potential (POFP), terrestrial acidification potential (TAP), CO_2, NO_x, PM and SO_x. These are emissions types calculated by the MariTEAM model and the impact categories to which these emissions contribute. The total impacts are mainly caused by the foreground system for all these except PM and SO_x. The construction and operational phases together dominate all impact categories, and the end of life phase is relatively negligible. The operational phase dominates all indicators except freshwater ecotoxicity potential (FETP), freshwater eutrophication potential (FEP), human toxicity potential (HTP), marine ecotoxicity potential (METP) and mineral depletion potential (MDP), which are dominated by the construction phase. Regarding the construction phase, the ferry construction is the major contributor in all categories, and the propulsion system construction and the shore system construction have fairly similar shares of total impacts.

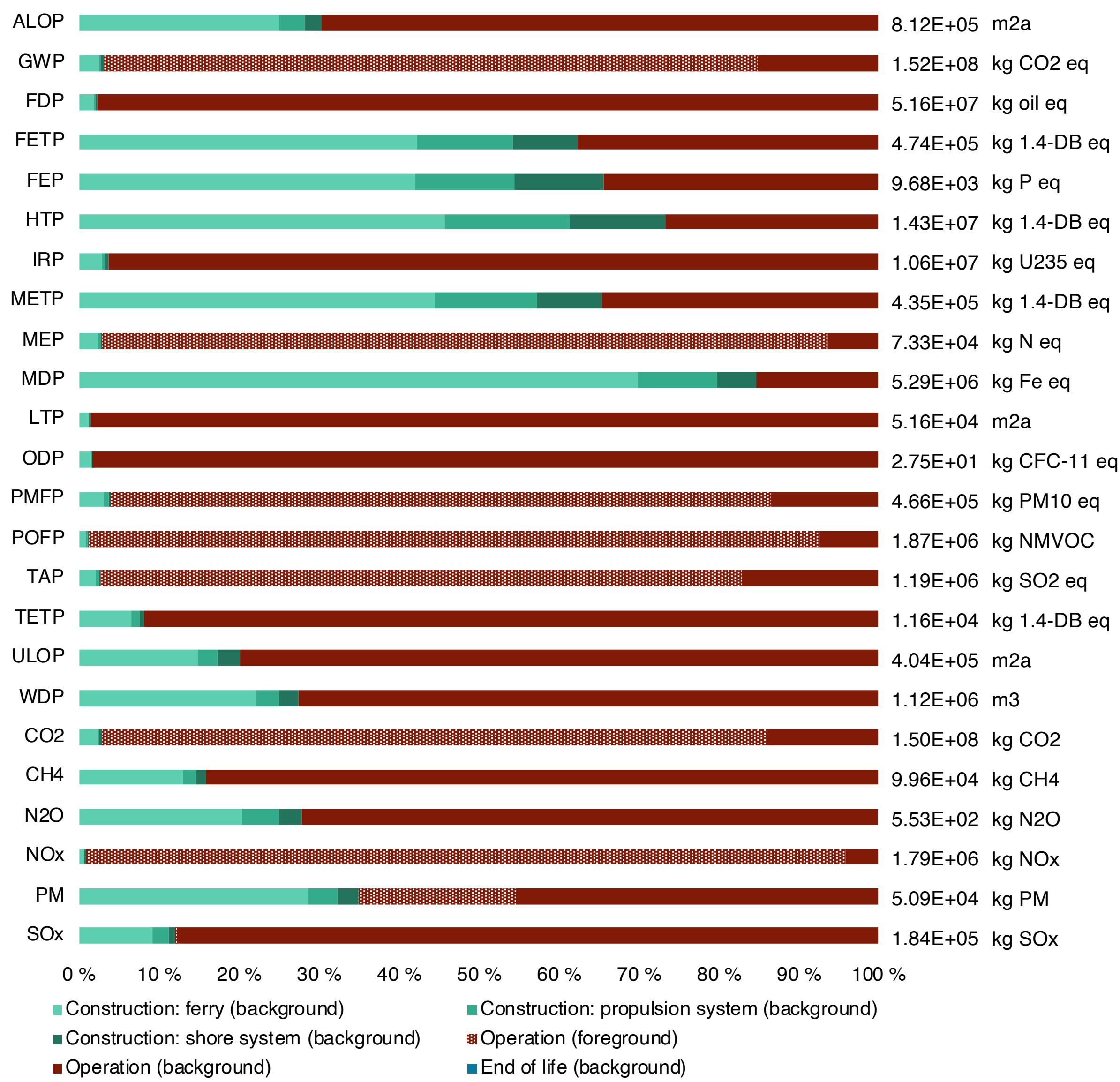


Figure 6.1: Distribution of LCA results from foreground and background system and life cycle phases for diesel electric case

6.1.2 Total results for battery electric case

As illustrated in Figure 6.2 on the following page, the construction and operational phases dominate all impact categories for the battery electric ferry, and the end of life phase is relatively negligible. The operational phase dominates the GWP, fossil depletion potential (FDP), ionising radiation potential (IRP), land transformation potential (LTP), ozone depletion potential (ODP) and water depletion potential (WDP) impacts and the CO_2 and CH_4 emissions, while the construction phase dominates the remaining indicators. The construction impacts make up more than half of impacts for more than half of the indicators. The propulsion system construction and the shore system construction have considerable shares of construction impacts in the battery electric case, and are especially significant in terms of FETP, FEP, HTP, METP, MEP, TAP, N_2O emissions and SO_x emissions. For HTP, propulsion system construction impacts are larger than ferry construction impacts, and for MEP and N_2O emissions, both propulsion system construction and shore system construction impacts are larger than ferry construction impacts. The end of life phase has its largest relative contribution in terms of urban land occupation potential (ULOP).

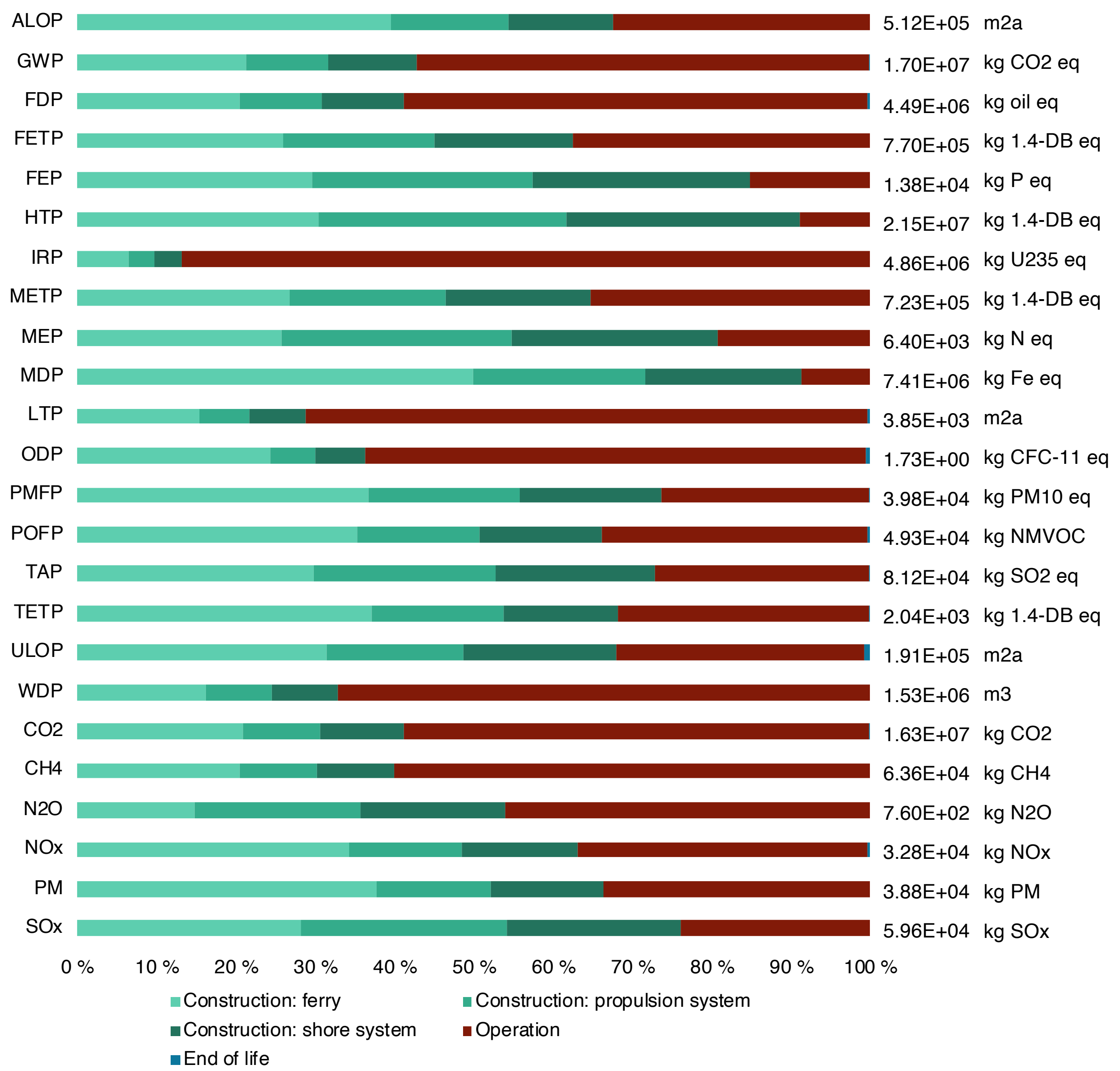


Figure 6.2: Distribution of LCA results from life cycle phases for battery electric case

6.1.3 Comparison of total results

When comparing the two cases based on Figure 6.3 on the following page, it is evident that toxicity impacts except terrestrial ecotoxicity potential (TETP) are higher for the battery electric case, while GHG, NO_x, PM and SO_x emission related impacts are generally larger for the diesel electric case. Impacts are lower in the battery electric case for all indicators except FETP, FEP, HTP, METP, MDP, WDP and N_2O. The reductions for GWP, FDP, MEP, LTP, ODP, PMFP, POFP, TAP, CO_2 and NO_x are remarkably large, around 90%. GWP is reduced with 89% or 134,792 tonnes CO_2 equivalents and NO_x with 98% or 1,759 tonnes during the ferry lifetime. The GWP payback time is 7.2 months of operation and the NO_x

payback time is 1.4 months. This means that the battery electric ferry has compensated for the additional construction and end of life impacts by reducing operational impacts in terms of GWP after 7.2 months and in terms of NO_x emissions after 1.4 months. All indicators with the majority of impacts occurring in the foreground system in the diesel electric case obtain large reductions in the battery electric case. All indicators with increases of total impacts in the battery electric case also have increases of construction impacts. For FETP, FEP, HTP, METP and MDP, the construction impacts for the battery electric case are larger than the total impacts for the diesel electric case. The indicators with the most remarkable reductions in the battery electric case obtain the majority of impacts from the operational phase in the diesel electric case. This implies that the construction phase causes a large share of increases in impacts and the operational phase mainly causes decreases in impacts for the battery electric case compared to the diesel electric case. Why this is the case is explored in the following sections.

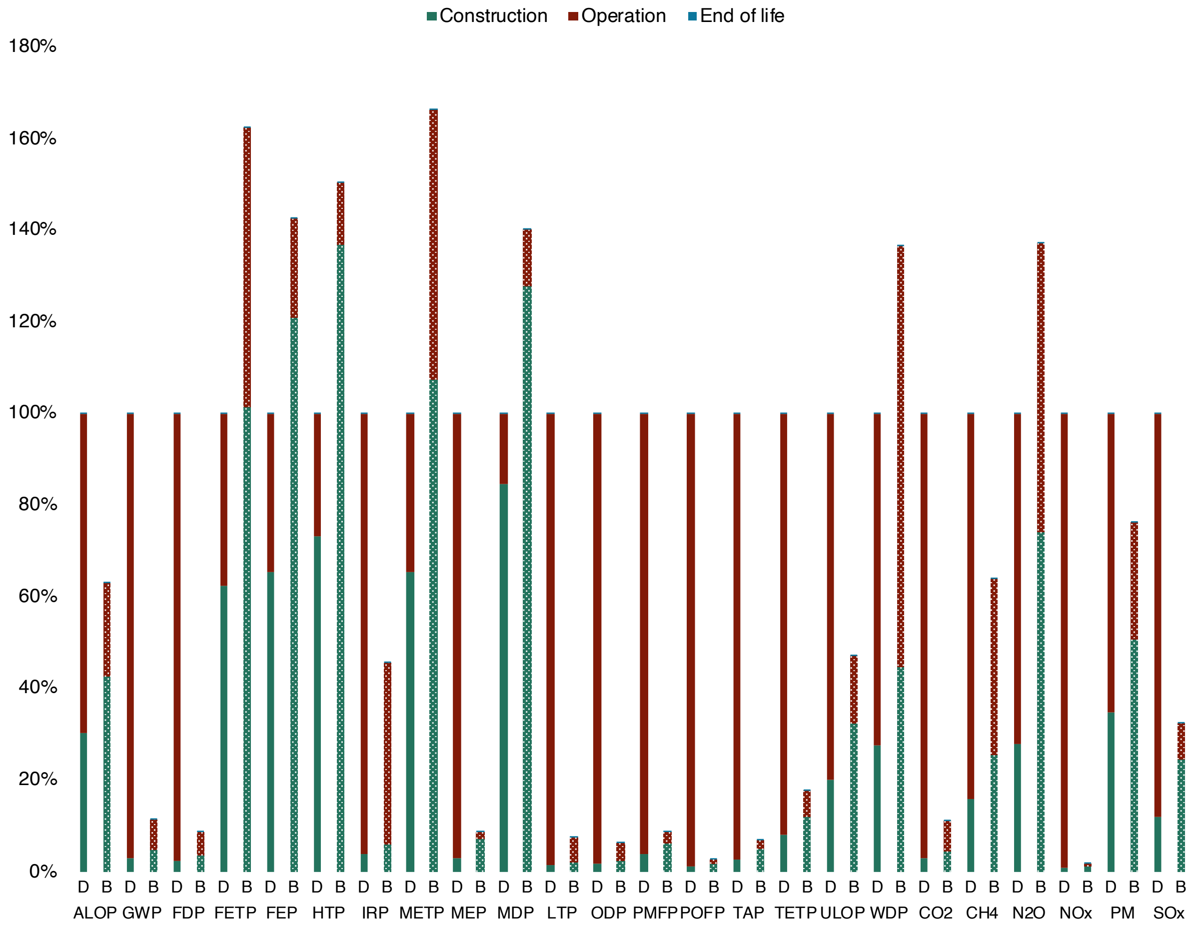


Figure 6.3: Distribution of LCA results for both cases from all life cycle phases normalised on diesel electric case

6.2 Base case construction results

In this section, the construction results are divided into ferry construction results, propulsion system construction results and shore system construction results, and examined in detail.

6.2.1 Diesel electric case construction results

As stated initially, the major share of environmental impacts from the construction phase for the diesel electric ferry is caused by the ferry construction. SPA results indicate which value chains that contribute significantly to the various indicators, and why impacts are distributed as illustrated in Figure 6.4 on the following page. The main contributor to impacts from the ferry construction is the structure, making up more than half of the impacts for all impact categories except HTP and ODP. The structure generally creates large impacts because of its large amount of metal needing to be produced and manufactured, as established in Chapter 5. Structure steel production contributes to impacts mainly due to treatment of sulphidic tailings[1] and nickel smelter slag. Structure metal working processes contribute due to treatment of municipal solid waste from the metal working factory and heat produced from hard coal among other factors. For HTP, the cables contribute the most, mainly due to copper production and related treatment of sulphidic tailing. The cables also contribute significantly to most other categories, especially FETP, FEP, METP, MEP, TAP and SO_x emissions. Cable impacts generally originate from copper production; the cables contribute to FETP, FEP and METP primarily due to treatment of sulphidic tailing from copper production, while MEP impacts are caused by dross from aluminium electrolysis during copper production. TAP and SO_x impacts from the cables are largely caused by the copper production process.

Other components also contribute to certain indicators. For ODP, the ventilation system is the second largest contributor after the structure due to the production of refrigerant R134a for the heat pumps. The interior creates significant impacts in terms of agricultural land occupation potential (ALOP), ODP and TETP. The interior cause ALOP impacts mainly due to forestry for the wooden parts and cotton production for the textiles. ODP impacts primarily originate from tetrafluoroethylene production for the textiles, while TETP impacts are largely created by cotton production for the textiles and treatment of wood ash related to the wooden parts. The assembly has noticeable impacts in several categories, especially LTP, POFP and NO_x emissions. These LTP impacts are for the major part caused by onshore well production related to petroleum production for diesel, and the POFP and NO_x impacts originate from combustion of diesel.

When considering the impacts of the ferry construction parts per weight of each part, the structure is about the same size as the hydraulic system and the anchor windlass for all categories. The cables are in general the major contributors normalised on weight, but the interior still dominates ALOP and TETP and the ventilation system clearly dominates ODP.

Regarding GWP, pig iron[2] and sinter production related to steel production as well as heat produced from hard coal for the metal working processes are the main reasons for high impacts from the ferry structure. Diesel combustion during assembly also contributes significantly.

[1] Sulphidic tailing is a waste generated by mining of metals and containing reactive minerals.

[2] Pig iron is iron with a high carbon content and an intermediate product of iron production.

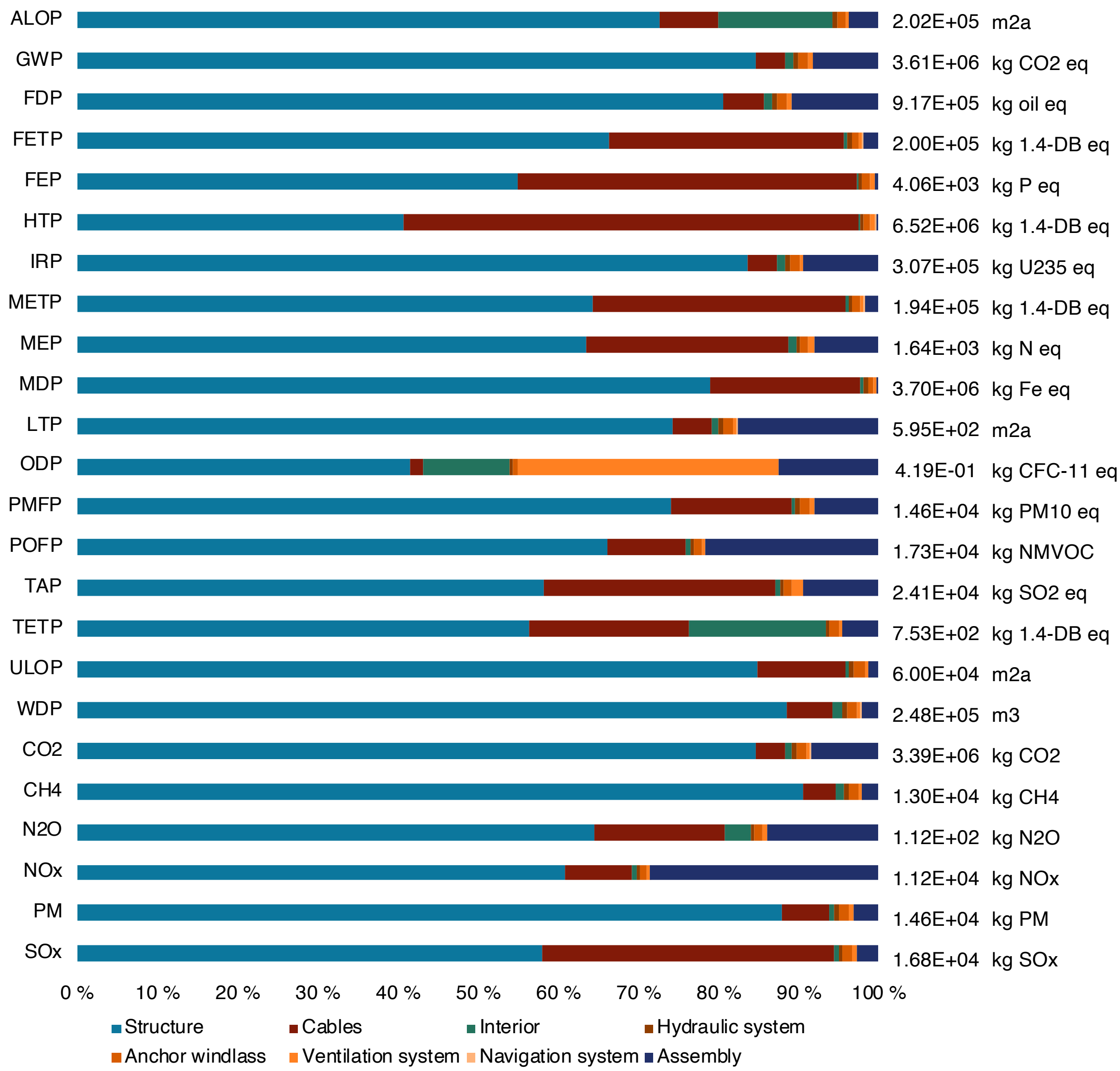


Figure 6.4: Distribution of LCA results from components in the diesel electric ferry construction

From Figure 6.5 on the following page it can be observed that for the diesel electric propulsion system, the thrusters are generally the largest contributor, due to metal production similarly to the structure. The diesel generating sets are also a noticeable contributor, especially to FETP and METP due to municipal incineration of scrap copper and residue from dismantling of the diesel engines, as well as treatment of sulphidic tailing from copper production for the generators. The BlueDrive PlusC switchboards, electric motors and integrated automation system also have significant impacts, while the impacts from the other propulsion system components are rather low. The BlueDrive PlusC switchboards are the major contributors to N_2O emissions due to nylon 6 production. The 300 kVA transformers produced using Finnish electricity have noticeable impacts in terms of ALOP due to forestry for wood chips used in electricity production and IRP due to nuclear electricity production.

When considering the impacts from the diesel propulsion system per weight of each component, the remote control system and integrated automation system are the largest contributors. The thrusters

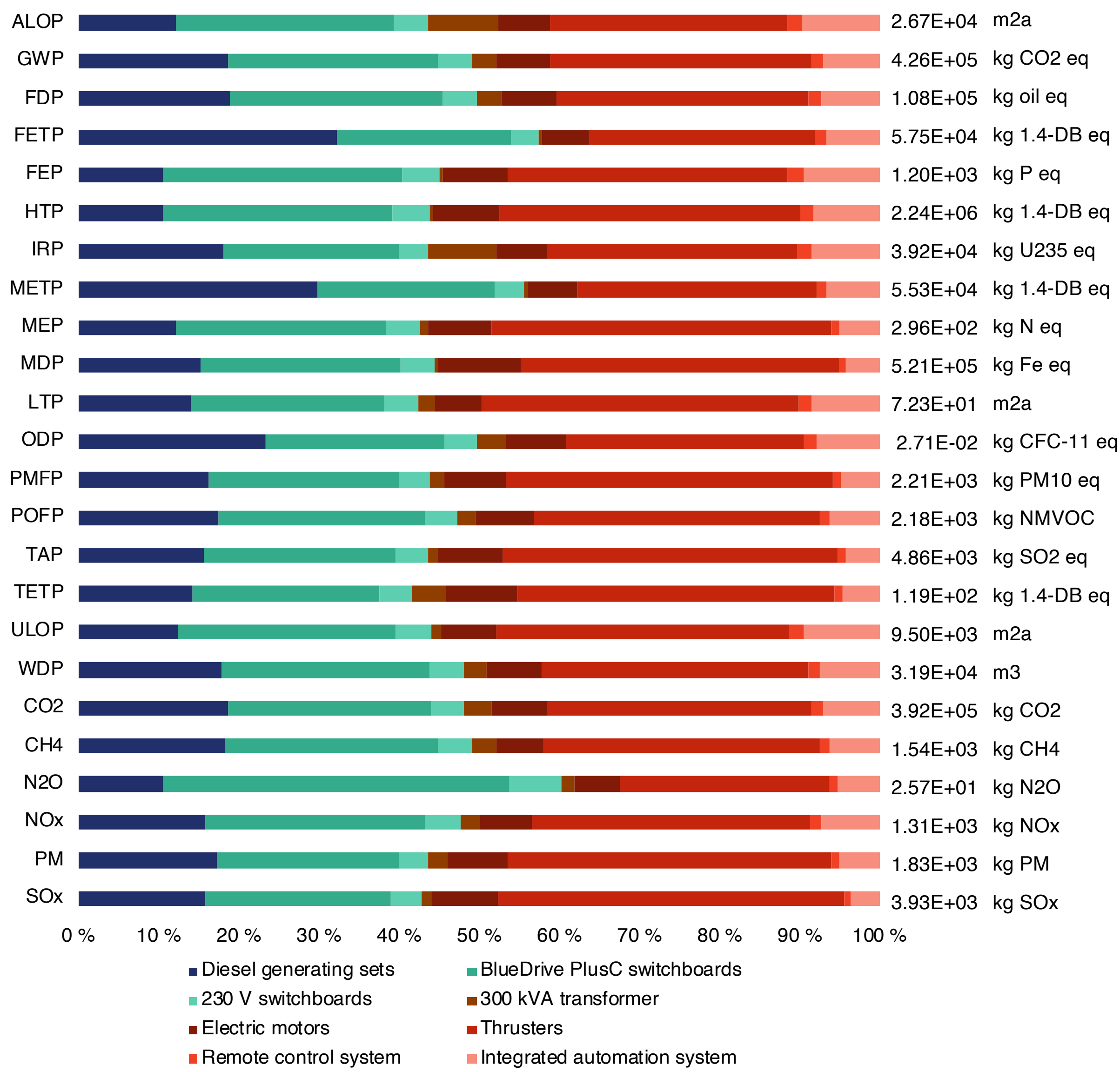


Figure 6.5: Distribution of LCA results from components in the diesel electric propulsion system construction

now have impacts of the same size as the electric motors and diesel generating sets. Similarly for the structure in the ferry construction, this indicates that the large impacts from the thrusters are due to the large amount of materials.

GWP impacts from the diesel electric propulsion system are mainly caused by iron and steel production for the thrusters due to related pig iron production and consumption of heat produced from hard coal.

The shore system impacts from the diesel electric system are not analysed on a per component basis as the shore system is only made up of the pier and the mooring systems, which are aggregated due to confidentiality. Gold production for electronic components in the mooring systems and related treatment of sulphidic tailing are generally causing the majority of impacts from the shore system. For GWP, clinker production for cement production for the pier is central.

6.2.2 Battery electric case construction results

The distribution of impacts between the ferry construction components for the battery electric ferry is similar to that of the diesel electric ferry as these parts of the ferries are similar, except the ventilation system which is somewhat larger for the battery electric ferry and the resulting changes to the transport weight part of the assembly process. This results in slightly higher FEP, MEP and POFP impacts for the battery electric case than for the diesel electric case, but the ferry construction analysis for the diesel electric ferry is still applicable for the battery electric ferry, and is therefore not repeated. A figure illustrating the battery electric ferry construction results can be found in Appendix C.

The battery electric propulsion system though vary significantly from the diesel electric propulsion system, as illustrated in Figure 6.6 on the following page. The battery electric propulsion system construction gets the largest impacts from the batteries, making up more than half the impacts in all categories except ALOP, and being especially significant for MEP and N_2O. The results for the batteries are analysed separately below. After the batteries, the most contributing component in general are the thrusters, followed by the BlueDrive PlusC switchboards. Based on the SPA results, the 2700 kVA transformers create significant impacts in terms of ALOP due to forestry for wood chips used in electricity production and IRP due to nuclear electricity production, similarly to the 300 kVA transformers. The components also part of the diesel electric propulsion system have unchanged impacts in the battery electric case and are therefore not discussed further. Regarding the other components added in the battery electric case, the 11 kV switchboard has considerable impacts while the shore connection box and the charging ship units are negligible compared to the other parts of the battery electric propulsion system. In addition to the battery, iron and steel production for the thruster are central for GWP similarly to the diesel electric case.

When considering the impacts from the battery electric propulsion system per weight of each component, the remote control system and the integrated automation system also here make up large shares of the impacts. The batteries are now of similar size as the switchboards. The sum of the impacts from the switchboards make up a significant share of impacts.

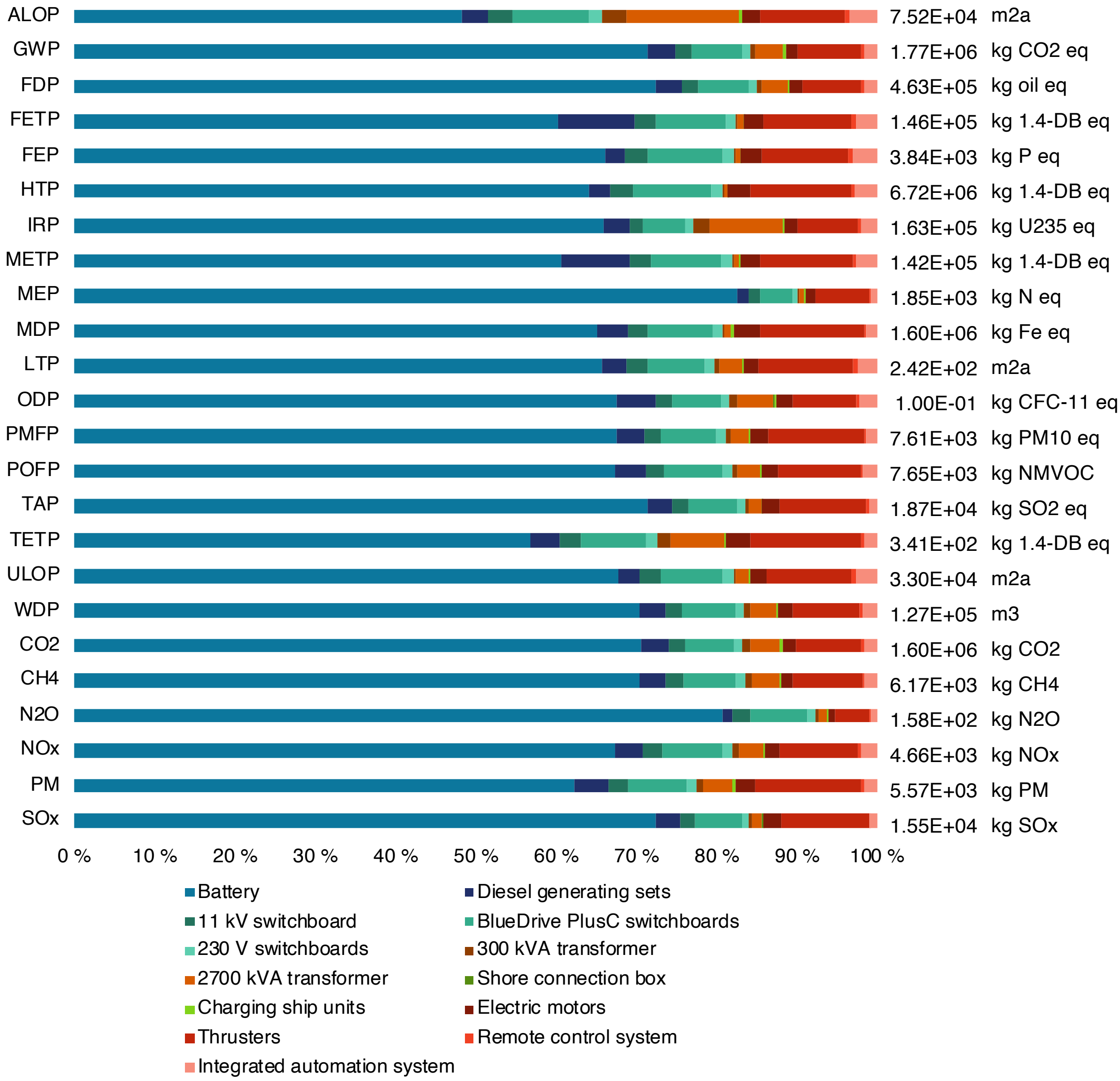


Figure 6.6: Distribution of LCA results from components in the battery electric propulsion system construction

The shore batteries also make up the major share of impacts related to shore construction, followed by the mooring systems and pier construction, as illustrated in Figure 6.7 following Figure 6.6. The charge towers and the cooling and climate system also have noticeable impacts, while the other components are less significant. Clinker production for concrete in the pier, pig iron production for steel in the mooring systems and charge towers and transport of the charge towers stand out as significant contributors to GWP.

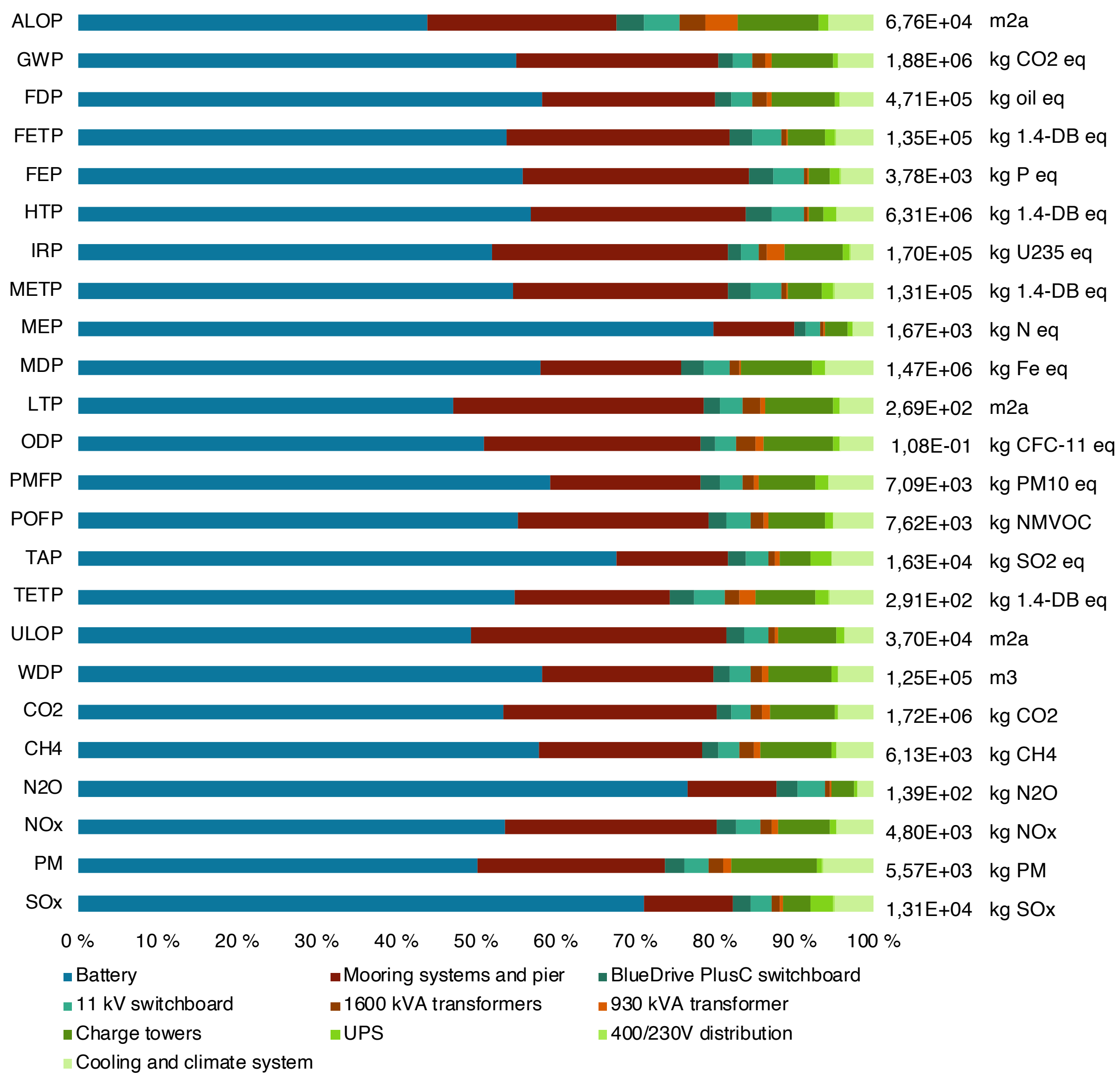


Figure 6.7: Distribution of LCA results from components in the battery electric shore system construction

When considering the impacts from the shore system construction for the battery electric case per weight of the components, the battery is still significant, but so are also the switchboards, the UPS and the 400/230 V distribution. The UPS has especially large TAP impacts and SO_x emissions due to mine operations for nickel in the battery. The 930 kVA transformer has noticeable impacts for ALOP and IRP due to forestry for wood chips and nuclear processes for electricity production, similarly to the 300 kVA transformer and the 2700 kVA transformer. All three transformers are produced in Finland consuming Finnish electricity and therefore obtain these similar results.

6.2.3 Battery production results

As mentioned in the previous section, the battery production contributes remarkably to MEP and N_2O impacts. The following results analysis of the batteries has aspects in common with the results analysis from the project preceding this thesis, as a comparable battery was analysed using a similar inventory

(Galaaen, 2019). The results analysis is based on the ferry battery production as the results are almost identical for the ferry and shore battery production. Figure 6.8 on the following page illustrates that the battery cell and the battery packaging stand out as the two main contributors to impacts for all indicators assessed, together creating more than 80% of contributions for each indicator. A corresponding figure for the shore battery production can be found in Appendix C. The battery cell makes up the major share of impacts for GWP, FDP, IRP, LTP, PMFP, POFP, TAP, TETP and WDP, as well as total emissions of CO_2, CH_4, PM and SO_x for the ferry batteries. For the shore system battery, the battery cell is also dominant in ODP and NO_x. Among the battery cell parts, the battery cell production is dominant for GWP, FDP, IRP, LTP, ODP, POFP, ULOP, WDP and total CO_2, CH_4, N_2O, NO_x and PM emissions while the anode is central for ALOP, FETP, FEP, HTP, METP, MEP, MDP and TETP and the cathode for PMFP, TAP and total SO_x emissions. The battery packaging makes up the major share of impacts in the other indicators, and here the module packaging is generally the most contributing process, making up the major share of battery packaging impacts for all indicators except MEP and MDP where the battery pack frame is the major contributor. The battery pack, control system and cooling system have relatively small contributions for all indicators, except for the impacts from the control system in terms of MEP and to some degree the battery pack in LTP. In the following paragraphs, results are further investigated presenting numbers for the ferry batteries. The results for the shore batteries are similar varying with approximately $\pm 1\%$, thus the same analysis applies for the shore batteries.

The battery cell is the largest contributor to GWP among the battery parts causing 58% of impacts, followed by the battery packaging causing 38% of impacts. The GWP of each battery part normalised on their weights is higher for the battery cell than the other battery parts, which is further explained in Appendix C. Within the battery cell, the battery cell production is the largest contributor, followed by the battery cell container. Electricity for production of the battery cell is an especially strong contributor, generating more than 34% of total GWP impacts. The module packaging makes up the largest share of battery packaging impacts, followed by the BIP. Nylon used in the module packaging causes a significant share of impacts, as well as steel and freight transport. For CO_2 and CH_4 which contribute to GWP, the battery cell is most significant and the battery cell production essential. Almost 90% of the stressors related to GWP are CO_2. CO_2 related to battery production is mainly emitted from natural gas and hard coal electricity production in Taiwan, while CH_4 is mainly emitted from hard coal mine operations and nylon 66 production. For N_2O on the other hand, the module packaging is more relevant in terms of emissions, which to a large extent is due to nylon production.

The toxicity impact categories are mainly affected by mining of metals causing emissions of chemicals. For both FETP, HTP and METP, the battery packaging is the most central activity and the most contributing process is treatment of sulphidic tailing from mining of metals like copper and aluminium, which creates more than 72% of impacts in all three categories. For TETP, the battery cell has the highest importance, and impacts are to a large extent caused by copper production (more than 24%) for the anode and waste treatment. The anode, which consists of a large share of copper, is an important process within the battery cell for all the four toxicity categories, creating between 46% and 76% of battery cell toxicity impacts.

The battery packaging is the most contributing activity for the eutrophication categories creating around 60% of impacts. In contrast to the other impact categories, also the control system make up a significant share of impacts for MEP due to copper. While the module packaging and the BIP are significantly creating battery packaging impacts for FEP, the battery pack frame is more important for MEP.

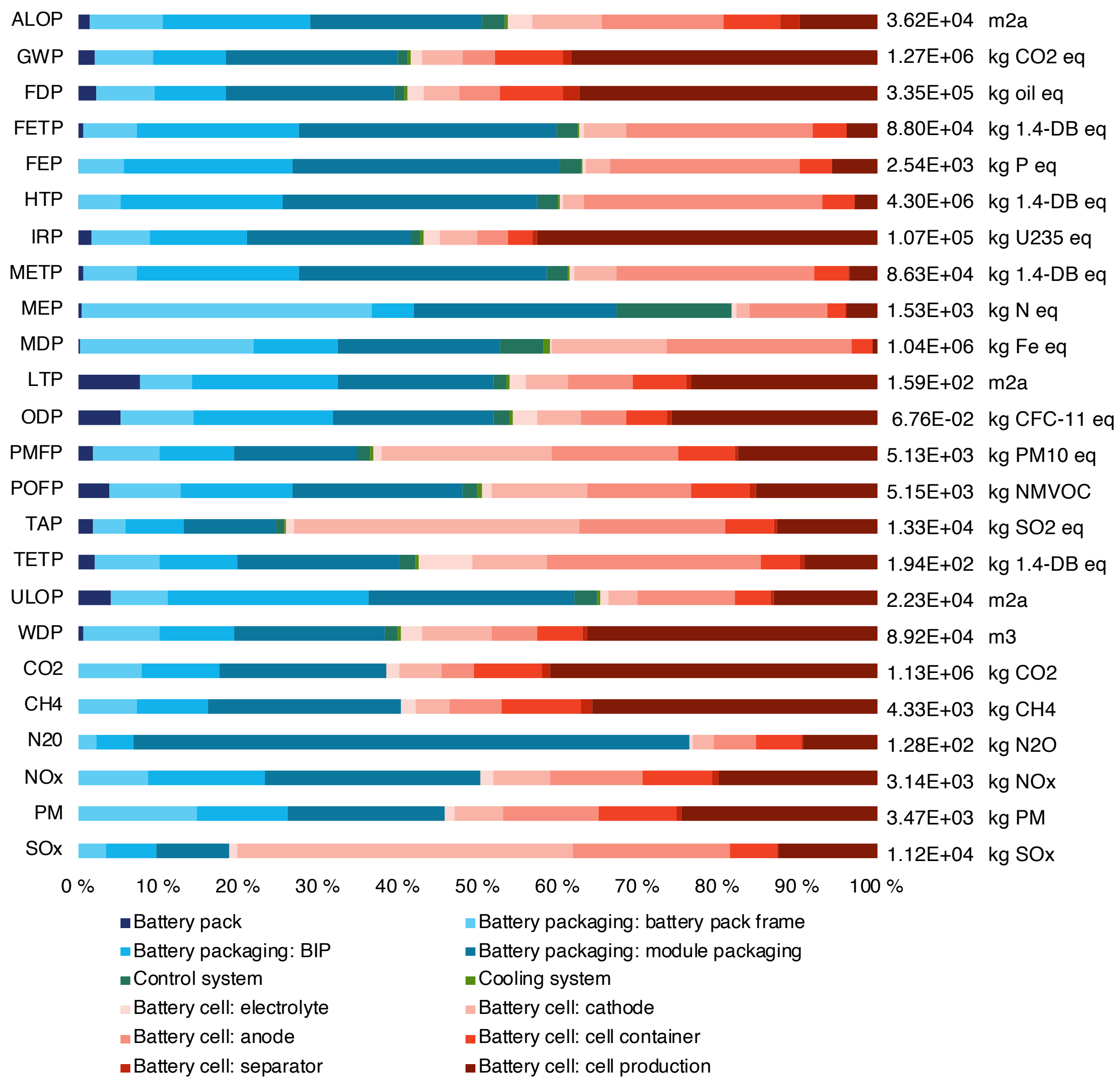


Figure 6.8: Distribution of LCA results from components in the ferry battery production

Similarly to the toxicity impacts, mining of metals creates a large amount of eutrophication impacts. Treatment of sulphidic tailing is central also here, contributing to more than 80% of FEP, as well as dross from aluminium electrolysis, contributing to more than 70% of MEP.

Also for MDP, the battery packaging makes up the major share of impacts. Impacts mainly originate from the module packaging and the battery pack frame, which are the most copper-intensive processes within the battery packaging. The anode and cathode, containing remarkable amounts of copper and aluminium, make up the majority of the battery cell impacts. Metal extraction processes, especially copper mine operation and manganese concentrate production are the most important processes in terms of impacts. More than 27% of the impacts are related to copper. Regarding the battery cell, the cell production is not so important in terms of MDP, in contrast to many of the other impact categories. This is because the cell production mainly includes processes related to electricity and transport, and not depletion of minerals.

The battery cell is the largest contributor for both PMFP and POFP creating more than half of the impacts in both categories, with impacts relatively evenly distributed between the battery cell production, the cell container, the anode and the cathode. Although many different processes contribute to PMFP and POFP, impacts in these categories are to a large degree related to electricity production from hard coal for use in battery cell production. Nickel mine operations for nickel in the cathode and electricity production from lignite also contribute to PMFP, while blasting and diesel burned in machines cause impacts in terms of POFP. For NO_x and PM, which are related to PMFP and POFP, the battery cell and packaging also make up a significant share of emissions each. For SO_x the battery cell is dominant and creates almost 80% of emissions due to the cathode and the anode. NO_x emissions are created by many different processes, but blasting is one of the most significant ones. For PM, electricity production from hard coal used in the cell production substantially contribute to emissions, while for SO_x, nickel mine operations are central with almost 40% of emissions.

Regarding the other indicators, TAP is the impact category where the battery cell makes up the largest share of impacts (74%), mainly due to the cathode, but also to a large degree the anode and battery cell production. Nickel mine operations linked to the cathode significantly contribute to burdens in this category, causing more than 30% of impacts. Hard coal mine operation[3] is generally an important contributing process for the remaining indicators. Treatment of different wastes as well as processes related to extraction of metals and nylon production also show up as central processes creating impacts.

The battery cell and the battery packaging are the two heaviest parts of the battery, and they are also the ones creating the largest impact for all impact categories. Still, the battery cell outweighs the battery packaging in terms of impacts, while the battery packaging outweighs the battery cell in terms of weight. Normalised results on weight and battery capacity can be found in Appendix C.

The battery production creates significant impacts for several categories, and contribute to differences in construction impacts between the diesel electric and the battery electric case. The construction impacts for the two base cases are compared in the following section.

6.2.4 Comparison of construction results

As evident from Figure 6.9 on the following page, the construction impacts are higher for the battery electric ferry for all indicators. The increase is especially significant for MEP and N_2O emissions, which also are the indicators to which the battery production contribute the most in the battery electric case. The ferry construction is similar for all impacts as the inventories of this part of the construction are almost identical for the two cases. The differences in impacts are therefore caused by the propulsion system construction and the shore system construction, and it is observed that impacts from both these construction parts increase for the battery electric ferry.

[3]Hard coal mine operation is a background process necessary for producing electricity from hard coal, which is used to a large extent in the battery cell production.

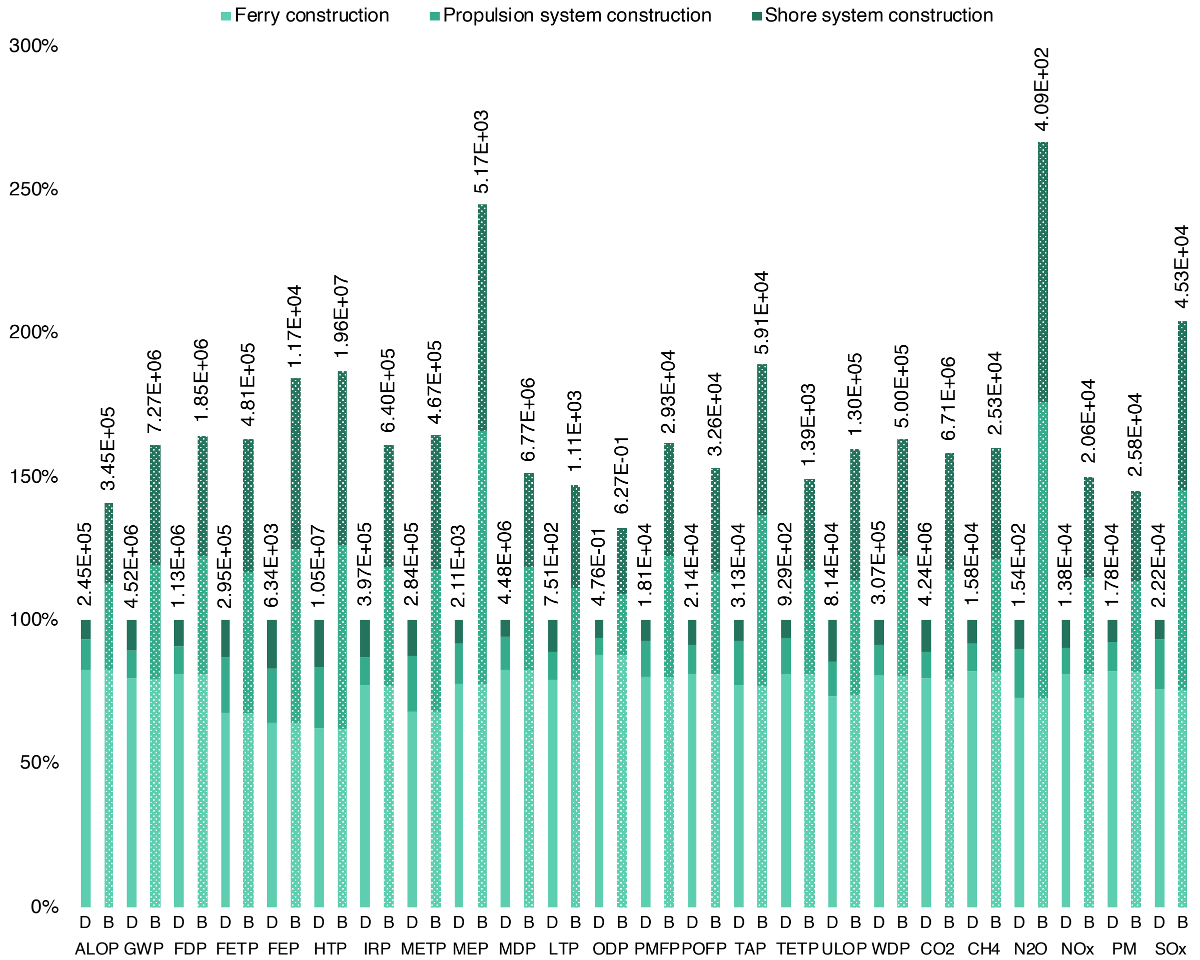


Figure 6.9: Distribution of LCA results for both cases from the construction phase normalised on diesel electric case

From Figure 6.10 on the following page it is clear that the battery is the major reason for increases in the battery electric case, although a significant share of impact increases for ALOP and IRP and some for GWP, FDP, ODP, TETP, WDP and emissions are also caused by the additional switchboards and transformers. The diesel generating sets cause higher impacts for the diesel electric case because it has one more generating set. The electric motors, thrusters and control systems are generally the most contributing group of components, and are similar between the two cases.

SPA results are used to identify why construction impacts increase in the battery electric case and where in the value chains the increases in impacts occur. The significant increase in MEP is caused by both the propulsion system construction and the shore system construction. The cooling and climate system and switchboards at shore, as well as the 11 kV and BlueDrive PlusC switchboards on board the ferry, obtain significant shares of impacts due to treatment of dross from aluminium electrolysis in copper production for the absorption chiller and drives. The same applies for the UPS. The charge towers cause impacts due to treatment of municipal solid waste and wastewater related to the metal working process. N_2O emissions are higher for the battery electric case mainly due to nylon production for the 11 kV switchboards and the BlueDrive PlusC switchboard on land.

Impacts also significantly increase for FEP, HTP, TAP and SO_x emissions. The increases in FEP and

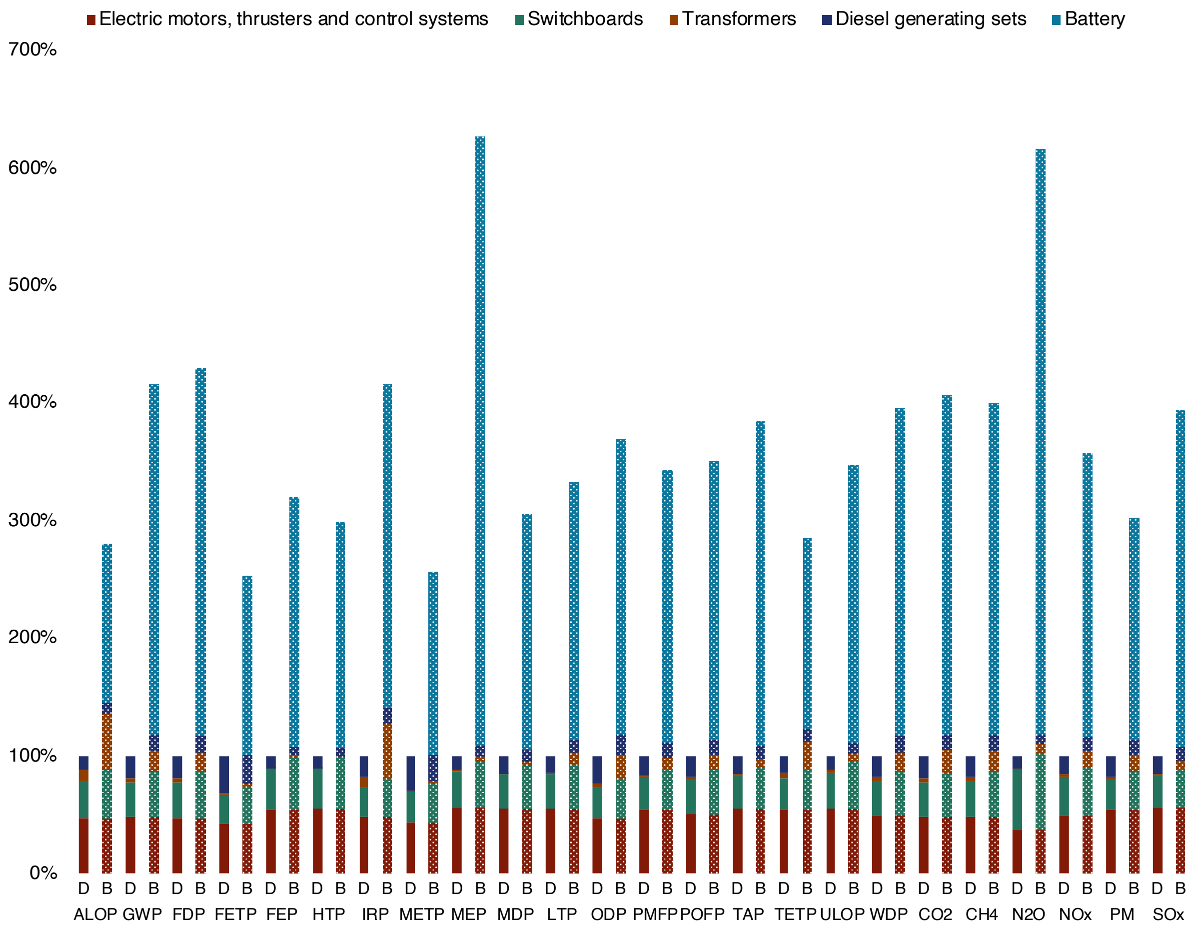


Figure 6.10: Distribution of LCA results for both cases from the propulsion system construction normalised on diesel electric case

The shore connection box, charging ship unit and transport of the propulsion system are excluded as they make up less than 1% of propulsion system construction impacts for all indicators.

HTP are caused by treatment of sulphidic tailing from copper production for the absorption chiller in the cooling and climate system at shore. Impacts are also created from gold production for the electronics and copper production for the drive in the 11 kV switchboards and the BlueDrive PlusC switchboard at shore, as well as from steel production for the charge towers. Regarding TAP and SO_x, impacts mainly increase due to mine operations for nickel in the UPS battery and copper production for the absorption chiller in the cooling and climate system at shore. TAP impacts also originate from hard coal heat production for metal working for the charge towers.

The GWP of the propulsion system construction and shore construction are respectively 317% and 293% higher for the battery electric case than for the diesel electric case. The total construction GWP is 61% higher for the battery electric case than for the diesel electric case. Aluminium production and electricity for the 2700 kVA transformer as well as pig iron production for steel, hard coal heat consumption in metal working and transport related to the charge towers stand out as significant contributors.

6.3 Base case operational results

Figure 6.11 illustrates that operational impacts are higher for the battery electric ferry in terms of FETP, METP and WDP, while higher for the diesel electric ferry in terms of the remaining indicators. Municipal incineration of scrap steel and copper from hydro power plants and wind turbine waste concrete are the major contributors to the FETP and METP increases in the battery electric case. This is related to the hydro and wind power in the electricity mix used for operation. Treatment of spoil from hard coal mining for heat and power co-generation and treatment of electric wiring scrap copper from photovoltaic plants producing electricity are also significant contributors. For WDP, electricity production from natural gas using a conventional power plant and from hard coal through heat and power co-generation as well as nuclear electricity production using a boiling water reactor are found to be the major contributors to increases in the battery electric case.

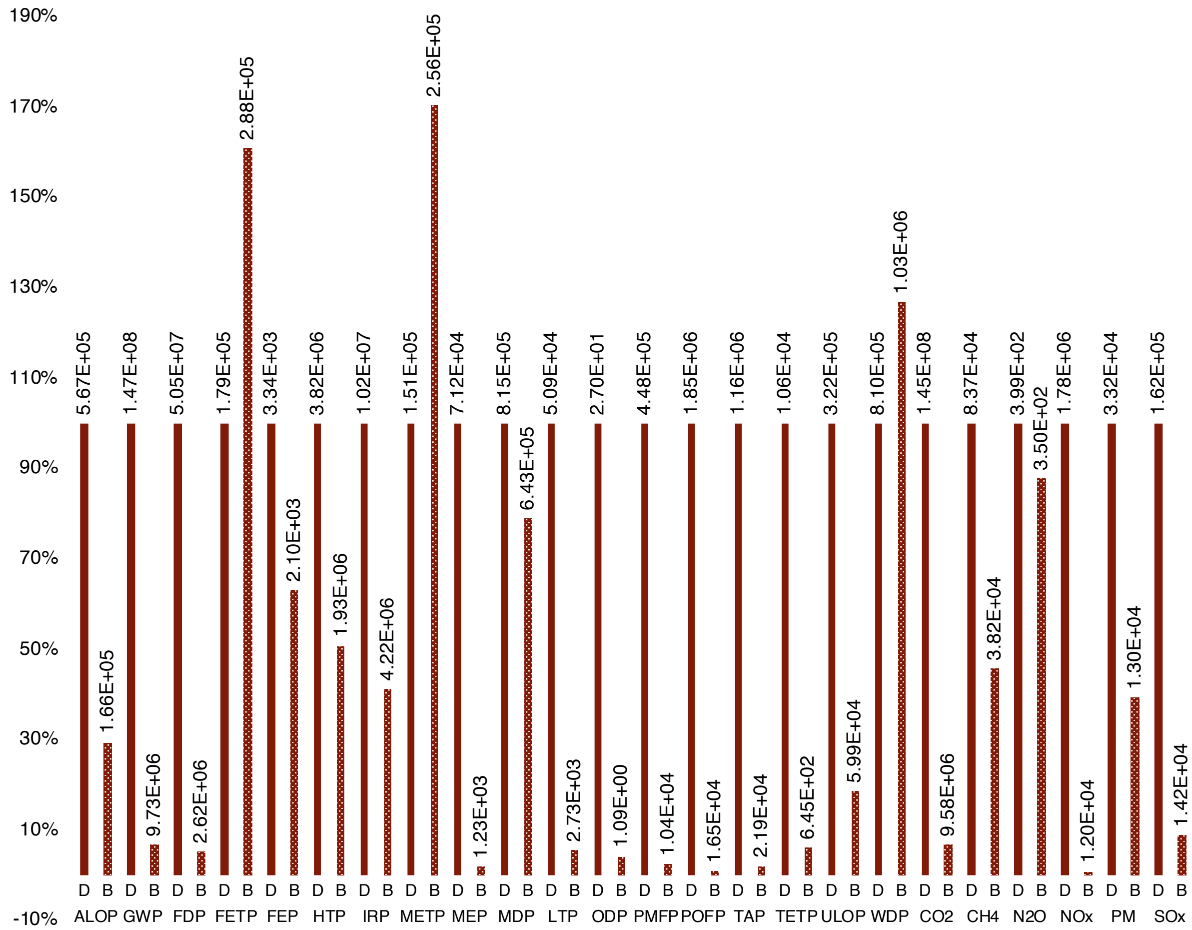


Figure 6.11: Distribution of LCA results for both cases from the operational phase normalised on diesel electric case

Impacts are remarkably lower for the battery electric case in terms of GWP, FDP, MEP, LTP, ODP, PMFP, POFP, TAP, TETP, CO_2, NO_x and SO_x with reductions between 91 and 99%. More than 80% of the total diesel electric ferry GWP impacts are caused by the direct emissions from the operational phase. The diesel value chain is the second largest contributor to operational impacts, caused by among other factors heat, HFO and petroleum production for the petroleum refinery operation. The GWP impacts of the battery electric ferry are reduced compared to the diesel electric ferry mainly due to the avoided direct emissions and diesel fuel value chain impacts. The major contributors to operational GWP impacts in the battery electric case are electricity production from natural gas using a conventional power plant and hard coal heat and power co-generation. The hard coal mining upstream the electricity production from heat and power co-generation as well as clinker production for cement used in hydro power plants are also significant contributors.

The reductions in FDP and ODP for the battery electric case are mainly due to avoided petroleum and gas production, making up more than 86% of FDP impacts and more than 92% of ODP impacts in the diesel electric case. For MEP, PMFP, POFP and TAP, reductions are mainly obtained due to avoided direct emissions from the combustion of diesel during operation, which make up more than 90% of MEP impacts, more than 82% of PMFP impacts, more than 91% of POFP impacts and more than 80% of TAP impacts in the diesel electric case. LTP impacts are reduced in the battery electric case mainly due to avoided onshore well and petroleum infrastructure construction. The battery electric case obtains TETP reductions mainly due to avoided treatment of drilling waste from onshore well production related to petroleum production in the diesel fuel value chain. The CO_2 and NO_x emissions reductions in the battery electric case are also mainly due to avoided direct emissions from the operational phase in the diesel electric case, with direct emissions making up more than 82% of CO_2 emissions and more than 95% of NO_x emissions in the diesel electric case. SO_x emissions are reduced in the battery electric case mainly due to avoided treatment of waste natural gas and combustion of HFO related to petroleum refinery operations in the diesel fuel value chain. Details on how much of the operational impacts originate from the ferry charging electricity, the shore power and the mooring system cannot be presented separately due to confidentiality.

6.4 Base case end of life results

As explained in previous chapters, the LCI regarding the end of life phase was simplified, and the results are presented accordingly. The battery electric ferry has larger end of life impacts than the diesel electric ferry for all indicators, as illustrated in Figure 6.12 on the following page. This is due to the additional electrical components like transformers and switchboards needed to be disposed of for the battery electric ferry. The only component creating end of life impacts in the diesel electric case and not the battery electric case is the fourth generator part of the diesel generating set.

For the diesel electric case, the ferry dismantling dominates impacts in all categories. ALOP also have noticeable contributions from the treatment of the electric motors, the generators and the BlueDrive PlusC switchboards drives. FETP and METP obtain noticeable impacts from the electric motors and the generators. ULOP have significant impacts from the BlueDrive PlusC switchboards drives, while LTP obtain negative impacts from the treatment of the propulsion system.

For the battery electric case, the ferry and shore batteries end of life is the major contributor to impacts, followed by the ferry dismantling. The batteries are dominant for ALOP, GWP, FETP, FEP, HTP, METP, MEP, MDP, PMFP, POFP, ULOP, CO_2, N_2O, NO_x and PM, while the ferry dismantling is dominant for the remaining indicators. The transport of the batteries stand out as the main contributor to GWP impacts. LTP obtain negative impacts from the shore system end of life treatment, while the 2700 kVA transformer create noticeable impacts in terms of WDP.

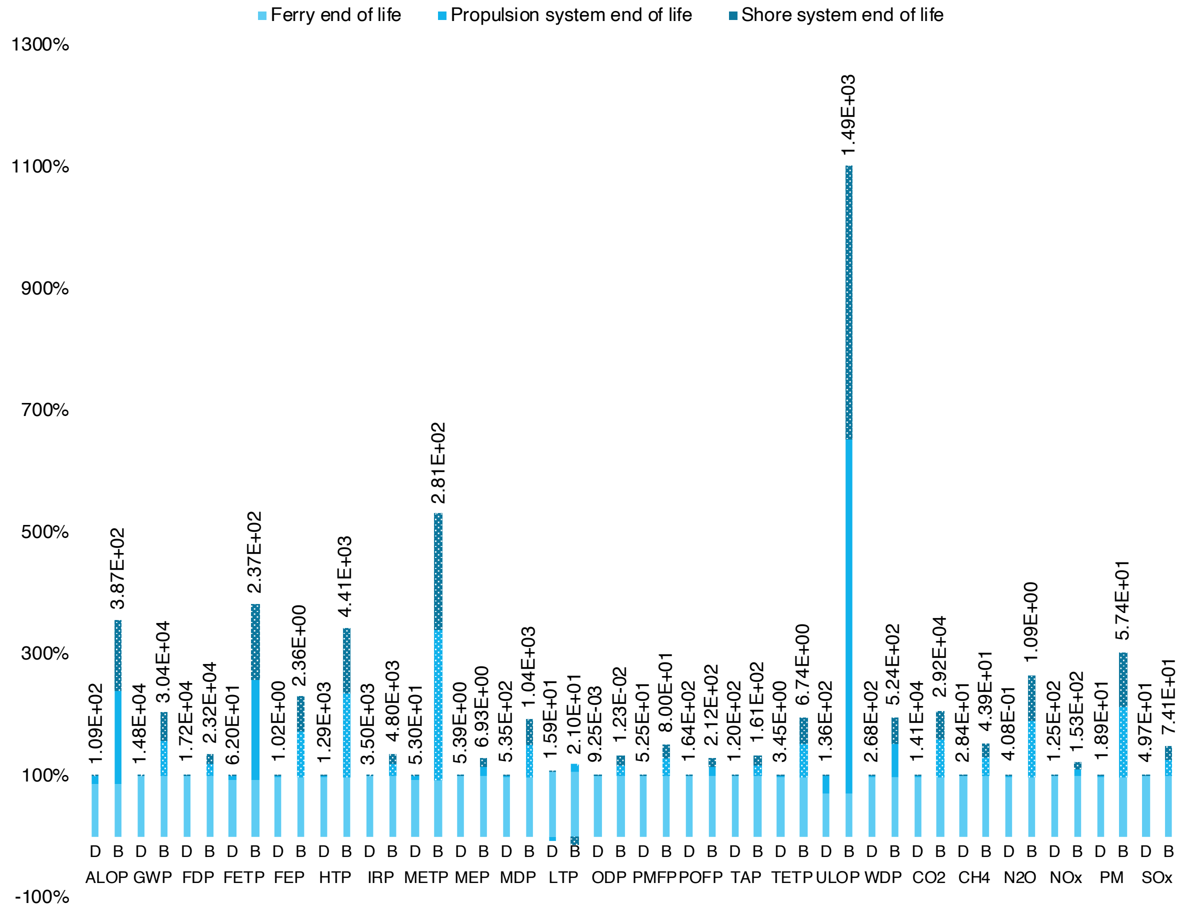


Figure 6.12: Distribution of LCA results for both cases from the end of life phase normalised on diesel electric case

6.5 Sensitivity analysis results

The results from the sensitivity analysis regarding operational electricity mix, losses in electrical components, shore power, battery cell production location, secondary material input in battery production and a future battery production scenario are analysed in this section. Each sensitivity case is compared to the base cases in terms of total results, and it is investigated whether the which of the diesel electric and the sensitivity battery electric case performs better in each category, and how the impacts from the sensitivity battery electric case are changed compared to the battery electric base case. In the results tables, green represents impact reductions not affecting which of the diesel and battery electric cases that performs better, blue represents impact reductions affecting which of the cases that performs better, orange represents increases not affecting which of the cases that performs better, and red represents increases affecting which of the cases that performs better.

6.5.1 Electricity mix sensitivity results

It can be observed from Table 6.1 on the following page that impacts decrease or remain unchanged for all indicators for the Norwegian production mix, while they increase for all indicators for both the current and the future European production mix. All indicators except TETP decrease or remain unchanged for the Norwegian production mix with imports from Sweden and Denmark. Impacts in terms of GWP, FDP, MEP, LTP, ODP, PMFP, POFP, TAP and TETP and total emissions of CO_2 and NO_x are lower for all the electricity mix cases than for the diesel electric case, as in the base case. This means that no matter which of these electricity mixes are used for operating the battery electric ferry, the battery electric ferry is an advantageous alternative over the diesel electric ferry in terms of these impacts and emissions. The GWP and NO_x electricity mix intensities necessary for making the battery electric ferry disadvantageous in terms of these indicators over the ferry life cycle compared to the diesel electric ferry are found to be 607 g CO_2 eq per kWh and 7 g gNO_x per kWh respectively. Impacts in terms of FETP, FEP, HTP, METP, MDP and N_2O remain higher for the battery electric case than for the diesel electric case in all sensitivity cases. For ALOP, the battery electric ferry performs worse than the diesel electric ferry for the European electricity mixes and the Ecoinvent mix. For IRP, ULOP, CH_4 and PM, the battery electric ferry performs worse than the diesel electric ferry for the European electricity mixes. WDP goes from being higher for the battery electric ferry than the diesel electric ferry in the base case to being lower in the sensitivity case with the Norwegian production mix.

Table 6.1: Total impact reductions for the electricity mix sensitivity cases relative to total impacts of the diesel electric case

		Base cases		Sensitivity cases				
Indicator	Unit	Diesel electric	BE	NP	EP	NSD	FEP	EM
ALOP	m2a	8.12E+05	-37%	-45%	90%	-37%	89%	143%
GWP	kg CO2 eq	1.52E+08	-89%	-92%	-35%	-91%	-51%	-90%
FDP	kg oil eq	5.16E+07	-91%	-94%	-50%	-93%	-62%	-93%
FETP	kg 1,4-DB eq	4.74E+05	62%	55%	169%	59%	235%	177%
FEP	kg P eq	9.68E+03	43%	28%	265%	34%	208%	44%
HTP	kg 1,4-DB eq	1.43E+07	50%	43%	159%	46%	143%	58%
IRP	kg U235 eq	1.06E+07	-54%	-91%	517%	-67%	507%	-70%
METP	kg 1,4-DB eq	4.35E+05	66%	59%	176%	63%	237%	175%
MEP	kg N eq	7.33E+04	-91%	-92%	-76%	-92%	-78%	-92%
MDP	kg Fe eq	5.29E+06	40%	39%	53%	40%	61%	46%
LTP	m2	5.16E+04	-93%	-93%	-85%	-93%	-88%	-91%
ODP	kg CFC-11 eq	2.75E+01	-94%	-96%	-59%	-95%	-63%	-95%
PMFP	kg PM10 eq	4.66E+05	-91%	-92%	-80%	-92%	-82%	-91%
POFP	kg NMVOC	1.87E+06	-97%	-98%	-92%	-98%	-93%	-97%
TAP	kg SO2 eq	1.19E+06	-93%	-94%	-78%	-94%	-82%	-93%
TETP	kg 1,4-DB eq	1.16E+04	-82%	-85%	-48%	-81%	-40%	-58%
ULOP	m2a	4.04E+05	-53%	-60%	59%	-57%	32%	-56%
WDP	m3	1.12E+06	37%	-20%	916%	1%	771%	15%
CO_2	kg CO2	1.50E+08	-89%	-93%	-36%	-91%	-48%	-91%
CH_4	kg CH4	9.96E+04	-36%	-58%	296%	-43%	246%	-57%
N_2O	kg N2O	5.53E+02	37%	3%	571%	23%	459%	262%
NO_x	kg NOx	1.79E+06	-98%	-98%	-94%	-98%	-95%	-98%
PM	kg PM	5.09E+04	-24%	-32%	97%	-28%	68%	-23%
SO_x	kg SOx	1.84E+05	-68%	-72%	4%	-70%	-16%	-68%

BE = Battery electric. NP = Norwegian production mix, EP = Current European production mix, NSD = Norwegian consumption mix with imports from Sweden and Denmark, FEP = future European production mix, EM = Ecoinvent 3.2 Norwegian market electricity. Green represents impact reductions not affecting which of the diesel and battery electric cases that performs better, blue represents impact reductions affecting which of the cases that performs better, orange represents increases not affecting which of the cases that performs better, and red represents increases affecting which of the cases that performs better.

6.5.2 Losses sensitivity results

It can be observed from Table 6.2 that the the losses affect total results. Though, impacts still decrease in the same categories as in the base case battery electric ferry compared to the diesel electric ferry for both the highest and lowest losses. This means that even though the losses are worst-case (highest), the same impact changes are found when moving from a diesel electric to a battery electric ferry, just with a slightly different size.

Table 6.2: Total impact reductions for the losses sensitivity cases relative to total impacts of the diesel electric case

		Base cases		Sensitivity cases	
Indicator	Unit	Diesel electric	Battery electric	Highest losses	Lowest losses
ALOP	m2a	8.12E+05	-37%	-36%	-38%
GWP	kg CO2 eq	1.52E+08	-89%	-89%	-89%
FDP	kg oil eq	5.16E+07	-91%	-91%	-91%
FETP	kg 1,4-DB eq	4.74E+05	62%	64%	60%
FEP	kg P eq	9.68E+03	43%	43%	42%
HTP	kg 1,4-DB eq	1.43E+07	50%	51%	50%
IRP	kg U235 eq	1.06E+07	-54%	-53%	-55%
METP	kg 1,4-DB eq	4.35E+05	66%	68%	65%
MEP	kg N eq	7.33E+04	-91%	-91%	-91%
MDP	kg Fe eq	5.29E+06	40%	40%	40%
LTP	m2	5.16E+04	-93%	-92%	-93%
ODP	kg CFC-11 eq	2.75E+01	-94%	-94%	-94%
PMFP	kg PM10 eq	4.66E+05	-91%	-91%	-92%
POFP	kg NMVOC	1.87E+06	-97%	-97%	-97%
TAP	kg SO2 eq	1.19E+06	-93%	-93%	-93%
TETP	kg 1,4-DB eq	1.16E+04	-82%	-82%	-83%
ULOP	m2a	4.04E+05	-53%	-52%	-53%
WDP	m3	1.12E+06	37%	39%	34%
CO_2	kg CO2	1.50E+08	-89%	-89%	-89%
CH_4	kg CH4	9.96E+04	-36%	-35%	-37%
N_2O	kg N2O	5.53E+02	37%	39%	35%
NO_x	kg NOx	1.79E+06	-98%	-98%	-98%
PM	kg PM	5.09E+04	-24%	-23%	-25%
SO_x	kg SOx	1.84E+05	-68%	-67%	-68%

Green represents impact reductions not affecting which of the diesel and battery electric cases that performs better, and orange represents increases not affecting which of the cases that performs better.

6.5.3 No shore power sensitivity results

The results from the sensitivity case considering a situation where no shore power is used and the hotel load during non-operating hours also is covered by the battery indicate that this change does not have a significant impact on total results. Impacts increases compared to the diesel electric base case are only 1% higher for FETP, METP and N_2O than in the battery electric base case, and zero otherwise. The results from this sensitivity case can be found in Appendix C.

6.5.4 Battery production sensitivity results

The results for the three battery production sensitivity analyses, cell production location, use of secondary material and future scenario are presented in this section respectively.

Cell production location sensitivity results

It is evident from Table 6.3 on the following page that both cell production location sensitivity cases improve the performance of the entire battery electric ferry for several indicators. Impacts do not increase for any indicators with battery cell production in Norway. FETP, IRP and METP impacts increase slightly for battery cell production in Germany, but not enough to make the battery electric case unfavourable compared to the diesel electric ferry. Both the avoided transport of the cell from Taiwan and the different electricity consumed during cell production affect the results. When considering only the battery production and not the full life cycle of the battery electric ferry, GWP results are reduced with 20% and 37% for Germany and Norway respectively, and NO_x with 14% and 21%. The battery cell production contributes significantly to FDP, IRP, WDP, CO_2 and CH_4 in addition to GWP in the base case, and these impacts are affected by the different electricity mixes consumed during battery cell production in the sensitivity cases. FDP battery production impacts are reduced with 19% and 37% in the German and Norwegian sensitivity cases respectively, CO_2 with 10% and 38%, CH_4 with 12% and 33%, and WDP with 4% and 34%. IRP increases with 120% for Germany due to the European electricity mix, but is significantly reduced for Norway. In addition to FETP, IRP and METP, battery production ODP impacts also increase for the cell production in Germany even though it is not visible in the total ferry results. These increases are also caused by the European electricity consumed during cell production.

Secondary material input sensitivity results

Table 6.4 following Table 6.3 illustrates that on a life cycle basis, all impacts are reduced or unchanged when secondary input materials are used in the current production. Reductions are due to the elimination of primary material production for the battery packaging, control system and cooling system. The use of secondary materials is found to significantly reduce battery production MEP impacts indicating a reduction of 34%. Battery production GWP impacts are reduced with 4%, MDP with 16%, and PM with 9%. The other indicators obtain reductions of 5% or less. On the battery production level, impacts are mainly reduced for all indicators and all the battery parts using secondary material input, and the few increases that exist for certain battery parts and indicators are minor and outweighed by the reductions. The control system, cooling system and battery pack frame obtain the largest reductions as these have significant amount of materials that are partially replaced with secondary materials.

Table 6.3: Total impact reductions for the battery cell production location sensitivity cases relative to total impacts of the diesel electric case

		Base cases		Sensitivity cases: cell production	
Indicator	Unit	Diesel electric	Battery electric	Germany	Norway
ALOP	m2a	8.12E+05	-37%	-37%	-38%
GWP	kg CO2 eq	1.52E+08	-89%	-89%	-89%
FDP	kg oil eq	5.16E+07	-91%	-92%	-92%
FETP	kg 1,4-DB eq	4.74E+05	62%	63%	62%
FEP	kg P eq	9.68E+03	43%	41%	40%
HTP	kg 1,4-DB eq	1.43E+07	50%	50%	49%
IRP	kg U235 eq	1.06E+07	-54%	-52%	-55%
METP	kg 1,4-DB eq	4.35E+05	66%	67%	66%
MEP	kg N eq	7.33E+04	-91%	-91%	-91%
MDP	kg Fe eq	5.29E+06	40%	40%	40%
LTP	m2	5.16E+04	-93%	-93%	-93%
ODP	kg CFC-11 eq	2.75E+01	-94%	-94%	-94%
PMFP	kg PM10 eq	4.66E+05	-91%	-92%	-92%
POFP	kg NMVOC	1.87E+06	-97%	-97%	-97%
TAP	kg SO2 eq	1.19E+06	-93%	-93%	-93%
TETP	kg 1,4-DB eq	1.16E+04	-82%	-82%	-83%
ULOP	m2a	4.04E+05	-53%	-53%	-54%
WDP	m3	1.12E+06	37%	36%	32%
CO_2	kg CO2	1.50E+08	-89%	-89%	-90%
CH_4	kg CH4	9.96E+04	-36%	-37%	-39%
N_2O	kg N2O	5.53E+02	37%	37%	35%
NO_x	kg NOx	1.79E+06	-98%	-98%	-98%
PM	kg PM	5.09E+04	-24%	-26%	-27%
SO_x	kg SOx	1.84E+05	-68%	-69%	-69%

Green represents impact reductions not affecting which of the diesel and battery electric cases that performs better, and orange represents increases not affecting which of the cases that performs better.

Table 6.4: Total impact reductions for the secondary material input sensitivity cases relative to total impacts of the diesel electric case

		Base cases		
Indicator	Unit	Diesel electric	Battery electric	Secondary materials
ALOP	m2a	8.12E+05	-37%	-37%
GWP	kg CO2 eq	1.52E+08	-89%	-89%
FDP	kg oil eq	5.16E+07	-91%	-91%
FETP	kg 1,4-DB eq	4.74E+05	62%	61%
FEP	kg P eq	9.68E+03	43%	41%
HTP	kg 1,4-DB eq	1.43E+07	50%	49%
IRP	kg U235 eq	1.06E+07	-54%	-54%
METP	kg 1,4-DB eq	4.35E+05	66%	65%
MEP	kg N eq	7.33E+04	-91%	-93%
MDP	kg Fe eq	5.29E+06	40%	34%
LTP	m2	5.16E+04	-93%	-93%
ODP	kg CFC-11 eq	2.75E+01	-94%	-94%
PMFP	kg PM10 eq	4.66E+05	-91%	-92%
POFP	kg NMVOC	1.87E+06	-97%	-97%
TAP	kg SO2 eq	1.19E+06	-93%	-93%
TETP	kg 1,4-DB eq	1.16E+04	-82%	-82%
ULOP	m2a	4.04E+05	-53%	-53%
WDP	m3	1.12E+06	37%	36%
CO_2	kg CO2	1.50E+08	-89%	-89%
CH_4	kg CH4	9.96E+04	-36%	-36%
N_2O	kg N2O	5.53E+02	37%	37%
NO_x	kg NOx	1.79E+06	-98%	-98%
PM	kg PM	5.09E+04	-24%	-25%
SO_x	kg SOx	1.84E+05	-68%	-68%

Green represents impact reductions not affecting which of the diesel and battery electric cases that performs better.

Future scenario

From Table 6.5 on the following page it is evident that the future battery production scenario leads to an improved battery production environmental performance for most indicators except IRP. Though, the increase of IRP impacts from battery production is not the main reason for the battery electric ferry performing worse than the diesel electric ferry in terms of IRP in the future European scenario, as observed in Table 6.6 following Table 6.5. The future European electricity mix used for operation is the reason for this, as established in the sensitivity analysis of electricity mixes. When considering only the battery production and not the full life cycle of the battery electric ferry and focusing on the indicators significant for the battery cell production and the battery packaging, FEP, ULOP and WDP are reduced with more than 15% in the future European battery production, CH_4 and NO_x with more than 20%, GWP, FDP and CO_2 with more than 30%, and MEP with 41%. All other impacts are also reduced, except IRP which increases with 116% and ODP. The other reductions are also significant, all between 11% and

36%, except ALOP and N_2O.

Table 6.5: Battery production impact reductions for the future scenario sensitivity case relative to the battery production impacts for the base case

Indicator	Unit	Base case	Future production
ALOP	m2a	6.59E+04	-3%
GWP	kg CO2 eq	2.30E+06	-33%
FDP	kg oil eq	6.09E+05	-31%
FETP	kg 1,4-DB eq	1.61E+05	-11%
FEP	kg P eq	4.65E+03	-17%
HTP	kg 1,4-DB eq	7.89E+06	-17%
IRP	kg U235 eq	1.96E+05	116%
METP	kg 1,4-DB eq	1.58E+05	-12%
MEP	kg N eq	2.86E+03	-41%
MDP	kg Fe eq	1.90E+06	-26%
LTP	m2	2.86E+02	-23%
ODP	kg CFC-11 eq	1.23E-01	3%
PMFP	kg PM10 eq	9.33E+03	-30%
POFP	kg NMVOC	9.36E+03	-25%
TAP	kg SO2 eq	2.44E+04	-24%
TETP	kg 1,4-DB eq	3.53E+02	-13%
ULOP	m2a	4.06E+04	-18%
WDP	m3	1.62E+05	-15%
CO_2	kg CO2	2.05E+06	-32%
CH_4	kg CH4	7.89E+03	-24%
N_2O	kg N2O	2.34E+02	-5%
NO_x	kg NOx	5.71E+03	-28%
PM	kg PM	6.26E+03	-36%
SO_x	kg SOx	2.05E+04	-23%

Green represents impact reductions not affecting which of the diesel and battery electric cases that performs better, and orange represents increases not affecting which of the cases that performs better.

Table 6.6: Total impact reductions for the future scenario sensitivity case relative to total impacts of the current diesel electric case

		Base cases			
Indicator	Unit	Diesel electric	Battery electric	Future operation	Future scenario
ALOP	m2a	8.12E+05	-37%	89%	89%
GWP	kg CO2 eq	1.52E+08	-89%	-51%	-51%
FDP	kg oil eq	5.16E+07	-91%	-62%	-63%
FETP	kg 1,4-DB eq	4.74E+05	62%	235%	231%
FEP	kg P eq	9.68E+03	43%	208%	200%
HTP	kg 1,4-DB eq	1.43E+07	50%	143%	134%
IRP	kg U235 eq	1.06E+07	-54%	507%	509%
METP	kg 1,4-DB eq	4.35E+05	66%	237%	233%
MEP	kg N eq	7.33E+04	-91%	-78%	-79%
MDP	kg Fe eq	5.29E+06	40%	61%	52%
LTP	m2	5.16E+04	-93%	-88%	-88%
ODP	kg CFC-11 eq	2.75E+01	-94%	-63%	-63%
PMFP	kg PM10 eq	4.66E+05	-91%	-82%	-83%
POFP	kg NMVOC	1.87E+06	-97%	-93%	-93%
TAP	kg SO2 eq	1.19E+06	-93%	-82%	-82%
TETP	kg 1,4-DB eq	1.16E+04	-82%	-40%	-40%
ULOP	m2a	4.04E+05	-53%	32%	30%
WDP	m3	1.12E+06	37%	771%	769%
CO_2	kg CO2	1.50E+08	-89%	-48%	-49%
CH_4	kg CH4	9.96E+04	-36%	246%	244%
N_2O	kg N2O	5.53E+02	37%	459%	457%
NO_x	kg NOx	1.79E+06	-98%	-95%	-95%
PM	kg PM	5.09E+04	-24%	68%	64%
SO_x	kg SOx	1.84E+05	-68%	-16%	-18%

Orange represents increases not affecting which of the cases that performs better, and red represents increases affecting which of the cases that performs better.

Moving the cell production from Taiwan to Germany significantly reduces transport impacts as in the sensitivity case considering cell production location. Among the other battery parts, impact reductions are generally largest for the control system, the cooling system, the battery cell and the battery pack frame. The impacts reduction for the battery cell are due to the use of European electricity instead of Taiwanese during cell production, while impact reductions for the other battery parts are due to the use of secondary material. All these battery parts contribute to GWP, FDP, MEP, ULOP, FEP, CO_2, CH_4, WDP and NO_x reductions. IRP increases are mainly caused by the European electricity mix. The European electricity mix also contribute with increases of FETP, METP, MDP and ODP, but these are outweighed by the impact reductions due to the use of secondary material input. Other impacts are mostly reduced for all battery parts, or only marginally increased.

When comparing the future scenario including both future operation and future battery production to the scenario with current production and future operation, it is evident that the future European battery production impact reductions have an influence on the total life cycle impacts of the battery electric ferry. Even though the life cycle impacts of the future scenario are worse than the base case for all indicators, the future scenario battery electric ferry performs better than the diesel electric ferry in terms of GWP, FDP, MEP, LTP, ODP, PMFP, POFP, TAP, TETP, CO_2, NO_x and SO_x.

6.6 Results bench-marking

Faessler and Einberger (2017), Nordtveit (2017), Mihaylov (2014) and Kullmann (2016) are used for results bench-marking as these are the studies from Chapter 1 most similar to the current study and with comparable results. Nordtveit (2017) considered both an electric case with and without batteries on land, and only the one including batteries on land is included in this results bench-marking as this is the most similar one to the case in this analysis. GWP is in focus. Because the studies vary regarding the vessels assessed, functional units and other parameters, the differences in GWP impacts between the diesel electric and battery electric cases within each study are calculated and compared in terms of the percentage of change from diesel electric to battery electric. Regarding the reduction in total GWP impacts, this analysis falls in between the other studies in magnitude, as shown in Figure 6.13 on the following page. Construction impacts are bench-marked using Faessler and Einberger (2017) and operational impacts using Faessler and Einberger (2017) and Nordtveit (2017) as these are found to be the most easily comparable studies in such terms. The increase in construction impacts of this study is significantly higher than the one in Faessler and Einberger (2017). It can be observed that this analysis found the smallest reduction in GWP operational impacts, although all three studies obtained values around 90%. This analysis is closer to Nordtveit (2017) than Faessler and Einberger (2017) in terms of operational impacts.

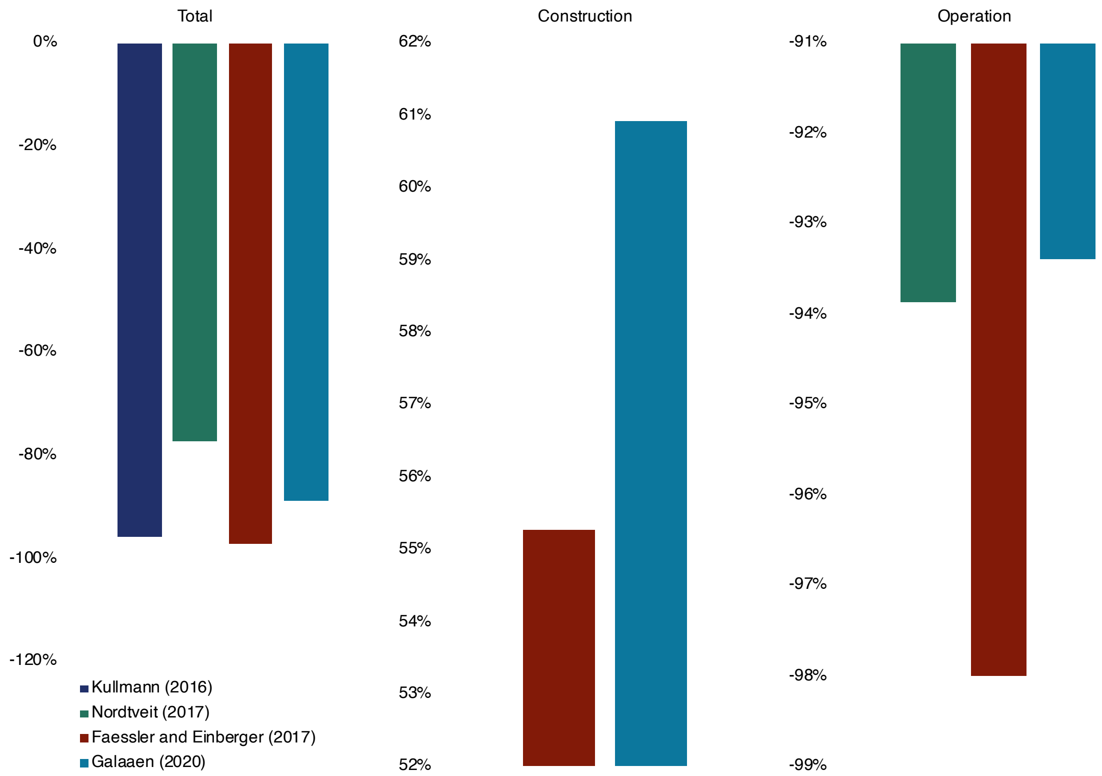


Figure 6.13: Results bench-marking in terms of total, construction and operational impacts

It can be observed from Table 6.7 on the following page that the studies mostly agree regarding which of the diesel electric and battery electric ferry that performs better for the various indicators, but there is some deviance.

Table 6.7: Results bench-marking for midpoint indicators

Indicator	Galaaen (2020)	Faessler and Einberger (2017)	Nordtveit (2017)	Mihaylov (2014)	Kullmann (2016)
ALOP	B	D	B		D
GWP	B	B	B	B	B
FDP	B	B	B	B	B
FETP	D	B	D	B	D
FEP	D	B	D	D	D
HTP	D	B	D	D	D
IRP	B	B	B		D
METP	D	B	D	D	D
MEP	B	B	B	B	B
MDP	D	B	D	D	D
LTP	B	B	B		B
ODP	B	B	B	B	B
PMFP	B	B	B	B	B
POFP	B	B	B	B	B
TAP	B	B	B	B	B
TETP	B	B	D	B	B
ULOP	B	B	D		B
WDP	D	D	D		D

B = the battery electric ferry performs better, D = the diesel electric ferry performs better.

The results from this analysis generally indicate that the battery electric ferry has lower impacts for all indicators except certain toxicity, eutrophication and depletion categories. The impacts that are higher in the battery electric case are caused by both additional construction and operational electricity consumption; the operational phase contributes to impact increases in terms of FETP, METP and WDP, while other increases are mainly caused by production of additional components. The results are remarkably sensitive to the electricity mix used for operation, and moving the cell production to Europe or using secondary material inputs in the battery production are found to potentially improve the environmental performance of the battery electric ferry. Removing the shore power hardly affects the total results for the battery electric ferry. These results are discussed and put into a wider context in the following chapter, together with discussions of strengths and weaknesses of the analysis as well as suggestions for further research.

Chapter 7

Discussion

A comparative LCA of a diesel electric and a battery electric ferry was conducted based on real construction, operational and weather data. The results indicate that the battery electric ferry is advantageous compared to the diesel electric ferry for the majority of indicators including global warming and GHG emissions, but disadvantageous in terms of freshwater ecotoxicity and eutrophication, human toxicity, marine ecotoxicity, mineral and water depletion and N_2O emissions. Avoided operational impacts from diesel production and combustion is the main reason for impact reductions in the battery electric case, while both the additional construction and electricity production in the operational phase contribute to higher impacts for the indicators mentioned. Additional construction impacts in the battery electric case mainly originate from metals production, particularly copper, and a large share of impacts is related to the battery production. The sensitivity analysis illustrates that results are sensitive to the operational electricity mix, but that realistic variances in electrical components losses and removing the shore power does not affect main conclusions. Moving the battery cell production to Europe or Norway and using secondary materials inputs generally improve the environmental performance of the battery electric ferry. The sensitivity analysis also indicates that a possible future scenario may have lower battery production impacts and an improved environmental performance for certain indicators. The modelling and inventory of the LCA were described in Chapters 3, 4 and 5, and the related strengths and weaknesses are discussed in the first section of this chapter. Following the strengths and weaknesses is a discussion of the study in context with other literature introduced in Chapter 1 based on the results bench-marking presented in Chapter 6. Finally, the implications of the analysis is discussed towards the end of this chapter, and suggestions for further research are presented. The discussion in this chapter is intended to contribute to the robustness of the study and its interpretation in a wider context.

7.1 Strengths, weaknesses and limitations

This LCA analysis both has strengths that contribute to its robustness and weaknesses that create uncertainty in the results. The strengths and weaknesses are in general related to the modelling choices and data quality of the analysis, and both the modelling of the construction and end of life phase based on primary data and to the MariTEAM simulation and modelling of the operational phase. Some strengths and weaknesses are also generic for the entire analysis. First, the generic strengths and weaknesses affecting the entire analysis are considered, before the construction and end of life phases are discussed, and finally the MariTEAM simulation and operational phase are assessed.

A strength of this analysis compared to other similar studies is that the whole life cycle of the ferry is included; both the construction phase, the operational phase and the end of life phase were modelled and assessed. In other similar studies, the end of life phase has often been excluded and some studies included few components in the construction phase. Inclusion of all three phases contributes to creating a more comprehensive picture and limits the risk of burden shifting. Though, maintenance and end of life treatment could have been modelled more thoroughly to create a more robust analysis, which is further discussed below.

As described in Chapter 2, the modelling choices made by the LCA practitioner to some degree affect the results of the analysis. This issue of subjectivity is central in LCA as modelling choices are dependent on the values, opinions and preferences of the practitioner and thus vary between practitioners. Subjectivity has in this analysis to some degree been dealt with through the sensitivity analysis by investigating changes in results following changes in modelling decisions that could have been made differently. The sensitivity analysis indicates that the debatable modelling decisions made did not affect the results drastically.

In LCA, data are preferably supposed to be reliable, relevant and accessible, as described in Chapter 2. The data provided by the supplier are specific for the case studied and generally well documented, supporting reliability and relevance especially in terms of time and geography. Also the battery data contribute to reliability and relevance as they have a fairly high resolution and are of recent date and valid for the specific case. The level of detail could have been higher in order to increase reliability and relevance. Confidential data reduce the accessibility of the data used in this analysis. Secondary data used are generally relevant, accessible and reliable, and support reproducibility and credibility.

Arda, the software used in this analysis, uses the Ecoinvent 3.2 database. This version of the Ecoinvent database is from 2015 and may be partially outdated. Especially electricity mixes, which were modelled using the database for the construction and end of life phases, have probably changed the last five years. The modelling may thus not be entirely representative of the current situation.

The components included in the inventory were defined based on literature, opinions of the ferry owner, the shipyard and the supplier and the visit taken to the ferry. Still, it is possible that ferry components excluded could have had a considerable impact on the results. At the same time, in an LCA considering a system with such a large number of components, certain elements eventually need to be excluded. It is assumed that the most central components were covered in the analysis.

The analysis is limited by the geographical context of Norway and the time period considered. The specific results of this LCA are not directly applicable to any ferry in the world, because processes like operational electricity, transport distances and ferry assembly were based on Norwegian conditions. Also, the analysis did not assess possible future changes in terms of e.g. battery technology or electricity mix. Battery technology is likely to be further developed in the following years possibly reducing operational losses, improving the production process and extending the lifetime. The electricity mix will probably move towards a more renewable energy based mix, lowering the environmental impacts of electricity consumed in the ferry system. Also, the European grid may become more interconnected, which may affect the electricity consumption mix of each country. The electricity aspects were to some degree assessed by considering a Norwegian mix with imports from the generic European mix in the base case and a future European mix in the sensitivity analysis, but only static electricity mixes were applied. The electricity mix change with time and this dynamic aspect was not accounted for in the analysis.

Impacts were only evaluated at the midpoint level, not the endpoint level. This choice was made because evaluations at the midpoint level often are less uncertain than the ones at the endpoint level, and because the midpoint level is more representative for the objective of the study. As a result of this choice, no quantitative results were obtained for damage to human health, ecosystems and resources.

One can argue that there is inconsistency in the analysis due to the minor differences in the battery inventory modelling and the remaining ferry inventory modelling. The two approaches used different sources for transport distances, and the battery inventory used transforming Ecoinvent 3.2 processes and average European transport distances while the remaining ferry inventory used market processes and specific transport distances where production location is known. Further, the transport of a component was allocated to the component it was part of in the battery inventory, while it was allocated to itself in the remaining inventory. Also, the use of metal working processes was only present in the remaining ferry inventory. Still, these differences are assumed to make a negligible impact on the final results.

The data affect the fairness of the comparison of the diesel electric and the battery electric ferries. The diesel electric case is only a model, while the battery electric case is a representation of the actual ferry. A model is more uncertain than case-specific values. Also, this thesis was conducted in cooperation with the supplier for the ferry, meaning that the level of detail regarding the batteries and other electric equipment was quite high, and in general higher than the level of detail regarding elements not delivered by the supplier. These aspects may imply that either the battery electric ferry obtain higher impacts due to more components included, or that the diesel electric ferry obtain inaccurate impacts due to incorrect modelling, and thus that the comparison may be slightly unfair. It is hard to know when a completely fair level of comparison is reached in a comparative LCA, and there will often be some degree of unfairness.

7.1.1 Construction and end of life phase

A strength of this analysis is the detailed inventory modelling. Most major ferry components were included based on primary data from the ferry owner, the shipyard and the supplier, resulting in a robust and representative model. Both materials, manufacturing waste, electricity and heat consumption, metal working and transport were included in the construction phase. The inclusion of a large number of components, particularly for the battery electric case, contributes to the robustness of the results and limits the risk of drawing inaccurate conclusions because of ignored stressors and impacts. Assumptions and approximations were though needed where data were missing.

The battery production modelling is also a strength of this analysis, as it represents a battery not earlier modelled based on primary data from the producer. This contributes to broadening the current literature and understanding other cases than the ones previously studied.

No case-specific data were obtained regarding energy consumption during production of the various components in the product system. Components modelled based on EPDs included the energy consumption used in the EPDs. For other components, metal working processes were used to model the manufacturing, as described in Chapter 5. This difference in manufacturing modelling may have created inconsistencies in the study. The metal working processes include more processes than energy consumption as described in Chapter 5, which may have implied higher impacts for processes modelled with metal working processes than for those modelled with energy consumption from EPDs. On the other hand, the metal working processes only consider the metal part of a product and not other materials like paint and plastic. This may have resulted in underestimations for the processes modelled with metal working processes for manufacturing as only the manufacturing of metals was accounted for. Overall, these differences may outweigh each other.

The details of the hull production in Gdansk were outside the knowledge of the contacted instances, and no data for the production in Gdansk were obtained. The modelling of the hull production using metal working processes may not be representative for the actual hull production, and may possibly have created unrealistic low impacts.

The data from the supplier concerning electrical components provide total weights of each component but do not include the material composition of the components or the energy consumption and waste production during manufacturing. Therefore, EPDs and PEPs were needed, and several limitations are related to their use. The EPDs and PEPs used were created by other manufacturers, which may have created inaccuracies as technologies vary between manufacturers. The material compositions from the EPDs and PEPs were somewhat adjusted to fit the actual components, but still the major share of the materials was only based on the EPDs or PEPs and not real data. Also, these EPDs and PEPs made assumptions and simplifications, and these were thus also affecting the results of this analysis. There is also a chance that the EPDs or PEPs may have been interpreted in the wrong way. In some cases, a PEP or EPD was used even though the specifications of the components were outside of the ranges defined in the PEP or EPD because no better data source was identified, thus the PEP or EPD may not have been fully representative of the component.

Another inconsistency between the components is the inclusion of manufacturing waste. Manufacturing waste was included for the components modelled with EPDs but not for the others as no data were obtained. However, the manufacturing waste did not have a significant impact on the total results.

The electric motors in the ventilation system were scaled from the EPD values based on power, which is inconsistent with the other components that were scaled based on weight. Scaling is somewhat imprecise and may create errors regardless of which method is used. Another inconsistency of the ventilation modelling is that the component processes were based on units and power instead of weight and therefore did not match the actual weight of the ventilation system, while the transport of the ventilation system applied the actual weight of the ventilation system calculated from the data sheet.

The lifetime of the engine and other components assumed to be equal to the ferry lifetime may actually be shorter in real life, or the components may need overhauling, which would have created higher environmental impacts for these components. The shore connection box was excluded from the diesel electric inventory, but is in retroperspective recognised to possibly be part of the diesel electric ferry after all. This inconsistency did not affect the results significantly as the shore connection box is not found to create significant impacts in the battery electric case. The transport of the ferry components was modelled using the sum of the distance from the production location to the shipyard and the distance from the shipyard to the shore. Though, the replacement components may not actually be transported the same distance as the original components.

The lifetime of the battery factory was set equal to 5 years, while the ferry and shore batteries need to be replaced after 10 and 20 years. With this model, the battery factory will not still be in operation when the replacement batteries are needed. The additional steel and cables included in the update of the battery inventory was added to the battery pack frame in the model, while in the real battery some of this may actually belong the control system instead.

The end of life phase was modelled in a simplified way, which may have produced inconsistencies and under- or over-estimations. The choice of modelling the end of life as taking place in Norway due to circular economy aspects may seem unrealistic and too little environmentally intensive, as currently these processes often take place in other parts of the world. Operation and end of life treatment in another country could increase environmental impacts. At the same time, the ferry being sold to and further used in another country implies an extended lifetime and reduced construction and end of life impacts normalised on the ferry lifetime. This could have positive effects on the overall environmental impact of the ferry and could to some extent compensate for increased emissions, supporting an environmentally lighter end of life modelling. Also, as described in Chapter 5, the cut-off system model in Ecoinvent 3.2 was used for the inventory modelling. As this system model does not include any impacts or benefits from recycling of materials at end of life, but covers waste treatment processes, and many of the components part of the ferry are recyclable, impacts could have been lower if another system model was used. Still, a deviance from the cut-off system model is the inclusion of battery transport, which according to the system model should have been cut off. The reason for including the transport was that extended producer responsibility was considered, and that the remaining part of the end of life may have been underestimated due to the exclusion of waste treatment of battery parts not being recycled, and only process-specific burdens being included for disposal and not specific waste treatment processes. Also, the article used to model dismantling in end of life may have errors and inaccuracies may occur when applying the values to this analysis. Whether these aspects of the end of life modelling result in over- or under-estimation is uncertain, but it is essential to be aware of them. End of life results are limited and do not fully represent the environmental impacts related to end of life treatment of ferries and required infrastructure. They were intended to only contribute to the entirety of the analysis.

7.1.2 MariTEAM simulation and operational phase

Using the MariTEAM model is a strength of this analysis. The model is able to simulate different vessel types and is found to predict the ferry power profile well even though it is not designed for simulating electric ferries. It can thus also be used for simulating the power profile for other electric ferries than the one analysed in this thesis. Also, the weather aspect is advantageous and something not all simulating tools include, as discussed in Chapter 1. As climate change becomes more evident in the future, models predicting energy consumption due to weather are increasingly valuable. More complex models than the ones used for simulating car operation are needed for maritime transport as vessels are more affected by weather than cars and the operational profile is more unpredictable.

Despite the advantages of using the MariTEAM model, there are several weaknesses related to the operational simulation. First of all, the ferry operation was only simulated for a two week period, and the output was scaled linearly in order to represent the full lifetime of the ferry. This means that yearly variances in weather were not accounted for, probably creating inconsistency compared to the actual ferry operation. For instance, the weather may be more extreme and operational conditions harder during the winter than during the summer. With this ferry operation being modelled in February, the yearly power demand may have been higher than what it would have been if the ferry was simulated throughout a year, also including the calmer summer time period. At the same time, the ferry is operating set routes inside a fjord, which limits the weather effects compared to open water. Another weakness of the operational modelling is that the original code and the Hollenbach method for power calculations are created for diesel direct ships and not particularly diesel electric and battery electric ferries. The calculation of the propeller diameter is based on the main engine of a ship, and may not be representative for electric ferries. The main engine and electric motor rated powers were set equal to the sum of the rated power of the 4 diesel engines and 2 electric motors respectively, while the use of multiple engines and motors instead of a single one may actually affect the power profile of the vessel. Also, more pre-processing and signal processing of the operational data could have improved the robustness of the simulation. The rate of hybridisation used was only obtained on a weekly basis, but applied on an hourly basis, which creates inconsistency. One last limitation to be mentioned for the operational simulation is the use of the same DWT and LDT for the battery electric and diesel electric ferries even though they probably not have the exact same weight. The simplification of using the same weight parameters was considered to be the best option as no data regarding the weight of the diesel electric ferry exist, and because the majority of the weight is the ferry structure which is equal for the two cases.

The case ferry is a hybrid ferry consuming both electricity and diesel for propulsion. The parties involved with the ferry have various opinions regarding whether the real ferry is actually able to operate fully battery electric or not. Certain parties believe that extended charging time periods, higher charging speed or more batteries on land would be necessary for obtaining fully electric operation (PC). On the other hand, other parties mean that the ferry with no problem can operate using only batteries and no diesel, and the ferry had been operating using only electricity for propulsion the days before the visit to the ferry was conducted.

The efficiencies used for electrical components in the calculations of losses during operation may be imprecise, as they were averages across different power factors and loads. This may have created errors as the actual operation may not be evenly distributed across loads and power factors. Exact losses are hard to obtain as they vary with the operation. The losses for some of the components may be too high, but at the same time some losses may have been ignored, so it may balance out overall. The sensitivity analysis highlights aspects of variances in losses.

Regarding the separately modelled Norwegian electricity mix, it should be mentioned that the exact sources of electricity consumed were hard to obtain due to the interlinked European electricity market. The size of imports and exports and the countries the electricity is imported from vary with time based on economics and demand, as explained in Chapter 5. The modelling was a simplification of this system based on assumptions and may therefore also be somewhat inaccurate. Still, the sensitivity analysis indicate that the Norwegian consumption mix modelled in this analysis is similar to the two other Norwegian consumption mixes assessed, implying that it was a fair estimate.

7.2 Context with other literature

After having discussed the strengths and weaknesses of this analysis isolated, the thesis is now put into context with other literature on the topic. The comparison is based on the results bench-marking from Chapter 6.

As described in Chapter 6, this thesis and the four other studies assessed in the results bench-marking found that the battery electric ferry is advantageous in terms of global warming, fossil and ozone depletion, marine eutrophication, particulate matter and photochemical oxidant formation and acidification. Agricultural land occupation is found to have less impacts for the battery electric ferry in this thesis and Nordtveit (2017), while less impacts for the diesel electric ferry by Faessler and Einberger (2017) and Kullmann (2016). Regarding freshwater ecotoxicity, this thesis agrees with Nordtveit (2017) and Kullmann (2016) that the diesel electric ferry is advantageous, while Faessler and Einberger (2017) and Mihaylov (2014) argued the opposite. In terms of freshwater eutrophication, human toxicity, marine ecotoxicity and mineral depletion, this thesis, Nordtveit (2017), Mihaylov (2014) and Kullmann (2016) all found the diesel electric ferry to be desirable, while only Faessler and Einberger (2017) argued for the battery electric ferry. This may imply that Faessler and Einberger (2017) to some extent underestimated the environmental burden of the battery electric ferry. For ionising radiation, only Kullmann (2016) disagrees with this thesis in that the impacts are lowest for the battery electric ferry. All the studies in the results bench-marking except Nordtveit (2017) identified the battery electric ferry as advantageous in terms of terrestrial ecotoxicity. This thesis, Faessler and Einberger (2017) and Kullmann (2016) found lower urban land occupation impacts for the battery electric ferry, while Nordtveit (2017) found the opposite. This thesis agrees with Faessler and Einberger (2017), Nordtveit (2017) and Kullmann (2016) that the battery electric ferry performs better in terms of land transformation and that the diesel electric ferry performs better in terms of water depletion. Thus, the most uncertain midpoint indicators seem to be agricultural land occupation and freshwater ecotoxicity, but also freshwater eutrophication, human toxicity, ionising radiation, marine and terrestrial ecotoxicity, mineral depletion and urban land occupation are inconsistent in current literature. For all indicators, there is at least one other study supporting the findings in this analysis.

The reason for higher construction impacts in this analysis compared to Faessler and Einberger (2017) is probably the higher level of detail and larger amount of components included. For instance, this thesis included batteries on land, while Faessler and Einberger (2017) did not. Also, the ferries are of different sizes and characters, which creates differences when comparing based on the ferry lifetime. The battery production results are similar to the highlights from the state of the art for LCA of battery production for electric transport, with the electricity consumption during cell production, the anode and the cathode creating significant impacts.

The reason for lower operational impacts reductions in this analysis compared to Nordtveit (2017) and Faessler and Einberger (2017) may be that the electricity mix in this analysis included imports from the generic European mix and not only Norwegian production, which generally is less impact intensive. Also, the advanced simulation used in this analysis may have created a more realistic picture of the actual operation and thus obtain these results.

This analysis included the end of life phase, which only Mihaylov (2014) did among the other studies considered in this comparison. Although the end of life phase was modelled in a simplified way, its inclusion is a valuable contribution and extension of the current literature. A detailed comparison with Mihaylov (2014) is though not performed due to the limitations.

7.3 Implications

The results from this thesis have implications both for LCA practitioners, technology design and electrification ferries. These implications are discussed in the following paragraphs.

7.3.1 Implications for LCA practitioners

Aspects regarding data are central in this analysis. This analysis contributes with a qualitative description of the end of life treatment of the batteries, but enough qualitative data for a thorough modelling were missing. LCA practitioners should seek to acquire such information to be able to create more complete LCA models of electric ferries. The Ecoinvent database should also be continuously improved to cover more geographies and processes.

This analysis indicates that the operational simulation and the batteries are of high importance when comparing diesel electric and battery electric ferries. These parts of the model should therefore be in focus for LCA practitioners conducting similar studies in the future.

The work performed in this thesis was based on engineering principles and a thorough operational simulation, contributing to the robustness of the analysis. It is advantageous to incorporate more information regarding the technology and physical phenomena in this way to create strong LCA analysis, and LCA practitioners should generally aim to base their analyses on engineering.

7.3.2 Implications for technology design

For reducing impacts for both ferry cases, the weight of the structure and thrusters can be minimised or the materials changed as these obtain high impacts due to their large weights. Cable and control system production processes can be improved as these are found to create high impacts normalised on weight. The diesel consumption at the shipyard can also be minimised and replaced with electricity consumption where possible.

As the battery electric ferry obtains higher construction impacts than the diesel electric ferry due to the propulsion and shore systems, technology improvements can be examined for reducing such impacts. The sensitivity analysis indicates that moving the battery cell production to Europe, and preferably Norway, may reduce life cycle impacts for the battery electric ferry due to avoided transport and consumption of cleaner electricity. Using secondary material inputs results in improved environmental performance for the battery electric ferry for all indicators assessed due to the avoided production of primary material. These measures may be implemented in the battery production process for further reducing environmental impacts for the battery electric ferry.

In addition to the approaches for improving the battery production process, the production of transformers creating significant land and ionising radiation impacts can be moved to another location with an electricity mix less based on forestry and nuclear energy. The production of the charge towers can be moved closer to the port so that the transport impacts are limited. A reduction of the charge tower weight may also improve the environmental performance. As copper is a generally impacting material contributing to a large share of impact increases in the battery electric case, replacing it with another material may be a possible improvement.

Another possible technology improvement to reduce operational emissions is to obtain lower losses in the electrical components. Though, the sensitivity analysis indicates that the changes caused by variances in losses are minor. Total losses may also be minimised by limiting the number of electrical components the electricity is transmitted through.

Generally, more components leads to higher impacts. Designing systems needing fewer components can possibly improve the environmental performance, as long as it does not result in more intense production and increased production impacts.

Technology producers should continue to develop EPDs of their products, so that technologies from different producers and with various characteristics are represented. As technology evolves, EPDs should be updated to be representative. With relevant, reliable and accessible EPDs of products, more comprehensive and robust LCAs can be performed.

Regarding design of models for simulating operation, it is discovered that the original model designed for international diesel direct ships predict the power consumption of inland electric ferries relatively well, which was not initially expected due to the model being based on diesel direct ships. This finding can be used when creating and improving such models.

7.3.3 Implications for electrification of ferries

Battery electric ferries are increasingly implemented in Norway and other locations, as introduced in Chapter 1. In this section, the results are discussed with focus on what they imply regarding the environmental aspects of full electrification of ferries.

GHG and NO_x emissions, which are central in marine transport, are remarkably reduced for battery electric ferries compared to diesel electric ferries. The battery electric ferry also performs better in terms of global warming, fossil and ozone depletion, particulate matter and photochemical oxidant formation, acidification, ionising radiation, marine eutrophication, land use as well as PM and SO_x emissions. The battery electric ferry can be argued to be the advantageous option as reductions are obtained for more indicators and are generally larger in magnitude than increases, and as global warming and NO_x emissions, which are in focus in this analysis, are minimised.

When implementing battery electric ferries in Norway, it should be kept in mind that impacts related to freshwater ecotoxicity and eutrophication, human toxicity, marine ecotoxicity, mineral and water depletion as well as N_2O emissions may be larger than for a diesel electric ferry, and that this may adversely affect human health, ecosystems and natural resources. Climate change is found to be significantly reduced when switching diesel electric ferries with battery electric ferries, but if further improvements are desirable there are measures that can be taken. Reduction of carbon-intensity of the electricity mix may further lower global warming impacts, which is a reasonable objective as the society moves towards a more extended use of renewable energy sources.

The sensitivity analysis indicate that battery electric ferries can be advantageous also in other locations than Norway. For all electricity mixes assessed, the battery electric ferry performs better than the diesel electric ferry regarding global warming, fossil and ozone depletion, marine eutrophication, land transformation, particulate matter and photochemical oxidant formation, acidification and terrestrial ecotoxicity as well as CO_2 and NO_x emissions. With a focus on reducing climate change and NO_x emissions, implementing battery electric ferries instead of diesel electric ferries can therefore be argued to be a beneficial measure also in other locations with an electricity mix similar to any of the ones assessed in the sensitivity analysis. Though, impacts in other categories are found to increase and for some become higher than for the diesel electric ferry if using European electricity for operation. This should be taken into account if planning to implement battery electric ferries in a location using an electricity mix similar to the European one. Though, the sensitivity analysis indicates that future European battery production may obtain improvements in terms of environmental impacts in most areas compared to the current battery production.

The sensitivity analysis generally indicates that the modelled scenario may be closer to a worst case scenario than a best case scenario, as the other Norwegian electricity mix models perform better in terms of global warming and several other categories, and the alternatives for modelling choices are found to be less impacting in several cases. This may imply that the actual performance of a battery electric ferry compared to a diesel electric ferry is even better in reality than modelled in this analysis. A worst case modelling is advantageous as it creates safety margins and makes the results more robust.

7.4 Further research

Aspects beyond the framework of this thesis interesting for further research are presented in this section, and are related to both the operational simulation and the LCA modelling.

The Python codes designed for data analysis can be further developed in future work. A significant amount of time was spent on developing different solutions during the work with this thesis, and only one ended up being used. Thus, there is a potential for further development of the codes so that they can be used for data analysis. The completed codes may provide a more detailed and robust calibration of the real operational data and the MariTEAM model.

The MariTEAM model was found to perform well for the electric ferries and can be subject for further research, both by the way of improving the model and by the way of using the model for other purposes. The model can be further developed to represent any diesel electric or battery electric vessel, by making the functions that are hard-coded for the specific case in this analysis generic and by making reefer use available also for electric vessels. Further, the MariTEAM model can be used to simulate other ferry crossings in Norway and potentially analyse the entire ferry fleet. It may also be interesting to investigate how energy consumption in ferries is affected by the changing climate and weather expected in the future as a result of climate change using the MariTEAM model. If operational data are collected for an extended time period it could also be possible to analyse how yearly variances affect the power profile.

Additional cases and more sensitivity analysis may also be beneficial as part of further research. It can be valuable to investigate which average rate of hybridisation is needed to make the battery electric ferry advantageous compared to the diesel electric ferry, to also assess hybrid electric ferries. This can be done by using the construction and end of life inventory for the battery electric ferry and modelling operation with various degrees of hybridisation. Comparing the diesel electric and battery electric ferries to a diesel direct ferry may be interesting to also assess the improvements of electrification with diesel. This can be done using the original MariTEAM model with the ferry specifics and the inventory without the electric equipment used for electric propulsion. Also, investigating how mooring using the diesel engine or the battery instead of the automated vacuum mooring system could affect the environmental impacts of the ferry systems could provide knowledge regarding the benefits of using the automated vacuum mooring system. This can be done by using values from literature regarding the power needed to keep the ferry at berth. Removing or adding more batteries on land could explore the sensitivity of the electric system setup, and is relevant for the instances arguing that the case ferry can not operate fully battery electric with the current setup. Some sensitivity should also be performed regarding the diesel electric case, e.g. varying the characteristics of the diesel value chain or the fuel. To investigate potential mitigation measures, inventories can be created e.g. by replacing copper with another material in the components for which copper impacts are significant, or reducing the weight of the charging towers.

Chapter 8

Conclusion

The objective of this thesis was to conduct a comparative LCA of a diesel electric and a battery electric ferry under real operational and weather conditions. The ferry lifetime was used as the functional unit, the system boundaries were cradle-to-grave, and primary data were obtained from the ferry owner, the shipyard and the supplier of batteries and other electric equipment. Both the ferry and the systems on land were analysed. 18 midpoint indicators and 6 substances were assessed using the LCA software Arda with the ReCiPe impact assessment method and the Ecoinvent 3.2 database. The MariTEAM model was used for simulating the operational phase based on AIS and weather data.

The battery electric ferry is found to perform better than the diesel electric ferry in terms of all indicators except freshwater ecotoxicity and eutrophication, human toxicity, marine ecotoxicity, mineral and water depletion as well as N_2O emissions. Remarkable improvements are identified for global warming, fossil and ozone depletion, marine eutrophication, land transformation, particulate matter and photochemical oxidant formation, terrestrial acidification and NO_x emissions. Lower impacts for the battery electric ferry are mainly a result from using electricity for operation instead of diesel, while higher impacts for the battery electric ferry are a combination of changes in the construction, operation and end of life life cycle phases. The only operational impact increases due to electricity production are freshwater and marine ecotoxicity as well as water depletion. Copper production is a central process for battery electric construction impacts, and the battery is the main component creating environmental burdens. The results are sensitive to the electricity mix used for operation, but the battery electric ferry is advantageous in terms of global warming and several other indicators across all electricity mixes assessed. The sensitivity analysis further highlights moving the battery cell production to Europe or using secondary materials as potential measures for reducing the environmental impacts from the battery production.

Battery electric ferries can be advantageous over diesel electric ferries using various electricity mixes if prioritising climate change and NO_x emissions, but burden shifting across life cycle phases and impact categories may occur when moving from diesel electric to battery electric ferries. The findings are based on primary data and a thorough simulation of the operational phase contributing to their robustness, but are still affected by the assumptions and simplifications of the analysis. The end of life phase was simplified and the study is limited in terms of geography and time. This should be considered if applying the results to other cases than the specific one analysed in this thesis. The results are though in line with current literature and provide extended knowledge. The comparative LCA conducted in this work is a contribution to the understanding of the environmental sustainability of electrification of ferries.

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Appendices

A Python codes

The modified MariTEAM code could not be included due to confidentiality.

A.1 Code for creating operational profile for MariTEAM

Main code

```
# Coded by Julie Sandnes Galaaen - 11.05.20
# Main module: Create operational profile for use in the MariTEAM model based on AIS data

import csv
import pandas as pd
import geopy.distance
import numpy as np
import weatherdata
import math

# Calculate ship bearing at each point:
# Formula based on Igismap
def get_bearing(c1, c2):
    lat1 = c1[0]
    lon1 = c1[1]
    lat2 = c2[0]
    lon2 = c2[1]
    d_lon = lon2 - lon1
    y = math.sin(d_lon) * math.cos(lat2)
    x = math.cos(lat1)*math.sin(lat2) - math.sin(lat1)*math.cos(lat2)*math.cos(d_lon)
    b = np.rad2deg(math.atan2(y, x))
    if b < 0:
        b += 360
    return b

# Remove additional rows for same unixtimestamp:
# Assumed that the last row is the actual value
df_lagatun3 = pd.read_csv('lagatun.csv')
df_lagatun3.drop_duplicates(subset="unixtimestamp", keep='last', inplace=True)
df_lagatun3.to_csv('lagatun2.csv')

# Calculate distances, bearings, ECA, original AIS data, weather data and times:
with open('lagatun2.csv', newline='') as csvfile:
    df_lagatun1 = csv.reader(csvfile, delimiter=',')
    delta_dist_km = [0]
    x = 0
    delta_time_s = [0]
    y = 0
    eca_exists = []
    origin = []
```

```
    bearing = [0]
    beaufort = []
    wind_speed = []
    wind_direction = []
    mean_wave_direction = []
    for row in df_lagatun1:
        if x > 1:
            c2 = (float(row[13]), float(row[14]))
            dist = geopy.distance.geodesic(c1, c2).km # Calculate distance
            delta_dist_km.append(dist)
            be = get_bearing(c1, c2)
            bearing.append(be)
        if x > 0:
            c1 = (float(row[13]), float(row[14]))
            eca_exists.append(1) # Set ECA status
            origin.append(1) # Set AIS status
            # Assign weather data:
            index = abs(weatherdata.weatherdata['unixtimestamp'] - float(row[22])).idxmin()
            beaufort.append(weatherdata.weatherdata['beaufort'][index])
            wind_speed.append(weatherdata.weatherdata['wind_speed'][index])
            wind_direction.append(weatherdata.weatherdata['wind_direction'][index])
            mean_wave_direction.append(weatherdata.weatherdata['mean_wave_direction'][index])
        x = x+1
        if y > 1:
            t2 = float(row[22])
            time = t2 - t1  # Calculate time
            delta_time_s.append(time)
        if y > 0:
            t1 = float(row[22])
        y = y+1

# Add results to dataframe:
df_lagatun3['delta_dist_km'] = delta_dist_km
df_lagatun3['delta_time_s'] = delta_time_s
df_lagatun3['eca_exists'] = eca_exists
df_lagatun3['origin'] = origin
df_lagatun3['bearing'] = bearing
df_lagatun3['wind_speed'] = wind_speed
df_lagatun3['wind_direction'] = wind_direction
df_lagatun3['beaufort'] = beaufort
df_lagatun3['mean_wave_direction'] = mean_wave_direction
df_lagatun3.sort_values(by=['unixtimestamp'], inplace=True)
df_lagatun3.rename(columns={"latitude": "y", "longitude": "x"})
df_lagatun3.to_csv('lagatun3.csv')
```

Code for weather calculations

```
# Coded by Julie Sandnes Galaaen - 11.05.20
# Weather module: Calculate Beaufort based on wind speed using https://snl.no/Beauforts_vindskala

import csv
import pandas as pd

with open('Weatherdata.csv', newline='') as csvfile:
    df = csv.reader(csvfile, delimiter=';', quotechar='|')
    beaufort = []
    x = 0

    # Calculate Beaufort number:
    for row in df:
        if x > 0:
            speed = float(row[4].replace(',', '.'))
```

```
            if speed < 0.3:
                b = 0
                beaufort.append(b)
            elif speed < 1.6:
                b = 1
                beaufort.append(b)
            elif speed < 3.4:
                b = 2
                beaufort.append(b)
            elif speed < 5.5:
                b = 3
                beaufort.append(b)
            elif speed < 8.0:
                b = 4
                beaufort.append(b)
            elif speed < 10.8:
                b = 5
                beaufort.append(b)
            elif speed < 13.9:
                b = 6
                beaufort.append(b)
            elif speed < 17.2:
                b = 7
                beaufort.append(b)
            elif speed < 20.8:
                b = 8
                beaufort.append(b)
            elif speed < 24.5:
                b = 9
                beaufort.append(b)
            elif speed < 28.5:
                b = 10
                beaufort.append(b)
            elif speed < 32.6:
                b = 11
                beaufort.append(b)
            else:
                b = 12
                beaufort.append(b)
        x = x+1

weatherdata = pd.read_csv('Weatherdata.csv', delimiter=';', quotechar='|')
weatherdata['beaufort'] = beaufort #adding list to dataframe
weatherdata.to_csv("WeatherdataModified.csv")
```

A.2 Code for calibration of the modified MariTEAM model

Identification of representative periods

```
# Coded by: Julie Sandnes Galaaen - 08.05.20
# Interpolate Siemens data in order to obtain consistent epochs

import pandas as pd
import numpy as np

# Battery 1, week 1
energy1_1 = pd.read_csv("ESF01_BSC01.Energy-1580622544987-1581201648000.csv", sep=';')
# Remove unnecessary columns:
energy1_1.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
# Remove additional rows for same epoch, only save the last:
energy1_1.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy1_1 = energy1_1.div([1000, 1], axis='columns')  # Convert siemens epochs to actual epochs
```

```
last_epoch_1 = energy1_1.iloc[-1][0]  # Define last epoch of first week

# Battery 1, week 2
energy1_2 = pd.read_csv("ESF01_BSC01.Energy-1581119313000-1581808329794.csv", sep=';')
energy1_2.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
energy1_2.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy1_2 = energy1_2.div([1000, 1], axis='columns')
# Find the index of the first row in second week after last row in first week:
index_1 = energy1_2[energy1_2['Epoch'].gt(last_epoch_1)].index[0]
# Create new dataframe with only the elements to be appended:
appending_1 = energy1_2.iloc[index_1:, ]
energy1 = energy1_1.append(appending_1)  # Append
last_epoch_1 = energy1.iloc[-1][0]  # Update last epoch

# Battery 2, week 1
energy2_1 = pd.read_csv("ESF02_BSC02.Energy-1580622544987-1581201648000.csv", sep=';')
energy2_1.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
energy2_1.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy2_1 = energy2_1.div([1000, 1], axis='columns')
last_epoch_2 = energy2_1.iloc[-1][0]

# Battery 2, week 2
energy2_2 = pd.read_csv("ESF02_BSC02.Energy-1581119313000-1581808329794.csv", sep=';')
energy2_2.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
energy2_2.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy2_2 = energy2_2.div([1000, 1], axis='columns')
index_2 = energy2_2[energy2_2['Epoch'].gt(last_epoch_2)].index[0]
appending_2 = energy2_2.iloc[index_2:, ]
energy2 = energy2_1.append(appending_2)
last_epoch_2 = energy2.iloc[-1][0]

# Battery 3, week 1
energy3_1 = pd.read_csv("ESF03_BSC03.Energy-1580622544987-1581201648000.csv", sep=';')
energy3_1.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
energy3_1.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy3_1 = energy3_1.div([1000, 1], axis='columns')
last_epoch_3 = energy3_1.iloc[-1][0]

# Battery 3, week 2
energy3_2 = pd.read_csv("ESF03_BSC03.Energy-1581119313000-1581808329794.csv", sep=';')
energy3_2.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
energy3_2.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy3_2 = energy3_2.div([1000, 1], axis='columns')
index_3 = energy3_2[energy3_2['Epoch'].gt(last_epoch_3)].index[0]
appending_3 = energy3_2.iloc[index_3:, ]
energy3 = energy3_1.append(appending_3)
last_epoch_3 = energy3.iloc[-1][0]

# Battery 4, week 1
energy4_1 = pd.read_csv("ESF04_BSC04.Energy-1580622544987-1581201648000.csv", sep=';')
energy4_1.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
energy4_1.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy4_1 = energy4_1.div([1000, 1], axis='columns')
last_epoch_4 = energy4_1.iloc[-1][0]

# Battery 4, week 2
energy4_2 = pd.read_csv("ESF04_BSC04.Energy-1581119313000-1581808329794.csv", sep=';')
energy4_2.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
energy4_2.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy4_2 = energy4_2.div([1000, 1], axis='columns')
index_4 = energy4_2[energy4_2['Epoch'].gt(last_epoch_4)].index[0]
appending_4 = energy4_2.iloc[index_4:, ]
```

```
energy4 = energy4_1.append(appending_4)
last_epoch_4 = energy4.iloc[-1][0]

# Define first epochs:
first_epoch_1 = energy1.iloc[0][0]
first_epoch_2 = energy2.iloc[0][0]
first_epoch_3 = energy3.iloc[0][0]
first_epoch_4 = energy4.iloc[0][0]

# Consider all possible epochs for interpolation:
first_epoch_s = min(float(first_epoch_1), float(first_epoch_2), float(first_epoch_3), \
                    float(first_epoch_4))
last_epoch_s = max(float(last_epoch_1), float(last_epoch_2), float(last_epoch_3), \
                    float(last_epoch_4))

# Create list with all epochs between first and last:
epochs = np.arange(first_epoch_s, last_epoch_s)  # create list with all epochs
epochs = pd.DataFrame(epochs, columns=['Epoch'])

# Rename column names to be separatable in total dataframe:
energy1.rename(columns={'Value': 'Value1'}, inplace=True)
energy2.rename(columns={'Value': 'Value2'}, inplace=True)
energy3.rename(columns={'Value': 'Value3'}, inplace=True)
energy4.rename(columns={'Value': 'Value4'}, inplace=True)

# Merge dataframes for each battery into one:
merged1 = pd.merge(left=epochs, right=energy1, how='left', left_on='Epoch', right_on='Epoch')
merged2 = pd.merge(left=merged1, right=energy2, how='left', left_on='Epoch', right_on='Epoch')
merged3 = pd.merge(left=merged2, right=energy3, how='left', left_on='Epoch', right_on='Epoch')
merged4 = pd.merge(left=merged3, right=energy4, how='left', left_on='Epoch', right_on='Epoch')
energy_df_s = merged4

interpolated = energy_df_s.interpolate(method='linear')  # Linear interpolation

# Consider only the epochs for which there are values for all batteries:
first_epoch_s = max(float(first_epoch_1), float(first_epoch_2), float(first_epoch_3), \
                    float(first_epoch_4))
last_epoch_s = min(float(last_epoch_1), float(last_epoch_2), float(last_epoch_3), \
                    float(last_epoch_4))

# Sum all values except epoch into a new column:
interpolated['Sum'] = interpolated.drop('Epoch', axis=1).sum(axis=1)

# Delete epochs that do not have values for all batteries:
interpolated = interpolated[interpolated['Epoch'] <= last_epoch_s]
interpolated = interpolated[interpolated['Epoch'] >= first_epoch_s]

# Calculate power:
P_list = []
E1 = 0
x = 0
for row in interpolated.itertuples():
    if x > 0:
        E2 = float(row[6])  # kWh
        T2 = float(row[1])  # seconds
        P = (E2-E1)*(-1)/((T2-T1)/3600)  # kW
        P_list.append(P)
    E1 = float(row[6])  # kWh
    T1 = float(row[1])  # seconds
    x = x + 1

P_list.append(0)  # The last power is unknown
```

```
interpolated['P'] = P_list
# Remove last row because power is unknown:
interpolated = interpolated.drop(index=interpolated.index[-1])
```

A.3 Codes for treatment of battery data

Cleaning and merging of operational data

This code was also the basis for SoC cleaning, in addition to the general cleaning. For SoC cleaning, a functionality removing values higher than the maximum SoC and lower than the minimum SoC was added in the code.

```
# Coded by: Julie Sandnes Galaaen - 29.04.20
# Clean battery data, merge batteries and prepare for further treatment

import pandas as pd

# Battery 1, week 1
energy1_1 = pd.read_csv("ESF01_BSC01.Energy-1580622544987-1581201648000.csv", sep=';')
# Remove unnecessary columns:
energy1_1.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
# Remove additional rows for same epoch, only save the last:
energy1_1.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy1_1 = energy1_1.div([1000, 1], axis='columns')  # Convert siemens epochs to actual epochs
last_epoch_1 = energy1_1.iloc[-1][0]  # Define last epoch of first week

# Battery 1, week 2
energy1_2 = pd.read_csv("ESF01_BSC01.Energy-1581119313000-1581808329794.csv", sep=';')
energy1_2.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
energy1_2.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy1_2 = energy1_2.div([1000, 1], axis='columns')
# Find the index of the first row in second week after last row in first week:
index_1 = energy1_2[energy1_2['Epoch'].gt(last_epoch_1)].index[0]
# Create new dataframe with only the elements to be appended:
appending_1 = energy1_2.iloc[index_1:, ]
energy1 = energy1_1.append(appending_1)  # Append
last_epoch_1 = energy1.iloc[-1][0]  # Update last epoch

# Battery 2, week 1
energy2_1 = pd.read_csv("ESF02_BSC02.Energy-1580622544987-1581201648000.csv", sep=';')
energy2_1.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
energy2_1.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy2_1 = energy2_1.div([1000, 1], axis='columns')
last_epoch_2 = energy2_1.iloc[-1][0]

# Battery 2, week 2
energy2_2 = pd.read_csv("ESF02_BSC02.Energy-1581119313000-1581808329794.csv", sep=';')
energy2_2.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
energy2_2.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy2_2 = energy2_2.div([1000, 1], axis='columns')
index_2 = energy2_2[energy2_2['Epoch'].gt(last_epoch_2)].index[0]
appending_2 = energy2_2.iloc[index_2:, ]
energy2 = energy2_1.append(appending_2)
last_epoch_2 = energy2.iloc[-1][0]

# Battery 3, week 1
energy3_1 = pd.read_csv("ESF03_BSC03.Energy-1580622544987-1581201648000.csv", sep=';')
energy3_1.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
energy3_1.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy3_1 = energy3_1.div([1000, 1], axis='columns')
last_epoch_3 = energy3_1.iloc[-1][0]
```

```
# Battery 3, week 2
energy3_2 = pd.read_csv("ESF03_BSC03.Energy-1581119313000-1581808329794.csv", sep=';')
energy3_2.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
energy3_2.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy3_2 = energy3_2.div([1000, 1], axis='columns')
index_3 = energy3_2[energy3_2['Epoch'].gt(last_epoch_3)].index[0]
appending_3 = energy3_2.iloc[index_3:, ]
energy3 = energy3_1.append(appending_3)
last_epoch_3 = energy3.iloc[-1][0]

# Battery 4, week 1
energy4_1 = pd.read_csv("ESF04_BSC04.Energy-1580622544987-1581201648000.csv", sep=';')
energy4_1.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
energy4_1.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy4_1 = energy4_1.div([1000, 1], axis='columns')
last_epoch_4 = energy4_1.iloc[-1][0]

# Battery 4, week 2
energy4_2 = pd.read_csv("ESF04_BSC04.Energy-1581119313000-1581808329794.csv", sep=';')
energy4_2.drop(['TagName', 'DateTime', 'Unit', 'Quality'], axis=1, inplace=True)
energy4_2.drop_duplicates(subset="Epoch", keep='last', inplace=True)
energy4_2 = energy4_2.div([1000, 1], axis='columns')
index_4 = energy4_2[energy4_2['Epoch'].gt(last_epoch_4)].index[0]
appending_4 = energy4_2.iloc[index_4:, ]
energy4 = energy4_1.append(appending_4)
last_epoch_4 = energy4.iloc[-1][0]

# Define first epochs:
first_epoch_1 = energy1.iloc[0][0]
first_epoch_2 = energy2.iloc[0][0]
first_epoch_3 = energy3.iloc[0][0]
first_epoch_4 = energy4.iloc[0][0]

# Consider all possible epochs for interpolation:
first_epoch_s = min(float(first_epoch_1), float(first_epoch_2), float(first_epoch_3), \
                    float(first_epoch_4))
last_epoch_s = max(float(last_epoch_1), float(last_epoch_2), float(last_epoch_3), \
                    float(last_epoch_4))

# Make the separate dataframes fit for further work by convertin Epochs:
energy1 = energy1_1.div([1000, 1], axis='columns')
energy2 = energy2_1.div([1000, 1], axis='columns')
energy3 = energy3_1.div([1000, 1], axis='columns')
energy4 = energy4_1.div([1000, 1], axis='columns')
```

Energy calculations for battery data

```
# Coded by: Julie Sandnes Galaaen - 02.05.20
# Treatment for comparison with MariTEAM: \
    calculate total energy over crossings in first and second period (days)

import mergebatteries

first_epoch_1 =  # Defined according to the test cases
last_epoch_1 =  # Defined according to the test cases
first_epoch_2 =  # Defined according to the test cases
last_epoch_2 =  # Defined according to the test cases

energy1 = mergebatteries.energy1
energy2 = mergebatteries.energy2
energy3 = mergebatteries.energy3
energy4 = mergebatteries.energy4
```

```
E1_1 = 0
E1_2 = 0
E1_3 = 0
E1_4 = 0

energysum1 = 0  # Energy sum for first period (calibration)
time1 = last_epoch_1 - first_epoch_1  # seconds
aux_energy_1 = 100*time1/3600  # kWh, constant hotel load of 100 kW

# Sum discharge energy for each battery in first period:
for row in energy1.itertuples():
    if E1_1 > 0 and last_epoch_1 >= row[1] >= first_epoch_1:
        E2_1 = float(row[2])
        dE = E2_1 - E1_1
        if dE < 0:  # Crossing
            energysum1 = energysum1 + dE
    E1_1 = float(row[2])

dE = 0

for row in energy2.itertuples():
    if E1_2 > 0 and last_epoch_1 >= row[1] >= first_epoch_1:
        E2_2 = float(row[2])
        dE = E2_2 - E1_2
        if dE < 0:  # Crossing
            energysum1 = energysum1 + dE
    E1_2 = float(row[2])

dE = 0

for row in energy3.itertuples():
    if E1_3 > 0 and last_epoch_1 >= row[1] >= first_epoch_1:
        E2_3 = float(row[2])
        dE = E2_3 - E1_3
        if dE < 0:  # Crossing
            energysum1 = energysum1 + dE
    E1_3 = float(row[2])

dE = 0

for row in energy4.itertuples():
    if E1_4 > 0 and last_epoch_1 >= row[1] >= first_epoch_1:
        E2_4 = float(row[2])
        dE = E2_4 - E1_4
        if dE < 0:  # Crossing
            energysum1 = energysum1 + dE
    E1_4 = float(row[2])

energysum2 = 0  # Energy sum for second period (testing)
time2 = last_epoch_2 - first_epoch_2  # seconds
aux_energy_2 = 100*time2/3600  # kWh, constant aux load of 100 kW

# Reset:
E1_1 = 0
E2_1 = 0
E1_2 = 0
E2_2 = 0
E1_3 = 0
E2_3 = 0
E1_4 = 0
E2_4 = 0
```

```
dE = 0

# Sum discharge energy for each battery in second period:
for row in energy1.itertuples():
    if E1_1 > 0 and last_epoch_2 >= row[1] >= first_epoch_2:
        E2_1 = float(row[2])
        dE = E2_1 - E1_1
        if dE < 0:  # Crossing
            energysum2 = energysum2 + dE
    E1_1 = float(row[2])

for row in energy2.itertuples():
    if E1_2 > 0 and last_epoch_2 >= row[1] >= first_epoch_2:
        E2_2 = float(row[2])
        dE = E2_2 - E1_2
        if dE < 0:  # Crossing
            energysum2 = energysum2 + dE
    E1_2 = float(row[2])

for row in energy3.itertuples():
    if E1_3 > 0 and last_epoch_2 >= row[1] >= first_epoch_2:
        E2_3 = float(row[2])
        dE = E2_3 - E1_3
        if dE < 0:  # Crossing
            energysum2 = energysum2 + dE
    E1_3 = float(row[2])

for row in energy4.itertuples():
    if E1_4 > 0 and last_epoch_2 >= row[1] >= first_epoch_2:
        E2_4 = float(row[2])
        dE = E2_4 - E1_4
        if dE < 0:  # Crossing
            energysum2 = energysum2 + dE
    E1_4 = float(row[2])

# Rates of hybridisation in first and second period:
r1 =  # Confidential
r2 =  # Confidential

# Final energy sum for first period:
energysum1 = energysum1*0.95  # Losses during battery discharging
energysum1 = energysum1*0.9875  # Losses in BlueDrive switchboard
energysum1 = energysum1*0.97  # Losses in electric motor
energysum1 = energysum1/r1  # Adding energy from diesel
energysum1 = energysum1*(-1)  # Convert from negative to positive
energysum1 = energysum1 - aux_energy_1  # Removing hotel energy from propulsion energy

# Final energy sum for second period:
energysum2 = energysum2*0.95  # Losses during battery discharging
energysum2 = energysum2*0.9875  # Losses in BlueDrive switchboard
energysum2 = energysum2*0.97  # Losses in electric motor
energysum2 = energysum2/r2  # Adding energy from diesel
energysum2 = energysum2*(-1)  # Convert from negative to positive
energysum2 = energysum2 - aux_energy_2  # Removing hotel energy from propulsion energy
```

A.4 Codes for treatment of MariTEAM data

Organisation of MariTEAM data

Two modules for the code for organisation of MariTEAM data were created, one for each period assessed. The modules are identical only importing different MariTEAM files, so only one is presented here.

```
# Coded by: Julie Sandnes Galaaen - 29.04.20
```

```
# Organise MariTEAM output and prepare for energy calculations

import pandas as pd

mariteam = pd.read_csv("ems.csv", sep=',')

# Remove unnecessary columns:
energy_df_m = mariteam.drop(columns=['Unnamed: 0', 'Unnamed: 0.1', 'Unnamed: 0.1.1', 'a', 'b',\
                                    'c', 'callsign', 'cog', 'd', 'dest', 'eta', 'heading',\
                                    'imo', 'draught', 'latitude', 'longitude', 'mmsi', 'name',\
                                    'navstat', 'rot', 'time', 'type', 'delta_dist_km',\
                                    'delta_time_s', 'eca_exists', 'origin', 'bearing',\
                                    'wind_speed', 'wind_direction', 'beaufort',\
                                    'mean_wave_direction', 'froude', 'weather_coeff_perc',\
                                    'sog_old', 'speed_ms'])

energy_df_m = energy_df_m.div([1, 1000, 1, 1, 1])  # Convert power in W to kW
```

Energy calculations for MariTEAM data

```
# Coded by: Julie Sandnes Galaaen - 02.05.20
# Treatment for comparison with Siemens: \
    calculate total energy over crossings in first and second period (days)

import orgmariteam
import orgmariteam2

first_epoch_1 =  # Defined according to the test cases
last_epoch_1 =  # Defined according to the test cases
first_epoch_2 =  # Defined according to the test cases
last_epoch_2 =  # Defined according to the test cases

energy_df_m = orgmariteam.energy_df_m
energy_df_m_2 = orgmariteam2.energy_df_m

energysum1 = 0  # Energy sum for first period (calibration)
energysum2 = 0  # Energy sum for second period (testing)

# Sum discharge energy in first period:
x = 0
for row in energy_df_m.itertuples():
    if last_epoch_1 >= row[1] >= first_epoch_1:
        if x > 0:
            T2 = float(row[1])
            dT_s = T2 - T1
            dT = dT_s/3600  # kWh: T1 and T2 given in seconds
            dE = PME*dT  # kWh
            if dE > 0:  # Crossing
                energysum1 = energysum1 + dE
        PME = float(row[2])
        T1 = float(row[1])
        x = x + 1

# Reset:
dT_s = 0
dT = 0
T1 = 0
T2 = 0
PME = 0
x = 0

# Sum discharge energy in second period:
```

```
for row in energy_df_m_2.itertuples():
    if last_epoch_2 >= row[1] >= first_epoch_2:
        if x > 0:
            T2 = float(row[1])
            dT_s = T2 - T1
            dT = dT_s/3600  # kWh: T1 and T2 given in seconds
            dE = PME*dT  # kWh
            if dE > 0:  # Crossing
                energysum2 = energysum2 + dE
        PME = float(row[2])
        T1 = float(row[1])
        x = x + 1
```

A.5 Codes for analysing MariTEAM output

Battery electric case

```
# Coded by: Julie Sandnes Galaaen - 10.05.20
# Analyse output for battery electric ferry from MariTEAM model to be used in LCA

import pandas as pd

# Import file from MariTEAM:
mariteam = pd.read_csv("mariteambattery1205.csv", sep=',')

# Remove unnecessary columns:
energy_df_m = mariteam.drop(columns=['Unnamed: 0', 'Unnamed: 0.1', 'Unnamed: 0.1.1', 'a', 'b',\
                                    'c', 'callsign', 'cog', 'd', 'dest', 'eta', 'heading',\
                                    'imo', 'draught', 'latitude', 'longitude', 'mmsi', 'name',\
                                    'navstat', 'rot', 'time', 'type', 'delta_dist_km',\
                                    'delta_time_s', 'eca_exists', 'origin', 'bearing',\
                                    'wind_speed', 'wind_direction', 'beaufort',\
                                    'mean_wave_direction', 'froude', 'weather_coeff_perc',\
                                    'sog_old', 'speed_ms'])

# Convert power from W to kW:
energy_df_m = energy_df_m.div([1, 1000, 1, 1, 1])  # Convert power in W to kW

# If a zero period is longer than 10 min it is counted as non-operating hours:
# Total time of period considered in MariTEAM model:
t_tot_orig = energy_df_m.iloc[-1][0] - energy_df_m.iloc[0][0]
t_tot = t_tot_orig
five_min = 5*60  # Charging time
x = 0
zeros_time = 0
for row in energy_df_m.itertuples():
    if x > 0:
        T2 = float(row[1])
        if P < 0.005:  # Normalised power is used to check if the ferry is not moving
            zeros_time = zeros_time + T2-T1  # The time for which the power has been zero
        elif zeros_time > 0:  # The first point of crossing after zero period
            # A period of not moving for more than 10 minutes is assumed to be non-operation:
            if zeros_time > 10*60:
                # Subtract non-operating time and adds charging period:
                t_tot = t_tot - zeros_time + five_min
            zeros_time = 0
    T1 = float(row[1])  # Update for next iteration
    P = float(row[3])
    x = x + 1  # Counting rows

# Calculate operating energy during time period:
x = 0
```

```
energysum = 0
for row in energy_df_m.itertuples():
    if x > 0:  # dE can be calculated
        T2 = float(row[1])
        dT_s = T2 - T1
        dT = dT_s/3600  # kWh: T1 and T2 given in seconds
        dE = PME*dT  # kWh
        if dE > 0:  # Crossing
            energysum = energysum + dE
    PME = float(row[2])  # Update for next iteration
    T1 = float(row[1])  # Update for next iteration
    x = x + 1  # Counting rows

# Calculating hotel energy during time period:
x = 0
hotelsum = 0
T1 = 0
T2 = 0
dT_s = 0
dT = 0
dE = 0
for row in energy_df_m.itertuples():
    if x > 0:  # dE can be calculated
        T2 = float(row[1])
        dT_s = T2 - T1
        dT = dT_s/3600  # kWh: T1 and T2 given in seconds
        dE = PAux*dT  # kWh
        if dE > 0:  # Crossing
            hotelsum = hotelsum + dE
    PAux = float(row[5])  # Update for next iteration
    T1 = float(row[1])  # Update for next iteration
    x = x + 1  # Counting rows

# Totals:
op_h = 7000  # The operating hours for one ferry are 7000 during one year
h_tot = t_tot/3600  # Time period considered, hours
d_tot = h_tot/24  # Time period considered, days
aux_load = 100  # kW
yearly_prop_energy = energysum*(op_h/h_tot)  # Scaling
hot_battery = 100*7000  # Hotel energy covered by battery
hot_shore = 100*1760  # Hotel energy covered by shore power
hot_tot = hot_battery + hot_shore
hotel = hotelsum*(op_h/(t_tot_orig/3600))  # Control of hotel energy from MariTEAM
lifetime_prop_energy = yearly_prop_energy*30*1.230119641  # Factors calculated in Excel
lifetime_hot_energy_shore = hot_shore*30*1.020310557  # Factors calculated in Excel
lifetime_hot_energy_shore_frombattery = hot_shore*30*1.230119641  # Factors calculated in Excel
lifetime_hot_energy_battery = hot_battery*30*1.229785867  # Factors calculated in Excel
lifetime_el_highest_losses = (yearly_prop_energy*1.268240031+hot_shore*1.025483259+ \
    hot_battery*1.27917423)*30  # Factors calculated in Excel
lifetime_el_lowest_losses = (yearly_prop_energy*1.194199431+hot_shore*1.015176895+ \
    hot_battery*1.185022497)*30  # Factors calculated in Excel
```

Diesel electric case

```
# Coded by: Julie Sandnes Galaaen - 10.05.20
# Analyse output from MariTEAM model to be used in LCA

import pandas as pd
import mariteamanalysis_battery

# Import file from MariTEAM:
mariteam = pd.read_csv("mariteamdiesel1205.csv", sep=',')
```

```
# Remove unnecessary columns:
energy_df_m = mariteam.drop(columns=['Unnamed: 0', 'Unnamed: 0.1', 'Unnamed: 0.1.1', 'a', 'b',\
                                     'c', 'callsign', 'cog', 'd', 'dest', 'eta', 'heading',\
                                     'imo', 'draught', 'latitude', 'longitude', 'mmsi', 'name',\
                                     'navstat', 'rot', 'sog', 'time', 'type', 'delta_dist_km',\
                                     'delta_time_s', 'eca_exists', 'origin', 'bearing',\
                                     'wind_speed', 'wind_direction', 'beaufort', \
                                     'mean_wave_direction', 'froude', 'weather_coeff_perc',\
                                     'sog_old', 'speed_ms', 'fuel_op'])

# Convert power from W to kW:
energy_df_m = energy_df_m.div([1, 1000, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, \
                                 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, \
                                 1, 1])

t_tot = mariteamanalysis_battery.t_tot
t_tot_orig = mariteamanalysis_battery.t_tot_orig

# Total fuel consumption and emissions:
FC_sum = energy_df_m['FC'].sum()
CO2_sum = energy_df_m['CO2'].sum()
SOx_sum = energy_df_m['SOx'].sum()
SO2_sum = energy_df_m['SO2'].sum()
SO4_sum = energy_df_m['SO4'].sum()
NOx_sum = energy_df_m['NOx'].sum()
CO_sum = energy_df_m['CO'].sum()
OC_sum = energy_df_m['OC'].sum()
EC_sum = energy_df_m['EC'].sum()
BC_sum = energy_df_m['BC'].sum()

# Fuel consumption without the part of aux load covered by shore power:
non_op_factor = 1 - t_tot/t_tot_orig
FC_sum_aux = energy_df_m['aux_engine_FC_kg'].sum()/1000  # tonnes
aux_FC_factor = FC_sum_aux/FC_sum
FC_sum -= FC_sum*aux_FC_factor*non_op_factor

# CO2 emissions without the part of aux load covered by shore power:
CO2_sum -= CO2_sum*aux_FC_factor*non_op_factor

# SOx emissions without the part of aux load covered by shore power:
SOx_sum -= SOx_sum*aux_FC_factor*non_op_factor

# SO2 emissions without the part of aux load covered by shore power:
SO2_sum -= SO2_sum*aux_FC_factor*non_op_factor

# SO4 emissions without the part of aux load covered by shore power:
SO4_sum -= SO4_sum*aux_FC_factor*non_op_factor

# NOx emissions without the part of aux load covered by shore power:
NOx_sum_aux = energy_df_m['aux_engine_NOx_kg'].sum()/1000  # tonnes
aux_NOx_factor = NOx_sum_aux/NOx_sum
NOx_sum -= NOx_sum*aux_NOx_factor*non_op_factor

# CO emissions without the part of aux load covered by shore power:
CO_sum_aux = energy_df_m['aux_engine_CO_kg'].sum()/1000  # tonnes
aux_CO_factor = CO_sum_aux/CO_sum
CO_sum -= CO_sum*aux_CO_factor*non_op_factor

# OC emissions without the part of aux load covered by shore power:
OC_sum_aux = energy_df_m['aux_engine_OC_kg'].sum()/1000  # tonnes
aux_OC_factor = OC_sum_aux/OC_sum
```

```
OC_sum -= OC_sum*aux_OC_factor*non_op_factor

# EC emissions without the part of aux load covered by shore power:
EC_sum_aux = energy_df_m['aux_engine_EC_kg'].sum()/1000  # tonnes
aux_EC_factor = EC_sum_aux/EC_sum
EC_sum -= EC_sum*aux_EC_factor*non_op_factor

# BC emissions without the part of aux load covered by shore power:
BC_sum_aux = energy_df_m['aux_engine_BC_kg'].sum()/1000  # tonnes
aux_BC_factor = BC_sum_aux/BC_sum
BC_sum -= BC_sum*aux_BC_factor*non_op_factor

# Totals:
op_h = 7000  # The operating hours for one ferry are 7000 during one year
h_tot = t_tot/3600  # Time period considered, hours
d_tot = h_tot/24  # Time period considered, days
aux_load = 100  # kW
FC_yearly = FC_sum*(op_h/h_tot)  # Scaling
CO2_yearly = CO2_sum*(op_h/h_tot)  # Scaling
SOx_yearly = SOx_sum*(op_h/h_tot)  # Scaling
SO2_yearly = SO2_sum*(op_h/h_tot)  # Scaling
SO4_yearly = SO4_sum*(op_h/h_tot)  # Scaling
NOx_yearly = NOx_sum*(op_h/h_tot)  # Scaling
CO_yearly = CO_sum*(op_h/h_tot)  # Scaling
OC_yearly = OC_sum*(op_h/h_tot)  # Scaling
EC_yearly = EC_sum*(op_h/h_tot)  # Scaling
BC_yearly = BC_sum*(op_h/h_tot)  # Scaling
hot_shore = 100*1760  # kWh
lifetime_FC = FC_yearly*30
lifetime_FC_aux = aux_FC_factor*lifetime_FC
lifetime_FC_main = (1-aux_FC_factor)*lifetime_FC
lifetime_CO2 = CO2_yearly*30
lifetime_SOx = SOx_yearly*30
lifetime_SO2 = SO2_yearly*30
lifetime_SO4 = SO4_yearly*30
lifetime_NOx = NOx_yearly*30
lifetime_CO = CO_yearly*30
lifetime_OC = OC_yearly*30
lifetime_EC = EC_yearly*30
lifetime_BC = BC_yearly*30
lifetime_hot_energy_shore = hot_shore*30*1.020310557  # Factors calculated in Excel
```

The full LCI models for the various cases can be found in the attachment to this thesis.

B LCI model

B.1 Supplementary descriptions of LCI modelling

Calculations for overhauling of thruster

The procedure for calculating the thruster lifetime based on overhauling is described in the following paragraphs and calculations. In year 0, the thruster is implemented. After 10 years, 10% of this thruster is replaced. The 10% taken out thus had a lifetime of 10 years. The 10% put in starts at year 0 of its lifetime in year 10. After 20 years, 90% of the thruster has lived for 20 years, while 10% has lived for 10 years. The current thruster has thus lived for 19 years, as calculated in Equation (8.1).

$$\text{Years lived in year } 20 = 0.9 * 20 + 0.1 * 10 = 19 \text{ years} \tag{8.1}$$

In year 20, 10% of the thruster is taken out, and this 10% has a lifetime of 19 years. 10% are put in starting at year 0 of its lifetime in year 20. In year 30, 90% of the current thruster has lived in 29 years as described in Equation (8.2), while 10% of the current thruster has lived in 10 years.

$$\text{Years lived by 90\% of the thruster in year } 30 = 19 + 10 = 29 \text{ years} \tag{8.2}$$

The total lifetime of the thruster is then the average of the lifetime of the current thruster and the 10% taken out twice. 90% of the current thruster has a lifetime of 29 years, 10% of the current thruster has a lifetime of 10 years, 10% taken out has a lifetime of 19 years, and 10% taken out has a lifetime of 10 years. The average lifetime for this 120% thruster is thus as calculated in Equation (8.3).

$$\text{Lifetime} = \frac{0.9 * 29 + 0.1 * 10 + 0.1 * 19 + 0.1 * 10}{1.2} = 25 \text{ years} \tag{8.3}$$

The lifetime of one thruster is equal to the average lifetime of this 120% thruster. The lifetime of 25 years results in 1.2 thrusters needed during the ferry lifetime of 30 years. This can also be explained by the fact that 10% extra thruster is added in year 10 and 20, resulting in 1.2 thrusters in total.

Battery production

A lot of equipment has higher lifetimes than the battery factory lifetime of 5 years, and can probably be re-purposed at the end of the battery factory lifetime. The anticipated lifetime of 5 years is still used in this analysis because only the current production is studied.

Even though it is stated that all components other than the battery cell are locally produced (PC), it is assumed that locally produced components can import raw materials and sub-components for their production from other parts of the world. Therefore, European values are used. This is also convenient as most processes in Ecoinvent 3.2 lack a specific Norwegian value, and only have a generic European value.

The amount of ethylene glycol and water is calculated based on the percentages and as the difference between the total module weight and the sum of the weights of the other module components and the 28 battery cells part of the module, illustrated for water in Equation (8.4).

$$\begin{aligned}&\text{Weight of water} = 0.7 * (57 - \\ &\text{Weight of other module components} - \text{Weight of battery cell} * 28)\end{aligned} \tag{8.4}$$

The number of modules produced during the factory lifetime is calculated as the product of the amount of modules produced per shift, the number of shifts per day, the number of working days per week, the number of weeks in a year, and the lifetime of the battery factory.

The yearly energy consumption of the module factory is calculated as the product of the monthly energy consumption per area, the area of the relevant part of the facility, and the number of months in a year. Only the effects of the aggregates are obtained, so the yearly aggregate electricity consumption is calculated by multiplying the effects with the length of shifts in hours, number of shifts per day, number of working days per week, and number of weeks in a year.

It is assumed that the Siemens battery cell has similarities with the battery cell in LCI template provided by the Industrial Ecology programme at NTNU, and that this inventory therefore can be used as a basis for modelling the battery cell.

The electricity consumption mix in Taiwan is set equal to the electricity production mix, as no imports or exports are listed for Taiwan. The electricity production mix is found by looking into ”electricity generation by source” for Chinese Taipei.

For the battery cell, the following procedure is adopted in order to estimate weights of the different components based on the primary data given:

1. The weights of essential cell components that are not specified in the BOM are computed based on the ratio between the weight of the component and the weight of the cell in the LCI template, multiplied with the weight of the battery cell considered in this study, as illustrated in Equation (8.5).

   $$\begin{aligned}&\text{Weight of component} = \\ &\frac{\text{Weight of component in LCI template}}{\text{Weight of cell in LCI template}} * \text{Weight of cell}\end{aligned} \tag{8.5}$$

   These weights are then subtracted from the total weight of the cell, and the other components listed in the BOM are scaled linearly as described in Equation (8.6) to make everything add up to the correct battery cell weight.

   $$\text{Adjusted weight} = \frac{\text{Original weight}}{\text{Total cell weight}} * \text{Weight of cell after subtraction} \tag{8.6}$$

2. The scaled data on materials that are used in only one component of the battery cell are implemented directly.

3. For the materials that are used in multiple components of the battery cell, first the different components relevant for each material based on the LCI template are listed. Then, ratios are computed from the LCI template by dividing the weight of a component by the total weight of the specific material in the cell. Then, the new component weight specific for this analysis is found by multiplying this ratio with the total weight of the material in the battery assessed. This procedure is described in Equation (8.7).

   $$\begin{aligned}&\text{Component weight} = \\ &\frac{\text{Component weight in LCI template}}{\text{Total material weight in LCI template}} * \text{Total material weight}\end{aligned} \tag{8.7}$$

B.2 Life cycle inventory

The foreground stressors matrix illustrated in Table 8.1 is only used for the diesel electric case.

Table 8.1: Foreground stressors matrix

Stressor name	Stressor row	Foreground process ID	Amount	Unit	Arda name
CO2	15521	10000009	1.24E+08	kg	Carbon dioxide/air/unspecified/kg
SOx	23027	10000009		kg	Sulfur oxides/air/unspecified/kg
SO2	506	10000009	3.76E+02	kg	Sulfur dioxide/air/unspecified/kg
SO4	502	10000009	1.16E+01	kg	Sulfate/air/unspecified/kg
NOx	383	10000009	1.70E+06	kg	Nitrogen oxides/air/unspecified/kg
CO	13377	10000009	1.62E+05	kg	Carbon Monoxide/air/unspecified/kg
OC	27130	10000009	2.10E+04	kg	Organic carbon/air/urban air close to ground/kg
EC + BC	396	10000009	1.01E+04	kg	Particulates, ¡ 2.5 um/air/unspecified/kg

Table 8.2: Ferry construction inventory common for diesel electric and battery electric ferry, part 1

Ferry construction					
Substance	Amount	Unit	Arda ID	Arda name	Reference
Structure	7.94E+05	kg			
Materials	7.94E+05	kg			
Hull and tubes	7.93E+05	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Mail Myklebust 11.03.20, case-specific
Superstructure	1.41E+03	kg	7850	steel, chromium steel 18/8, hot rolled/market for steel, chromium steel 18/8, hot rolled/GLO/kg	Mail Myklebust 11.03.20, case-specific
Energy and infrastructure					
Metal working steel	7.93E+05	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on actual data
Metal working chromium steel	1.41E+03	kg	1925	metal working, average for chromium steel product manufacturing/metal working, average for chromium steel product manufacturing/RER/kg	Assumed based on actual data
Transport					
Transport from Poland to Norway	1.28E+06	tkm	13980	transport, freight, sea, transoceanic ship/transport, freight, sea, transoceanic ship/GLO/metric ton*km	Phone meeting FosenNamsos 24.02.20, Sea-distances.org, case-specific
Cables	3.60E+04	kg	8662	cable, unspecified/market for cable, unspecified/GLO/kg	Mail Brattvaag Electro 27.03.20, estimated
Interior					
Seats wood	3.21E+01	kg			EPD Norge
Materials	3.82E+01	kg			
Steel	1.42E+01	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	EPD Norge
Wood	8.90E+00	kg	4730	cleft timber, measured as dry mass/market for cleft timber, measured as dry mass/Europe without Switzerland/kg	EPD Norge
Polyethylene	6.50E+00	kg	7036	polyethylene, high density, granulate/market for polyethylene, high density, granulate/GLO/kg	EPD Norge
Packaging	6.14E+00	kg	5697	kraft paper, unbleached/market for kraft paper, unbleached/GLO/kg	EPD Norge
Textiles	1.60E+00	kg	5211	textile, woven cotton/market for textile, woven cotton/GLO/kg	EPD Norge
Paint	8.20E-01	kg	7239	electrostatic paint/market for electrostatic paint/GLO/kg	EPD Norge
Energy					
Electricity	8.33E+01	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	EPD Norge
Sofas	2.40E+01	kg			EPD Norge
Materials	2.44E+01	kg			
Wood	1.15E+01	kg	4730	cleft timber, measured as dry mass/market for cleft timber, measured as dry mass/Europe without Switzerland/kg	EPD Norge
Polyurethane	5.45E+00	kg	7049	polyurethane, flexible foam/market for polyurethane, flexible foam/GLO/kg	EPD Norge
Steel	4.61E+00	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	EPD Norge
Textiles	1.75E+00	kg	5211	textile, woven cotton/market for textile, woven cotton/GLO/kg	EPD Norge
Polyethylene	5.00E-01	kg	7036	polyethylene, high density, granulate/market for polyethylene, high density, granulate/GLO/kg	EPD Norge
Packaging	4.00E-01	kg	5697	kraft paper, unbleached/market for kraft paper, unbleached/GLO/kg	EPD Norge
Polypropylene	1.90E-01	kg	7043	polypropylene, granulate/market for polypropylene, granulate/GLO/kg	EPD Norge
Energy					
Electricity	4.57E+02	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	EPD Norge

Table 8.3: Ferry construction inventory common for diesel electric and battery electric ferry, part 2

Ferry construction					
Substance	Amount	Unit	Arda ID	Arda name	Reference
Seats metal	1.06E+01	kg			EPD Norge
Materials	1.26E+01	kg			
Wood	3.40E+00	kg	4730	cleft timber, measured as dry mass/market for cleft timber, measured as dry mass/Europe without Switzerland/kg	EPD Norge
Polyurethane	1.70E+00	kg	7049	polyurethane, flexible foam/market for polyurethane, flexible foam/GLO/kg	EPD Norge
Steel	3.40E+00	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	EPD Norge
POM	1.00E-01	kg	6318	acetaldehyde/market for acetaldehyde/GLO/kg	EPD Norge
Aluminium	1.00E+00	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	EPD Norge
Textiles	1.00E+00	kg	5211	textile, woven cotton/market for textile, woven cotton/GLO/kg	EPD Norge
Packaging	2.00E+00	kg	5697	kraft paper, unbleached/market for kraft paper, unbleached/GLO/kg	EPD Norge
Energy					
Electricity	2.10E+02	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	EPD Norge
Tables	1.16E+01	kg			EPD Norge
Materials	1.36E+01	kg			
Steel	6.40E+00	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	EPD Norge
Wood	4.60E+00	kg	4730	cleft timber, measured as dry mass/market for cleft timber, measured as dry mass/Europe without Switzerland/kg	EPD Norge
Packaging	2.00E+00	kg	5697	kraft paper, unbleached/market for kraft paper, unbleached/GLO/kg	EPD Norge
POM	4.00E-01	kg	6318	acetaldehyde/market for acetaldehyde/GLO/kg	EPD Norge
Polyethylene	2.00E-01	kg	7036	polyethylene, high density, granulate/market for polyethylene, high density, granulate/GLO/kg	EPD Norge
Energy					
Electricity	1.68E+02	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	EPD Norge
Benches	3.49E+01	kg			EPD Norge
Materials	3.79E+01	kg			
Wood	3.20E+01	kg	4730	cleft timber, measured as dry mass/market for cleft timber, measured as dry mass/Europe without Switzerland/kg	EPD Norge
Other	2.20E+00	kg	7025	nylon 6/market for nylon 6/GLO/kg	EPD Norge
ABS	7.00E-01	kg	7009	acrylonitrile-butadiene-styrene copolymer/market for acrylonitrile-butadiene-styrene copolymer/GLO/kg	EPD Norge
Packaging	3.00E+00	kg	5697	kraft paper, unbleached/market for kraft paper, unbleached/GLO/kg	EPD Norge
Energy					
Electricity	1.61E+02	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	EPD Norge
Transport					
Neglected	0.00E+00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Phone meeting FosenNamsos 24.02.20, case-specific
Hydraulic system	6.03E+03	kg			
Materials	6.03E+03	kg			
Power pack, steel and cylinders	5.57E+03	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Microsoft Teams meeting Myklebust 13.03.20, power pack weight from data sheet but cylinder weight guessed
Power pack, oil	4.70E+02	kg	5851	lubricating oil/market for lubricating oil/GLO/kg	Microsoft Teams meeting Myklebust 13.03.20, guessed
Energy and infrastructure					
Metal working	5.57E+03	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on actual data
Transport					
Neglected	0.00E+00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Maritimt Magasin, case-specific

Table 8.4: Ferry construction inventory common for diesel electric and battery electric ferry, part 3

Ferry construction					
Substance	Amount	Unit	Arda ID	Arda name	Reference
Anchor windlass	1.00E+04	kg			
Materials	1.00E+04	kg			
Cast iron	1.00E+04	kg	7831	cast iron/market for cast iron/GLO/kg	Microsoft Teams meeting Myklebust 13.03.20, guessed
Energy and infrastructure					
Metal working	1.00E+04	kg	1928	metal working, average for metal product manufacturing/metal working, average for metal product manufacturing/RER/kg	Assumed based on actual data
Transport					
Transport from Croatia to Norway	2.75E+04	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Microsoft Teams meeting Myklebust 13.03.20, case-specific

Table 8.5: Ferry construction inventory specific for diesel electric ferry

Diesel electric ferry construction					
Substance	Amount	Unit	Arda ID	Arda name	Reference
Ventilation system	7.30E+03	kg			
Materials					
Steel ducts	3.00E+02	m	8902	spiral-seam duct, steel, DN 400/market for spiral-seam duct, steel, DN 400/GLO/m	Data sheet from Myklebust 11.03.20, case-specific
Heat pumps 10 kW	2.00E+00	unit	8892	heat pump, brine-water, 10kW/market for heat pump, brine-water, 10kW/GLO/unit	Data sheet from Myklebust 11.03.20, case-specific
Heat pumps 30 kW	1.00E+00	unit	8891	heat pump, 30kW/market for heat pump, 30kW/GLO/unit	Data sheet from Myklebust 11.03.20, case-specific
Ventilation control panel	4.00E+00	unit	8597	ventilation control and wiring, central unit/market for ventilation control and wiring, central unit/GLO/unit	Data sheet from Myklebust 11.03.20, case-specific
Fans and other motors	1.19E+02	kW			
Materials	1.50E+03	kg			
Electrical steel	6.35E+02	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	ABB EPD
Other steel	9.37E+01	kg	7852	steel, low-alloyed, hot rolled/market for steel, low-alloyed, hot rolled/GLO/kg	ABB EPD
Cast iron	6.26E+02	kg	7831	cast iron/market for cast iron/GLO/kg	ABB EPD
Aluminium	2.25E+01	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	ABB EPD
Copper	6.41E+01	kg	4912	copper/market for copper/GLO/kg	ABB EPD
Insulation material	1.19E+00	kg	7424	glass fibre/market for glass fibre/GLO/kg	ABB EPD
Wooden packing material	5.34E+01	kg	4730	cleft timber, measured as dry mass/market for cleft timber, measured as dry mass/Europe without Switzerland/kg	ABB EPD
Impregnation resin	7.12E+00	kg	7030	phenolic resin/market for phenolic resin/GLO/kg	ABB EPD
Paint	8.30E+00	kg	7239	electrostatic paint/market for electrostatic paint/GLO/kg	ABB EPD
Hazardous waste	2.37E+00	kg	12858	hazardous waste, for incineration/market for hazardous waste, for incineration/GLO/kg	ABB EPD
Regular waste to landfill	5.93E+00	kg	12870	process-specific burdens, residual material landfill/market for process-specific burdens, residual material landfill/GLO/kg	ABB EPD
Energy					
Electrical energy manufacturing	4.48E+02	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD
Heat energy manufacturing natural gas	3.70E+01	MJ	11728	heat, district or industrial, natural gas/market for heat, district or industrial, natural gas/Europe without Switzerland/MJ	ABB EPD, IEA, proxy
Heat energy manufacturing other than natural gas	1.33E+03	MJ	11763	heat, district or industrial, other than natural gas/market for heat, district or industrial, other than natural gas/Europe without Switzerland/MJ	ABB EPD, IEA, proxy
Transport					
Neglected	0.00E+00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Maritimt Magasin, Aeron Mollier, case-specific
Energy					
Accounted for in processes	0.00E+00	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	Ecoinvent
Transport					
Accounted for in processes	0.00E+00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Ecoinvent
Assembly					
Energy					
Electricity	1.00E+06	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	Mail Myklebust 11.03.20, generic for ferry
Diesel value chain	0.00E+00	kg	5832	diesel/market for diesel/Europe without Switzerland/kg	Mail Myklebust 11.03.20, generic for ferry
Diesel	2.87E+06	MJ	896	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	
Transport					
Transport from Myklebust to Trondheim	2.51E+05	tkm	13980	transport, freight, sea, transoceanic ship/transport, freight, sea, transoceanic ship/GLO/metric ton*km	Sea-distances.org, case-specific but approximate
Navigation system	5.00E+00	unit	8573	computer, desktop, without screen/market for computer, desktop, without screen/GLO/unit	

Table 8.6: Ferry construction inventory specific for battery electric ferry

Battery electric ferry construction					
Substance	Amount	Unit	Arda ID	Arda name	Reference
Ventilation system	9.23E+03	kg			
Materials					
Steel ducts	3.00E+02	m	8902	spiral-seam duct, steel, DN 400/market for spiral-seam duct, steel, DN 400/GLO/m	Data sheet from Myklebust 11.03.20, case-specific
Heat pumps 10 kW	2.00E+00	unit	8892	heat pump, brine-water, 10kW/market for heat pump, brine-water, 10kW/GLO/unit	Data sheet from Myklebust 11.03.20, case-specific
Heat pumps 30 kW	1.00E+00	unit	8891	heat pump, 30kW/market for heat pump, 30kW/GLO/unit	Data sheet from Myklebust 11.03.20, case-specific
Ventilation control panels	4.00E+00	unit	8597	ventilation control and wiring, central unit/market for ventilation control and wiring, central unit/GLO/unit	Data sheet from Myklebust 11.03.20, case-specific
Fans and other motors	1.56E+02	kW			
Materials	1.98E+03	kg			
Electrical steel	8.35E+02	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	ABB EPD
Other steel	1.23E+02	kg	7852	steel, low-alloyed, hot rolled/market for steel, low-alloyed, hot rolled/GLO/kg	ABB EPD
Cast iron	8.25E+02	kg	7831	cast iron/market for cast iron/GLO/kg	ABB EPD
Aluminium	2.97E+01	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	ABB EPD
Copper	8.43E+01	kg	4912	copper/market for copper/GLO/kg	ABB EPD
Insulation material	1.56E+00	kg	7424	glass fibre/market for glass fibre/GLO/kg	ABB EPD
Wooden packing material	7.03E+01	kg	4730	cleft timber, measured as dry mass/market for cleft timber, measured as dry mass/Europe without Switzerland/kg	ABB EPD
Impregnation resin	9.37E+00	kg	7030	phenolic resin/market for phenolic resin/GLO/kg	ABB EPD
Paint	1.09E+01	kg	7239	electrostatic paint/market for electrostatic paint/GLO/kg	ABB EPD
Hazardous waste	3.12E+00	kg	12858	hazardous waste, for incineration/market for hazardous waste, for incineration/GLO/kg	ABB EPD
Regular waste to landfill	7.81E+00	kg	12870	process-specific burdens, residual material landfill/market for process-specific burdens, residual material landfill/GLO/kg	ABB EPD
Energy					
Electrical energy manufacturing	5.90E+02	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD
Heat energy manufacturing natural gas	4.87E+01	MJ	11728	heat, district or industrial, natural gas/market for heat, district or industrial, natural gas/Europe without Switzerland/MJ	ABB EPD
Heat energy manufacturing other than natural gas	1.74E+03	MJ	11763	heat, district or industrial, other than natural gas/market for heat, district or industrial, other than natural gas/Europe without Switzerland/MJ	ABB EPD
Transport					
Neglected	0.00E+00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Maritimt Magasin, Aeron Mollier, case-specific
Energy					
Accounted for in processes	0.00E+00	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	Ecoinvent
Transport					
Accounted for in processes	0.00E+00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Ecoinvent
Assembly					
Energy					
Electricity	1.00E+06	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	Mail Myklebust 11.03.20, generic for ferry
Diesel value chain	0.00E+00	kg	5832	diesel/market for diesel/Europe without Switzerland/kg	Mail Myklebust 11.03.20, generic for ferry
Diesel	2.87E+06	MJ	896	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	
Transport					
Transport from Myklebust to Trondheim	2.52E+05	tkm	13980	transport, freight, sea, transoceanic ship/transport, freight, sea, transoceanic ship/GLO/metric ton*km	Sea-distances.org, case-specific but approximate
Navigation system	5.00E+00	unit	8573	computer, desktop, without screen/market for computer, desktop, without screen/GLO/unit	

Table 8.7: Propulsion system construction inventory common for diesel electric and battery electric ferry, part 1

Propulsion construction					
Substance	Amount	Unit	Arda ID	Arda name	Reference
Electric motors	5050.00	kg			Mail with data sheet Siemens 24.02.20, case-specific
Materials	5081.17	kg			
Electrical steel	2887.43	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	ABB EPD
Other steel	576.24	kg	7852	steel, low-alloyed, hot rolled/market for steel, low-alloyed, hot rolled/GLO/kg	ABB EPD
Copper	558.43	kg	4912	copper/market for copper/GLO/kg	ABB EPD
Aluminium	0.71	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	ABB EPD
Cast iron	1043.82	kg	7831	cast iron/market for cast iron/GLO/kg	ABB EPD
Insulation material	20.48	kg	7424	glass fibre/market for glass fibre/GLO/kg	ABB EPD
Impregnation resin	13.80	kg	7030	phenolic resin/market for phenolic resin/GLO/kg	ABB EPD
Paint	7.13	kg	7239	electrostatic paint/market for electrostatic paint/GLO/kg	ABB EPD
Wooden packing material	31.17	kg	4730	cleft timber, measured as dry mass/market for cleft timber, measured as dry mass/Europe without Switzerland/kg	ABB EPD
Hazardous waste: oil emulsions and various	21.06	kg	12858	hazardous waste, for incineration/market for hazardous waste, for incineration/GLO/kg	ABB EPD
Regular waste to landfill	36.99	kg	12870	process-specific burdens, residual material landfill/market for process-specific burdens, residual material landfill/GLO/kg	ABB EPD
Energy					
Electrical energy manufacturing	3746.89	kWh	1153	electricity, medium voltage/market for electricity, medium voltage/DE/kWh	ABB EPD
Heat energy manufacturing natural gas	2193.21	MJ	11728	heat, district or industrial, natural gas/market for heat, district or industrial, natural gas/Europe without Switzerland/MJ	ABB EPD, IEA
Heat energy manufacturing other than natural gas	2271.54	MJ	11763	heat, district or industrial, other than natural gas/market for heat, district or industrial, other than natural gas/Europe without Switzerland/MJ	ABB EPD, IEA
Transport					
Transport from Germany to Norway	8643.07	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Google Maps, mail Siemens 24.02.20, case-specific
300kVA shipnet supply transformer	1150.00	kg			Mail with data sheet Siemens 24.02.20, case-specific
Materials	1150.00	kg			
Aluminium	152.95	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	Schneider PEP
Steel	177.10	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Schneider PEP
Epoxy resin	94.30	kg	7017	epoxy resin, liquid/market for epoxy resin, liquid/GLO/kg	Schneider PEP
Copper	4.60	kg	4912	copper/market for copper/GLO/kg	Schneider PEP
Glass fiber	6.90	kg	7424	glass fibre/market for glass fibre/GLO/kg	Schneider PEP
PET	10.35	kg	7034	polyethylene terephthalate, granulate, amorphous/market for polyethylene terephthalate, granulate, amorphous/GLO/kg	Schneider PEP
Ferrous alloys	699.20	kg	7831	cast iron/market for cast iron/GLO/kg	Schneider PEP
UP Polyester	4.60	kg	7033	polyester resin, unsaturated/market for polyester resin, unsaturated/GLO/kg	Schneider PEP
Energy					
Electrical energy manufacturing	4410.18	kWh	1155	electricity, medium voltage/market for electricity, medium voltage/FI/kWh	ABB EPD
Heat energy manufacturing	370.60	MJ	11728	heat, district or industrial, natural gas/market for heat, district or industrial, natural gas/Europe without Switzerland/MJ	ABB EPD, IEA
	2511.94	MJ	11763	heat, district or industrial, other than natural gas/market for heat, district or industrial, other than natural gas/Europe without Switzerland/MJ	ABB EPD, IEA
Transport					
Transport from Finland to Norway	1587.00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Google Maps, mail Siemens 24.02.20, case-specific

Table 8.8: Propulsion system construction inventory common for diesel electric and battery electric ferry, part 2

Propulsion construction					
Substance	Amount	Unit	Arda ID	Arda name	Reference
Thruster	13000.00	kg			Rolls Royce
Materials	13000.00	kg			
Thruster house	7800.00	kg	7831	cast iron/market for cast iron/GLO/kg	Microsoft Teams meeting Myklebust 13.03.20, estimated
Gear	3250.00	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Microsoft Teams meeting Myklebust 13.03.20, estimated
Propeller	1950.00	kg	7963	bronze/market for bronze/GLO/kg	Microsoft Teams meeting Myklebust 13.03.20, estimated
Energy and infrastructure					
Metal working steel	3250.00	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on actual data
Metal working iron and bronze	9750.00	kg	1928	metal working, average for metal product manufacturing/metal working, average for metal product manufacturing/RER/kg	Assumed based on actual data
Transport					
	0.00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Nogva, data sheet from mail Myklebust 11.03.20, case-specific
Diesel gensets	4621.00	kg			
Engine	1600.00	kg	8991	internal combustion engine, for passenger car/market for internal combustion engine, passenger car/GLO/kg	Nogva, data sheet from mail Myklebust 11.03.20, case-specific
Base frame	440.00	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Nogva, data sheet from mail Myklebust 11.03.20, case-specific
550kVA generator	2581.00	kg			Mail with data sheet Siemens 24.02.20, case-specific
Materials	2596.93	kg			
Electrical steel	1475.74	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	ABB EPD
Other steel	294.51	kg	7852	steel, low-alloyed, hot rolled/market for steel, low-alloyed, hot rolled/GLO/kg	ABB EPD
Copper	285.41	kg	4912	copper/market for copper/GLO/kg	ABB EPD
Aluminium	0.36	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	ABB EPD
Cast iron	533.49	kg	7831	cast iron/market for cast iron/GLO/kg	ABB EPD
Insulation material	10.47	kg	7424	glass fibre/market for glass fibre/GLO/kg	ABB EPD
Impregnation resin	7.06	kg	7030	phenolic resin/market for phenolic resin/GLO/kg	ABB EPD
Paint	3.64	kg	7239	electrostatic paint/market for electrostatic paint/GLO/kg	ABB EPD
Wooden packing material	15.93	kg	4730	cleft timber, measured as dry mass/market for cleft timber, measured as dry mass/Europe without Switzerland/kg	ABB EPD
Hazardous waste: oil emulsions and various	10.76	kg	12858	hazardous waste, for incineration/market for hazardous waste, for incineration/GLO/kg	ABB EPD
Regular waste to landfill	18.91	kg	12870	process-specific burdens, residual material landfill/market for process-specific burdens, residual material landfill/GLO/kg	ABB EPD
Energy					
Electrical energy manufacturing	1915.00	kWh	1156	electricity, medium voltage/market for electricity, medium voltage/GB/kWh	ABB EPD
Heat energy manufacturing	2090.13	MJ	11728	heat, district or industrial, natural gas/market for heat, district or industrial, natural gas/Europe without Switzerland/MJ	ABB EPD, IEA
	191.75	MJ	11763	heat, district or industrial, other than natural gas/market for heat, district or industrial, other than natural gas/Europe without Switzerland/MJ	ABB EPD, IEA
Transport					
Transport from England to Norway	4064.04	tkm	13980	transport, freight, sea, transoceanic ship/transport, freight, sea, transoceanic ship/GLO/metric ton*km	Sea-distances.org, mail Siemens 24.02.20, case-specific
Energy					
Metal working	440.00	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on actual data
Transport					
Neglected	0.00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Assumed

Table 8.9: Propulsion system construction inventory common for diesel electric and battery electric ferry, part 3

Propulsion construction					
Substance	Amount	Unit	Arda ID	Arda name	Reference
BlueDrive PlusC swbd FWD	5800.00	kg			Mail with data sheet Siemens 24.02.20, case-specific
Materials	9118.16	kg			
Steel cabinets	1419.60	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 24.02.20, phone meeting Siemens 28.02.20, estimated
Busbars	232.70	kg	4912	copper/market for copper/GLO/kg	Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 24.02.20, phone meeting Siemens 28.02.20, estimated
Drive BDPC swbd FWD	3318.16	kg			Mail with data sheet Siemens 24.02.20, phone meeting Siemens 20.03.20, estimated
Materials	3318.16	kg			
Aluminium	78.98	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	ABB EPD
Copper	313.95	kg	4912	copper/market for copper/GLO/kg	ABB EPD
Plastic	157.47	kg	7025	nylon 6/market for nylon 6/GLO/kg	ABB EPD
	157.47	kg	7027	nylon 6-6/market for nylon 6-6/GLO/kg	ABB EPD
Steel	1885.65	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	ABB EPD
Iron	575.57	kg	7831	cast iron/market for cast iron/GLO/kg	ABB EPD
Cardboard	22.71	kg	5697	kraft paper, unbleached/market for kraft paper, unbleached/GLO/kg	ABB EPD
Other	379.11	kg	8004	zinc/market for zinc/GLO/kg	ABB EPD
Waste: hazardous waste	157.96	kg	12858	hazardous waste, for incineration/market for hazardous waste, for incineration/GLO/kg	ABB EPD
Waste: regular waste to landfill	94.78	kg	12870	process-specific burdens, residual material landfill/market for process-specific burdens, residual material landfill/GLO/kg	ABB EPD
Energy					
Electricity	78.98	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD
Electronics	829.54	kg	8594	electronics, for control units/market for electronics, for control units/GLO/kg	Mail with data sheet Siemens 24.02.20, phone meeting Siemens 20.03.20, estimated
Energy and infrastructure					
Metal working steel	1419.60	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on actual data
Metal working copper	232.70	kg	1926	metal working, average for copper product manufacturing/metal working, average for copper product manufacturing/RER/kg	Assumed based on actual data
Transport					
No transport since production is in Trondheim	0.00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Mail Siemens 24.02.20, case-specific

Table 8.10: Propulsion system construction inventory common for diesel electric and battery electric ferry, part 4

Propulsion construction					
Substance	Amount	Unit	Arda ID	Arda name	Reference
BlueDrive PlusC swbd AFT	6500.00	kg			Mail with data sheet Siemens 24.02.20, case-specific
Materials	10378.16	kg			
Steel cabinets	1419.60	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 24.02.20, phone meeting Siemens 28.02.20, estimated
Busbars	232.70	kg	4912	copper/market for copper/GLO/kg	Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 24.02.20, phone meeting Siemens 28.02.20, estimated
Drive BDPC swbd AFT	3878.16	kg			Mail with data sheet Siemens 24.02.20, phone meeting Siemens 20.03.20, estimated
Materials	3878.16	kg			
Aluminium	92.31	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	ABB EPD
Copper	366.93	kg	4912	copper/market for copper/GLO/kg	ABB EPD
Plastic	184.04	kg	7025	nylon 6/market for nylon 6/GLO/kg	ABB EPD
	184.04	kg	7027	nylon 6-6/market for nylon 6-6/GLO/kg	ABB EPD
Steel	2203.89	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	ABB EPD
Iron	672.71	kg	7831	cast iron/market for cast iron/GLO/kg	ABB EPD
Cardboard	26.54	kg	5697	kraft paper, unbleached/market for kraft paper, unbleached/GLO/kg	ABB EPD
Other	443.09	kg	8004	zinc/market for zinc/GLO/kg	ABB EPD
Waste: hazardous waste	184.62	kg	12858	hazardous waste, for incineration/market for hazardous waste, for incineration/GLO/kg	ABB EPD
Waste: regular waste to landfill	110.77	kg	12870	process-specific burdens, residual material landfill/market for process-specific burdens, residual material landfill/GLO/kg	ABB EPD
Energy					
Electricity	92.31	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD
Electronics	969.54	kg	8594	electronics, for control units/market for electronics, for control units/GLO/kg	Mail with data sheet Siemens 24.02.20, phone meeting Siemens 20.03.20, estimated
Energy					
Metal working steel	1419.60	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on actual data
Metal working copper	232.70	kg	1926	metal working, average for copper product manufacturing/metal working, average for copper product manufacturing/RER/kg	Assumed based on actual data
Transport					
No transport since production is in Trondheim	0.00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Mail Siemens 24.02.20, case-specific

Table 8.11: Propulsion system construction inventory common for diesel electric and battery electric ferry, part 5

Propulsion construction					
Substance	Amount	Unit	Arda ID	Arda name	Reference
230V FWD switchboard	1225.00	kg			Mail with data sheet Siemens 24.02.20, case-specific
Materials	1798.28	kg			
Steel cabinets	436.80	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 24.02.20, phone meeting Siemens 28.02.20, estimated
Busbars	71.60	kg	4912	copper/market for copper/GLO/kg	Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 24.02.20, phone meeting Siemens 28.02.20, estimated
Drive 230V FWD switchboard	573.28	kg			Mail with data sheet Siemens 24.02.20, phone meeting Siemens 20.03.20, estimated
Materials	573.28	kg			
Aluminium	13.65	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	ABB EPD
Copper	54.24	kg	4912	copper/market for copper/GLO/kg	ABB EPD
Plastic	27.21	kg	7025	nylon 6/market for nylon 6/GLO/kg	ABB EPD
	27.21	kg	7027	nylon 6-6/market for nylon 6-6/GLO/kg	ABB EPD
Steel	325.79	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	ABB EPD
Iron	99.44	kg	7831	cast iron/market for cast iron/GLO/kg	ABB EPD
Cardboard	3.92	kg	5697	kraft paper, unbleached/market for kraft paper, unbleached/GLO/kg	ABB EPD
Other	65.50	kg	8004	zinc/market for zinc/GLO/kg	ABB EPD
Waste: hazardous waste	27.29	kg	12858	hazardous waste, for incineration/market for hazardous waste, for incineration/GLO/kg	ABB EPD
Waste: regular waste to landfill	16.37	kg	12870	process-specific burdens, residual material landfill/market for process-specific burdens, residual material landfill/GLO/kg	ABB EPD
Energy					
Electricity	13.65	kWh	10760	electricity, medium voltage/market for electricity, medium voltage/LV/kWh	ABB EPD
Electronics	143.32	kg	8594	electronics, for control units/market for electronics, for control units/GLO/kg	Mail with data sheet Siemens 24.02.20, phone meeting Siemens 20.03.20, estimated
Energy					
Metal working steel	436.80	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on actual data
Metal working copper	71.60	kg	1926	metal working, average for copper product manufacturing/metal working, average for copper product manufacturing/RER/kg	Assumed based on actual data
Transport					
Transport from Latvia to Sweden	719.37	tkm	13980	transport, freight, sea, transoceanic ship/transport, freight, sea, transoceanic ship/GLO/metric ton*km	Sea-distances.org, mail Siemens 24.02.20, case-specific
Transport from Sweden to Norway	1803.67	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Google Maps, mail Siemens 24.02.20, case-specific

Table 8.12: Propulsion system construction inventory common for diesel electric and battery electric ferry, part 6

Propulsion construction					
Substance	Amount	Unit	Arda ID	Arda name	Reference
230V AFT switchboard	1018.00	kg			Mail with data sheet Siemens 24.02.20, case-specific
Materials	1425.68	kg			
Steel cabinets	436.80	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 24.02.20, phone meeting Siemens 28.02.20, estimated
Busbars	71.60	kg	4912	copper/market for copper/GLO/kg	Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 24.02.20, phone meeting Siemens 28.02.20, estimated
Drive 230V AFT switchboard	407.68	kg			Mail with data sheet Siemens 24.02.20, phone meeting Siemens 20.03.20, estimated
Materials	407.68	kg			
Aluminium	9.70	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	ABB EPD
Copper	38.57	kg	4912	copper/market for copper/GLO/kg	ABB EPD
Plastic	19.35	kg	7025	nylon 6/market for nylon 6/GLO/kg	ABB EPD
	19.35	kg	7027	nylon 6-6/market for nylon 6-6/GLO/kg	ABB EPD
Steel	231.68	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	ABB EPD
Iron	70.72	kg	7831	cast iron/market for cast iron/GLO/kg	ABB EPD
Cardboard	2.79	kg	5697	kraft paper, unbleached/market for kraft paper, unbleached/GLO/kg	ABB EPD
Other	46.58	kg	8004	zinc/market for zinc/GLO/kg	ABB EPD
Waste: hazardous waste	19.41	kg	12858	hazardous waste, for incineration/market for hazardous waste, for incineration/GLO/kg	ABB EPD
Waste: regular waste to landfill	11.64	kg	12870	process-specific burdens, residual material landfill/market for process-specific burdens, residual material landfill/GLO/kg	ABB EPD
Energy					
Electricity	9.70	kWh	10760	electricity, medium voltage/market for electricity, medium voltage/LV/kWh	ABB EPD
Electronics	101.92	kg	8594	electronics, for control units/market for electronics, for control units/GLO/kg	Mail with data sheet Siemens 24.02.20, phone meeting Siemens 20.03.20, estimated
Energy					
Metal working steel	436.80	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on actual data
Metal working copper	71.60	kg	1926	metal working, average for copper product manufacturing/metal working, average for copper product manufacturing/RER/kg	Assumed based on actual data
Transport					
Transport from Latvia to Sweden	570.32	tkm	13980	transport, freight, sea, transoceanic ship/transport, freight, sea, transoceanic ship/GLO/metric ton*km	Sea-distances.org, mail Siemens 24.02.20, case-specific
Transport from Sweden to Norway	1429.96	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Google Maps, mail Siemens 24.02.20, case-specific

Table 8.13: Propulsion system construction inventory common for diesel electric and battery electric ferry, part 7

Propulsion construction					
Substance	Amount	Unit	Arda ID	Arda name	Reference
Remote control system	110.00	kg	8594	electronics, for control units/market for electronics, for control units/GLO/kg	Mail with data sheet Siemens 24.02.20, case-specific
Integrated automation system/Control and monitoring system	549.92	kg	8594	electronics, for control units/market for electronics, for control units/GLO/kg	Mail with data sheet Siemens 24.02.20, case-specific
Operator stations					
Main operator panels, LCD touchscreen	32.50	kg			
PC runtime systems, industrial PC	7.20	kg			
Process control units cabinets	200.00	kg			
Simatic CPU	2.50	kg			
Simatic I/O-station	6.00	kg			
Simatic switch	1.04	kg			
230VAC power supply	4.40	kg			
Redundancy module	0.80	kg			
Iso monitor	0.30	kg			
Remote I/O cabinets					
Process control units cabinet (C2)	80.00	kg			
Process control units cabinet (C1)	90.00	kg			
Simatic I/O-station	6.00	kg			
Simatic switch	1.04	kg			
230VAC power supply	4.40	kg			
Redundancy module	0.80	kg			
Iso monitor	0.30	kg			
Main operator panels, LCD touchscreen	6.50	kg			
PC runtime systems, industrial PC	1.20	kg			
DC/DC transducer	0.70	kg			
HMI cabinets	80.00	kg			
Main operator panels, LCD touchscreen	13.00	kg			
PC runtime systems, industrial PC	2.40	kg			
230VAC power supply	2.20	kg			
ECR console					
230VAC power supply	2.20	kg			
Bridge console					
230VAC power supply	1.10	kg			
Epcos EMC filter type b84113-c-b30					
Epcos EMC filter type b84113-c-b60					
Extension alarm system panels					
Simatic HMI cabin panels	0.54	kg			
Simatic bridge panel	2.80	kg			
Dead man system					
Watch entrance units containing switches and lamp					
Reset boxes containing pushbutton and lamp					
Printer					
Keyboard and mouse in ECR					
Keyboard					
Mouse					

Table 8.14: Propulsion system construction inventory specific for diesel electric ferry

Transport to Trondheim	24707.42	tkm	13980	transport, freight, sea, transoceanic ship/transport, freight, sea, transoceanic ship/GLO/metric ton*km

Table 8.15: Propulsion system construction inventory specific for battery electric ferry, part 1

			Battery electric propulsion construction		
Substance	Amount	Unit	Arda ID	Arda name	Reference
2700kVA charge transformer	5200.00	kg			Mail with data sheet Siemens 24.02.20, case-specific
Materials	5200.00	kg			
Aluminium	691.60	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	Schneider Electric
Steel	800.80	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Schneider Electric
Epoxy resin	426.40	kg	7017	epoxy resin, liquid/market for epoxy resin, liquid/GLO/kg	Schneider Electric
Copper	20.80	kg	4912	copper/market for copper/GLO/kg	Schneider Electric
Glass fiber	31.20	kg	7424	glass fibre/market for glass fibre/GLO/kg	Schneider Electric
PET	46.80	kg	7034	polyethylene terephthalate, granulate, amorphous/market for polyethylene terephthalate, granulate, amorphous/GLO/kg	Schneider Electric
Ferrous alloys	3161.60	kg	7831	cast iron/market for cast iron/GLO/kg	Schneider Electric
UP Polyester	20.80	kg	7033	polyester resin, unsaturated/market for polyester resin, unsaturated/GLO/kg	Schneider Electric
Energy					
Electrical energy manufacturing	19941.67	kWh	1155	electricity, medium voltage/market for electricity, medium voltage/FI/kWh	ABB EPD
Heat energy manufacturing natural gas	1675.76	MJ	11728	heat, district or industrial, natural gas/market for heat, district or industrial, natural gas/Europe without Switzerland/MJ	ABB EPD, IEA
Heat energy manufacturing other than natural gas	11358.36	MJ	11763	heat, district or industrial, other than natural gas/market for heat, district or industrial, other than natural gas/Europe without Switzerland/MJ	ABB EPD, IEA
Transport					
Transport from Finland to Norway	7176.00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Google Maps, mail Siemens 24.02.20, case-specific
11kV charging switchboard ferry	3500.00	kg			Mail with data sheet Siemens 24.02.20, case-specific
Materials	5893.28	kg			
Steel cabinets	436.80	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Mail with data sheet Siemens 24.02.20, phone meeting Siemens 28.02.20, estimated
Busbars	71.60	kg	4912	copper/market for copper/GLO/kg	Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 24.02.20, phone meeting Siemens 28.02.20, estimated
Drive 11 kV charging switchboard ferry	2393.28	kg			Data sheet Siemens 24.02.20, meeting Siemens 20.03.20, estimated
Materials	2393.28	kg			
Aluminium	56.97	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	ABB EPD
Copper	226.44	kg	4912	copper/market for copper/GLO/kg	ABB EPD
Plastic, nylon 6	113.58	kg	7025	nylon 6/market for nylon 6/GLO/kg	ABB EPD
Plastic, nylon 6-6	113.58	kg	7027	nylon 6-6/market for nylon 6-6/GLO/kg	ABB EPD
Steel	1360.06	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	ABB EPD
Iron	415.14	kg	7831	cast iron/market for cast iron/GLO/kg	ABB EPD
Cardboard	16.38	kg	5697	kraft paper, unbleached/market for kraft paper, unbleached/GLO/kg	ABB EPD
Other	273.44	kg	8004	zinc/market for zinc/GLO/kg	ABB EPD
Waste: hazardous waste	113.93	kg	12858	hazardous waste, for incineration/market for hazardous waste, for incineration/GLO/kg	ABB EPD
Waste: regular waste to landfill	68.36	kg	12870	process-specific burdens, residual material landfill/market for process-specific burdens, residual material landfill/GLO/kg	ABB EPD
Energy					
Electricity	56.97	kWh	1153	electricity, medium voltage/market for electricity, medium voltage/DE/kWh	ABB EPD
Electronics	598.32	kg	8594	electronics, for control units/market for electronics, for control units/GLO/kg	Mail with data sheet Siemens 24.02.20, phone meeting Siemens 20.03.20, estimated
Energy					
Metal working steel	436.80	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on actual data
Metal working copper	71.60	kg	1926	metal working, average for copper product manufacturing/metal working, average for copper product manufacturing/RER/kg	Assumed based on actual data
Transport					
Transport from Germany to Norway	10024.47	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Google Maps, mail Siemens 24.02.20, case-specific

Table 8.16: Propulsion system construction inventory specific for battery electric ferry, part 2

Battery electric propulsion construction					
Substance	Amount	Unit	Arda ID	Arda name	Reference
Shore connection box	50.00	kg			Mail Siemens 13.02.20, phone meeting Siemens 20.03.20, phone meeting Siemens 20.03.20, estimated
Materials	50.00	kg			
Steel	33.33	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Phone meeting Siemens 20.03.20, estimated
Copper	16.67	kg	4912	copper/market for copper/GLO/kg	Phone meeting Siemens 20.03.20, estimated
Energy					
Metal working steel	33.33	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on estimates
Metal working copper	16.67	kg	1926	metal working, average for copper product manufacturing/metal working, average for copper product manufacturing/RER/kg	Assumed based on estimates
Transport					
Neglected, produced in Norway	0.00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Phone meeting Siemens 20.03.20, case-specific
Charging ship units	500.00	kg			Phone meeting Siemens 20.03.20, estimated
Materials	500.00	kg			
Steel	500.00	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Phone meeting Siemens 20.03.20, estimated
Energy					
Metal working	500.00	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on estimates
Transport					
Transport from Germany to Norway	850.50	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Google Maps, mail Siemens 24.02.20, phone meeting Siemens 20.03.20, case-specific
Transport to Trondheim	28740.97	tkm	13980	transport, freight, sea, transoceanic ship/transport, freight, sea, transoceanic ship/GLO/metric ton*km	

Table 8.17: Shore system construction common for diesel electric and battery electric ferry

Shore system construction					
Substance	Amount	Unit	Arda ID	Arda name	Reference
Vacuum mooring system and pier	15650.00	kg			Mail with data sheet Cavotec 03.03.20, case-specific
Materials	15653.67	kg			
Inox steel	1001.60	kg	7849	steel, chromium steel 18/8/market for steel, chromium steel 18/8/GLO/kg	Mail Cavotec 06.03.20, case-specific
Plastic/composites, nylon 6	125.20	kg	7025	nylon 6/market for nylon 6/GLO/kg	Mail Cavotec 06.03.20, case-specific
Plastic/composites, nylon 6-6	125.20	kg	7027	nylon 6-6/market for nylon 6-6/GLO/kg	Mail Cavotec 06.03.20, case-specific
Rubber	406.90	kg	7061	synthetic rubber/market for synthetic rubber/GLO/kg	Mail Cavotec 06.03.20, case-specific
Fluids (oils/lubricants)	391.25	kg	5851	lubricating oil/market for lubricating oil/GLO/kg	Mail Cavotec 06.03.20, case-specific
Mild steel	12316.55	kg	7853	steel, unalloyed/market for steel, unalloyed/GLO/kg	Mail Cavotec 06.03.20, case-specific
Electrical components, active	125.20	kg	8455	electronic component, active, unspecified/market for electronic component, active, unspecified/GLO/kg	Mail Cavotec 06.03.20, case-specific
Electrical components, passive	125.20	kg	8456	electronic component, passive, unspecified/market for electronic component, passive, unspecified/GLO/kg	Mail Cavotec 06.03.20, case-specific
Electrical cabling (copper, plastic)	406.90	kg	8662	cable, unspecified/market for cable, unspecified/GLO/kg	Mail Cavotec 06.03.20, case-specific
Electrical motors mooring system	594.70	kg			Mail Cavotec 06.03.20, case-specific
Materials	598.37	kg			
Electrical steel	340.03	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	ABB EPD
Other steel	67.86	kg	7852	steel, low-alloyed, hot rolled/market for steel, low-alloyed, hot rolled/GLO/kg	ABB EPD
Copper	65.76	kg	4912	copper/market for copper/GLO/kg	ABB EPD
Aluminium	0.08	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	ABB EPD
Cast iron	122.92	kg	7831	cast iron/market for cast iron/GLO/kg	ABB EPD
Insulation material	2.41	kg	7424	glass fibre/market for glass fibre/GLO/kg	ABB EPD
Impregnation resin	1.63	kg	7030	phenolic resin/market for phenolic resin/GLO/kg	ABB EPD
Paint	0.84	kg	7239	electrostatic paint/market for electrostatic paint/GLO/kg	ABB EPD
Wooden packing material	3.67	kg	4730	cleft timber, measured as dry mass/market for cleft timber, measured as dry mass/Europe without Switzerland/kg	ABB EPD
Hazardous waste: oil emulsions and various	2.48	kg	12858	hazardous waste, for incineration/market for hazardous waste, for incineration/GLO/kg	ABB EPD
Regular waste to landfill	4.36	kg	12870	process-specific burdens, residual material landfill/market for process-specific burdens, residual material landfill/GLO/kg	ABB EPD
Energy					
Electrical energy manufacturing	441.24	kWh	1149	electricity, medium voltage/market for electricity, medium voltage/IT/kWh	ABB EPD
Heat energy manufacturing natural gas	330.35	MJ	11728	heat, district or industrial, natural gas/market for heat, district or industrial, natural gas/Europe without Switzerland/MJ	ABB EPD
Heat energy manufacturing other than natural gas	195.43	MJ	11763	heat, district or industrial, other than natural gas/market for heat, district or industrial, other than natural gas/Europe without Switzerland/MJ	ABB EPD
Paint	31.30	kg	7239	electrostatic paint/market for electrostatic paint/GLO/kg	Mail Cavotec 06.03.20, case-specific
Pier	495.00	m3	7732	concrete, normal/market for concrete, normal/CH/m3	Vegvesen.no
Light columns	728.28	kg	7852	steel, low-alloyed, hot rolled/market for steel, low-alloyed, hot rolled/GLO/kg	Vegvesen.no
Energy and infrastructure					
Metal working steel	13044.83	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on actual data
Metal working chromium steel	1001.60	kg	1925	metal working, average for chromium steel product manufacturing/metal working, average for chromium steel product manufacturing/RER/kg	Assumed based on actual data
Transport					
Transport from Milano, Italy to Norway	37935.60	tkm	13905	transport, freight, lorry ¿32 metric ton, EURO6/transport, freight, lorry ¿32 metric ton, EURO6/RER/metric ton*km	Google Maps, mail Cavotec 03.03.20, case-specific

Table 8.18: Shore system construction specific for the battery electric ferry, part 1

Shore system construction battery electric					
Substance	Amount	Unit	Arda ID	Arda name	Reference
1600kVA grid transformer	3983.00	kg			Mail with data sheet Siemens 02.03.20, case-specific
Materials	3983.00	kg			
Copper	23.90	kg	4912	copper/market for copper/GLO/kg	Schneider Electric PEP
Steel	2744.29	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Schneider Electric PEP
Epoxy resin	11.95	kg	7017	epoxy resin, liquid/market for epoxy resin, liquid/GLO/kg	Schneider Electric PEP
UP polyester	11.95	kg	7033	polyester resin, unsaturated/market for polyester resin, unsaturated/GLO/kg	Schneider Electric PEP
Mineral oil	732.87	kg	5851	lubricating oil/market for lubricating oil/GLO/kg	Schneider Electric PEP
Aluminium	370.42	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	Schneider Electric PEP
Paper	55.76	kg	2536	paper, woodfree, coated/market for paper, woodfree, coated/RER/kg	Schneider Electric PEP
Cardboard	15.93	kg	5697	kraft paper, unbleached/market for kraft paper, unbleached/GLO/kg	Schneider Electric PEP
Wood	15.93	kg	4730	cleft timber, measured as dry mass/market for cleft timber, measured as dry mass/Europe without Switzerland/kg	Schneider Electric PEP
Energy					
Electrical energy manufacturing	15274.56	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD
Heat energy manufacturing natural gas	271.24	MJ	11728	heat, district or industrial, natural gas/market for heat, district or industrial, natural gas/Europe without Switzerland/MJ	ABB EPD
Heat energy manufacturing other than natural gas	9712.39	MJ	11763	heat, district or industrial, other than natural gas/market for heat, district or industrial, other than natural gas/Europe without Switzerland/MJ	ABB EPD
Transport					
Neglected	0.00	tkm	13905	transport, freight, lorry ¿32 metric ton, EURO6/transport, freight, lorry ¿32 metric ton, EURO6/RER/metric ton*km	Phone meeting Siemens 20.03.20, case-specific
930kVA CVC transformer	2700.00	kg			Mail with data sheet Siemens 02.03.20, case-specific
Materials	2700.00	kg			
Aluminium	359.10	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	Schneider Electric PEP
Steel	415.80	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Schneider Electric PEP
Epoxy resin	221.40	kg	7017	epoxy resin, liquid/market for epoxy resin, liquid/GLO/kg	Schneider Electric PEP
Copper	10.80	kg	4912	copper/market for copper/GLO/kg	Schneider Electric PEP
Glass fiber	16.20	kg	7424	glass fibre/market for glass fibre/GLO/kg	Schneider Electric PEP
PET	24.30	kg	7034	polyethylene terephthalate, granulate, amorphous/market for polyethylene terephthalate, granulate, amorphous/GLO/kg	Schneider Electric PEP
Ferrous alloys	1641.60	kg	7831	cast iron/market for cast iron/GLO/kg	Schneider Electric PEP
UP polyester	10.80	kg	7033	polyester resin, unsaturated/market for polyester resin, unsaturated/GLO/kg	Schneider Electric PEP
Energy					
Electrical energy manufacturing	10354.33	kWh	1155	electricity, medium voltage/market for electricity, medium voltage/FI/kWh	ABB EPD
Heat energy manufacturing natural gas	870.11	MJ	11728	heat, district or industrial, natural gas/market for heat, district or industrial, natural gas/Europe without Switzerland/MJ	ABB EPD, IEA
Heat energy manufacturing other than natural gas	5897.61	MJ	11763	heat, district or industrial, other than natural gas/market for heat, district or industrial, other than natural gas/Europe without Switzerland/MJ	ABB EPD, IEA
Transport					
Transport from Finland to Norway	2840.40	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Google Maps, phone meeting Siemens 20.02.20, case-specific

Table 8.19: Shore system construction specific for the battery electric ferry, part 1

Shore system construction battery electric					
Substance	Amount	Unit	Arda ID	Arda name	Reference
1600kVA ESS transformer	3949.00	kg			Mail with data sheet Siemens 02.03.20, case-specific
Materials	3949.00	kg			
Copper	23.69	kg	4912	copper/market for copper/GLO/kg	Schneider Electric PEP
Steel	2720.86	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Schneider Electric PEP
Epoxy resin	11.85	kg	7017	epoxy resin, liquid/market for epoxy resin, liquid/GLO/kg	Schneider Electric PEP
UP polyester	11.85	kg	7033	polyester resin, unsaturated/market for polyester resin, unsaturated/GLO/kg	Schneider Electric PEP
Mineral oil	726.62	kg	5851	lubricating oil/market for lubricating oil/GLO/kg	Schneider Electric PEP
Aluminium	367.26	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	Schneider Electric PEP
Paper	55.29	kg	2536	paper, woodfree, coated/market for paper, woodfree, coated/RER/kg	Schneider Electric PEP
Cardboard	15.80	kg	5697	kraft paper, unbleached/market for kraft paper, unbleached/GLO/kg	Schneider Electric PEP
Wood	15.80	kg	4730	cleft timber, measured as dry mass/market for cleft timber, measured as dry mass/Europe without Switzerland/kg	Schneider Electric PEP
Energy					
Electrical energy manufacturing	15144.17	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD
Heat energy manufacturing natural gas	268.93	MJ	11728	heat, district or industrial, natural gas/market for heat, district or industrial, natural gas/Europe without Switzerland/MJ	ABB EPD, IEA
Heat energy manufacturing other than natural gas	9629.49	MJ	11763	heat, district or industrial, other than natural gas/market for heat, district or industrial, other than natural gas/Europe without Switzerland/MJ	ABB EPD, IEA
Transport					
Neglected, produced in Norway	0.00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Phone meeting Siemens 20.03.20, case-specific

Table 8.20: Shore system construction specific for the battery electric ferry, part 1

Shore system construction battery electric					
Substance	Amount	Unit	Arda ID	Arda name	Reference
BlueDrive PlusC switchboard	3900.00	kg			Mail with data sheet Siemens 02.03.20, case-specific
Materials	6206.56	kg			
Steel cabinets	873.60	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 02.03.20, phone meeting Siemens 28.02.20, estimated
Busbars	143.20	kg	4912	copper/market for copper/GLO/kg	Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 02.03.20, phone meeting Siemens 28.02.20, estimated
Drive BDPC switchboard port	2306.56	kg			Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 02.03.20, phone meeting Siemens 28.02.20, estimated
Materials	2306.56	kg			
Aluminium	54.90	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	ABB EPD
Copper	218.23	kg	4912	copper/market for copper/GLO/kg	ABB EPD
Plastic, nylon 6	109.46	kg	7025	nylon 6/market for nylon 6/GLO/kg	ABB EPD
Plastic, nylon 6-6	109.46	kg	7027	nylon 6-6/market for nylon 6-6/GLO/kg	ABB EPD
Steel	1310.78	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	ABB EPD
Iron	400.10	kg	7831	cast iron/market for cast iron/GLO/kg	ABB EPD
Cardboard	15.78	kg	5697	kraft paper, unbleached/market for kraft paper, unbleached/GLO/kg	ABB EPD
Other	263.53	kg	8004	zinc/market for zinc/GLO/kg	ABB EPD
Waste: hazardous waste	109.80	kg	12858	hazardous waste, for incineration/market for hazardous waste, for incineration/GLO/kg	ABB EPD
Waste: regular waste to landfill	65.88	kg	12870	process-specific burdens, residual material landfill/market for process-specific burdens, residual material landfill/GLO/kg	ABB EPD
Energy					
Electricity	54.90	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD
Electronics	576.64	kg	8594	electronics, for control units/market for electronics, for control units/GLO/kg	Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 02.03.20, phone meeting Siemens 28.02.20, estimated
Energy and infrastructure					
Metal working steel	873.60	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on actual data
Metal working copper	143.20	kg	1926	metal working, average for copper product manufacturing/metal working, average for copper product manufacturing/RER/kg	Assumed based on actual data
Transport					
Neglected, produced in Norway	0.00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Mail with data sheet Siemens 24.02.20

Table 8.21: Shore system construction specific for the battery electric ferry, part 3

Shore system construction battery electric					
Substance	Amount	Unit	Arda ID	Arda name	Reference
11kV switchboard port	4500.00	kg			Mail with data sheet Siemens 02.03.20, case-specific
Materials	7591.60	kg			
Steel cabinets	546.00	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 02.03.20, phone meeting Siemens 28.02.20, estimated
Busbars	89.50	kg	4912	copper/market for copper/GLO/kg	Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 02.03.20, phone meeting Siemens 28.02.20, estimated
Drive 11 kV switchboard port	3091.60	kg			Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 02.03.20, phone meeting Siemens 28.02.20, estimated
Materials	3091.60	kg			
Aluminium	73.59	kg	7958	aluminium, wrought alloy/market for aluminium, wrought alloy/GLO/kg	ABB EPD
Copper	292.51	kg	4912	copper/market for copper/GLO/kg	ABB EPD
Plastic, nylon 6	146.72	kg	7025	nylon 6/market for nylon 6/GLO/kg	ABB EPD
Plastic, nylon 6-6	146.72	kg	7027	nylon 6-6/market for nylon 6-6/GLO/kg	ABB EPD
Steel	1756.90	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	ABB EPD
Iron	536.27	kg	7831	cast iron/market for cast iron/GLO/kg	ABB EPD
Cardboard	21.16	kg	5697	kraft paper, unbleached/market for kraft paper, unbleached/GLO/kg	ABB EPD
Other	353.22	kg	8004	zinc/market for zinc/GLO/kg	ABB EPD
Waste: hazardous waste	147.18	kg	12858	hazardous waste, for incineration/market for hazardous waste, for incineration/GLO/kg	ABB EPD
Waste: regular waste to landfill	88.31	kg	12870	process-specific burdens, residual material landfill/market for process-specific burdens, residual material landfill/GLO/kg	ABB EPD
Energy					
Electricity	73.59	kWh	1153	electricity, medium voltage/market for electricity, medium voltage/DE/kWh	ABB EPD
Electronics	772.90	kg	8594	electronics, for control units/market for electronics, for control units/GLO/kg	Mail with powerpoint Siemens 29.10.19, mail with data sheet Siemens 02.03.20, phone meeting Siemens 28.02.20, estimated
Energy					
Metal working steel	546.00	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on actual data
Metal working copper	89.50	kg	1926	metal working, average for copper product manufacturing/metal working, average for copper product manufacturing/RER/kg	Assumed based on actual data
Transport					
Transport from Germany to Norway	12624.83	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Google Maps, mail Siemens 24.02.20, case-specific
Charge tower	18000.00	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Mail with data sheet Siemens 02.03.20, phone meeting Siemens 20.03.20, case-specific
Materials	18000.00	kg			
Steel	18000.00	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Mail with data sheet Siemens 02.03.20, phone meeting Siemens 20.03.20, case-specific
Energy					
Metal working	18000.00	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on actual data
Transport					
Transport from Germany to Norway	29934.00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Google Maps, phone meeting Siemens 20.03.20, case-specific

Table 8.22: Shore system construction specific for the battery electric ferry, part 4

Shore system construction battery electric					
Substance	Amount	Unit	Arda ID	Arda name	Reference
UPS (Uninterruptable Power Supply)	435.00	kg			Mail with data sheet Siemens 20.03.20, case-specific
Materials	435.00	kg			
Copper	106.58	kg	4912	copper/market for copper/GLO/kg	Schneider Electric PEP
Steel	75.69	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Schneider Electric PEP
Acrylonitrile Butadiene Styrene (ABS)	3.48	kg	7009	acrylonitrile-butadiene-styrene copolymer/market for acrylonitrile-butadiene-styrene copolymer/GLO/kg	Schneider Electric PEP
Polychlorure de vinyle (PVC) and other thermoplastiques	3.05	kg	7051	polyvinylchloride, bulk polymerised/market for polyvinylchloride, bulk polymerised/GLO/kg	Schneider Electric PEP
Batteries (Pb)	189.66	kg	8654	battery, NaCl/market for battery, NaCl/GLO/kg	Schneider Electric PEP
Electronic circuit ¿ 10 cm2	39.15	kg	8594	electronics, for control units/market for electronics, for control units/GLO/kg	Schneider Electric PEP
Connectors	5.00	kg	8451	electric connector, wire clamp/market for electric connector, wire clamp/GLO/kg	Schneider Electric PEP
Cables	5.00	kg	8662	cable, unspecified/market for cable, unspecified/GLO/kg	Schneider Electric PEP
Paper	6.09	kg	2536	paper, woodfree, coated/market for paper, woodfree, coated/RER/kg	Schneider Electric PEP
Fan	1.31	kg	8457	fan, for power supply unit, desktop computer/market for fan, for power supply unit, desktop computer/GLO/kg	Schneider Electric PEP
Energy					
Metal working steel	75.69	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on actual data
Metal working copper	106.58	kg	1926	metal working, average for copper product manufacturing/metal working, average for copper product manufacturing/RER/kg	Assumed based on actual data
Transport					
Transport from Italy to Norway	1318.49	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Mail with data sheet Siemens 20.03.20, assumed
400/230V distribution	100.00	kg			Phone meeting Siemens 20.03.20, guessed
Materials	100.00	kg			
Steel	66.67	kg	7851	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	Phone meeting Siemens 20.03.20, guessed
Copper	33.33	kg	4912	copper/market for copper/GLO/kg	Phone meeting Siemens 20.03.20, guessed
Energy					
Metal working steel	66.67	kg	1939	metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Assumed based on actual data
Metal working copper	33.33	kg	1926	metal working, average for copper product manufacturing/metal working, average for copper product manufacturing/RER/kg	Assumed based on actual data
Transport					
Neglected, produced in Norway	0.00	tkm	13888	transport, freight, lorry 16-32 metric ton, EURO6/transport, freight, lorry 16-32 metric ton, EURO6/RER/metric ton*km	Phone meeting Siemens 20.03.20, case-specific
Cooling and climate system					
Materials					
Tubes	25.00	m	8901	spiral-seam duct, steel, DN 125/market for spiral-seam duct, steel, DN 125/GLO/m	Assumed length, DN125 from data sheet from mail Siemens 20.03.20, case-specific
Dry cooler 175 kW + cooling machine 131 kW	3.06	unit	8867	absorption chiller, 100kW/market for absorption chiller, 100kW/GLO/unit	Data sheet from mail Siemens 20.03.20, case-specific
Pumps	0.32	unit	8722	pump, 40W/market for pump, 40W/GLO/unit	Data sheet from mail Siemens 20.03.20, case-specific

Table 8.23: Operation diesel electric case

Operation diesel					
Process	Amount	Unit	Arda ID	Arda name	Reference
Diesel value chain	3.87E+07	kg	5834	diesel, low-sulfur/market for diesel, low-sulfur/Europe without Switzerland/kg	
Electricity consumption mooring system and shore electricity	Confidential	kWh	1159		Mail Cavotec 03.03.20, Mail Fosen-Namsos 17.03.20
Coal	Confidential	kWh	10293	electricity, high voltage/heat and power co-generation, hard coal/NO/kWh	https://www.iea.org/countries/norway
Oil	Confidential	kWh	11078	electricity, high voltage/electricity production, oil/NO/kWh	https://www.iea.org/countries/norway
Natural gas	Confidential	kWh	9567	electricity, high voltage/electricity production, natural gas, conventional power plant/NO/kWh	https://www.iea.org/countries/norway
Biofuels + waste	Confidential	kWh	12016	electricity, high voltage/heat and power co-generation, biogas, gas engine/NO/kWh	https://www.iea.org/countries/norway
Nuclear	Confidential	kWh	9599	electricity, high voltage/electricity production, nuclear, boiling water reactor/SE/kWh	https://www.iea.org/countries/norway
Hydro	Confidential	kWh	9264	electricity, high voltage/electricity production, hydro, reservoir, alpine region/NO/kWh	https://www.iea.org/countries/norway
Geothermal + tide + other sources	Confidential	kWh	14141	electricity, high voltage/electricity, high voltage, production mix/NORDEL/kWh	https://www.iea.org/countries/norway
Solar PV + solar thermal	Confidential	kWh	11276	electricity, low voltage/electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted/SE/kWh	https://www.iea.org/countries/norway
Wind	Confidential	kWh	9763	electricity, high voltage/electricity production, wind, 1-3MW turbine, onshore/NO/kWh	https://www.iea.org/countries/norway
Sulfur hexafluoride	Confidential	kg	6638	sulfur hexafluoride, liquid/market for sulfur hexafluoride, liquid/GLO/kg	Ecoinvent
Transmission network medium voltage	Confidential	km	13376	transmission network, electricity, medium voltage/market for transmission network, electricity, medium voltage/GLO/km	Ecoinvent
Engine oil	7.75E+04	kg	5851	lubricating oil/market for lubricating oil/GLO/kg	FosenNamsos

Table 8.24: Operation battery electric case

Operation battery					
Process	Amount	Unit	Arda ID	Arda name	Reference
Fuel consumption	0	kg	5832	diesel/market for diesel/Europe without Switzerland/kg	
Electricity consumption ferry + mooring system	Confidential	kWh	1159		Mail Cavotec 03.03.20, mail Fosen-Namsos 17.03.20, mail FosenNamsos 03.03.20, phone meeting FosenNamsos 17.03.20
Coal	Confidential	kWh	10293	electricity, high voltage/heat and power co-generation, hard coal/NO/kWh	https://www.iea.org/countries/norway
Oil	Confidential	kWh	11078	electricity, high voltage/electricity production, oil/NO/kWh	https://www.iea.org/countries/norway
Natural gas	Confidential	kWh	9567	electricity, high voltage/electricity production, natural gas, conventional power plant/NO/kWh	https://www.iea.org/countries/norway
Biofuels + waste	Confidential	kWh	12016	electricity, high voltage/heat and power co-generation, biogas, gas engine/NO/kWh	https://www.iea.org/countries/norway
Nuclear	Confidential	kWh	9599	electricity, high voltage/electricity production, nuclear, boiling water reactor/SE/kWh	https://www.iea.org/countries/norway
Hydro	Confidential	kWh	9264	electricity, high voltage/electricity production, hydro, reservoir, alpine region/NO/kWh	https://www.iea.org/countries/norway
Geothermal + tide + other sources	Confidential	kWh	14141	electricity, high voltage/electricity, high voltage, production mix/NORDEL/kWh	https://www.iea.org/countries/norway
Solar PV + solar thermal	Confidential	kWh	11276	electricity, low voltage/electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted/SE/kWh	https://www.iea.org/countries/norway
Wind	Confidential	kWh	9763	electricity, high voltage/electricity production, wind, 1-3MW turbine, onshore/NO/kWh	https://www.iea.org/countries/norway
Sulfur hexafluoride	Confidential	kg	6638	sulfur hexafluoride, liquid/market for sulfur hexafluoride, liquid/GLO/kg	Ecoinvent
Transmission network medium voltage	Confidential	km	13376	transmission network, electricity, medium voltage/market for transmission network, electricity, medium voltage/GLO/km	Ecoinvent

Table 8.25: End of life common for the diesel electric and battery electric ferry, part 1

End of life					
Process	Amount	Unit	Arda ID	Arda name	Reference
Ferry dismantling					
Energy					
Electricity	1.88E+02	kWh	1159		Energy Consumption for Ship Dismantling through Beaching Method
Diesel	9.81E+04	MJ	896	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	Energy Consumption for Ship Dismantling through Beaching Method
LPG	1.23E+04	kg	2083	liquefied petroleum gas/market for liquefied petroleum gas/CH/kg	Energy Consumption for Ship Dismantling through Beaching Method
Electric motors	5.05E+03	kg			
Waste	1.92E+02	kg			
Regular waste to landfill	1.92E+02	kg	3317	process-specific burdens, residual material landfill/process-specific burdens, residual material landfill/CH/kg	ABB EPD
Energy					
Electrical energy	2.39E+02	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD
300kVA shipnet supply transformer	1.15E+03	kg			
Waste	3.36E+02	kg			
Hazardous waste treatment	0.00E+00	kg	3067	hazardous waste, for incineration/treatment of hazardous waste, hazardous waste incineration/CH/kg	ABB EPD
Hazardous waste process-specific	2.84E+02	kg	3073	process-specific burdens, hazardous waste incineration plant/process-specific burdens, hazardous waste incineration plant/CH/kg	ABB EPD
Landfill waste	5.19E+01	kg	3317	process-specific burdens, residual material landfill/process-specific burdens, residual material landfill/CH/kg	ABB EPD
Diesel gensets	4.62E+03	kg			
550kVA generator	2.58E+03	kg			
Waste	9.80E+01	kg			
Regular waste to landfill	9.80E+01	kg	3317	process-specific burdens, residual material landfill/process-specific burdens, residual material landfill/CH/kg	ABB EPD
Energy					
Electrical energy	1.22E+02	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD
BlueDrive PlusC swbd FWD	5.80E+03	kg			
Drive BDPC swbd FWD	3.32E+03	kg			
Waste	3.41E+03	kg			
Hazardous waste treatment	0.00E+00	kg	3067	hazardous waste, for incineration/treatment of hazardous waste, hazardous waste incineration/CH/kg	ABB EPD
Hazardous waste process-specific	3.16E+01	kg	3073	process-specific burdens, hazardous waste incineration plant/process-specific burdens, hazardous waste incineration plant/CH/kg	ABB EPD
Regular waste to landfill	3.38E+03	kg	3317	process-specific burdens, residual material landfill/process-specific burdens, residual material landfill/CH/kg	ABB EPD
Energy				+	
Electrical energy	0.00E+00	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD

Table 8.26: End of life common for the diesel electric and battery electric ferry, part 2

End of life					
Process	Amount	Unit	Arda ID	Arda name	Reference
BlueDrive PlusC swbd AFT	6.50E+03	kg			
Drive BDPC swbd AFT	3.88E+03	kg			
Waste	3.99E+03	kg			
Hazardous waste treatment	0.00E+00	kg	3067	hazardous waste, for incineration/treatment of hazardous waste, hazardous waste incineration/CH/kg	ABB EPD
Hazardous waste process-specific	3.69E+01	kg	3073	process-specific burdens, hazardous waste incineration plant/process-specific burdens, hazardous waste incineration plant/CH/kg	ABB EPD
Regular waste to landfill	3.95E+03	kg	3317	process-specific burdens, residual material landfill/process-specific burdens, residual material landfill/CH/kg	ABB EPD
Energy					
Electrical energy	0.00E+00	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD
230V FWD switchboard	1.23E+03	kg			
Drive 230V FWD switchboard	5.73E+02	kg			
Waste	5.89E+02	kg			
Hazardous waste treatment	0.00E+00	kg	3067	hazardous waste, for incineration/treatment of hazardous waste, hazardous waste incineration/CH/kg	ABB EPD
Hazardous waste process-specific	5.46E+00	kg	3073	process-specific burdens, hazardous waste incineration plant/process-specific burdens, hazardous waste incineration plant/CH/kg	ABB EPD
Regular waste to landfill	5.84E+02	kg	3317	process-specific burdens, residual material landfill/process-specific burdens, residual material landfill/CH/kg	ABB EPD
Energy					
Electrical energy	0.00E+00	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD
230V AFT switchboard	1.02E+03	kg			
Drive 230V AFT switchboard	4.08E+02	kg			
Waste	4.19E+02	kg			
Hazardous waste treatment	0.00E+00	kg	3067	hazardous waste, for incineration/treatment of hazardous waste, hazardous waste incineration/CH/kg	ABB EPD
Hazardous waste process-specific	3.88E+00	kg	3073	process-specific burdens, hazardous waste incineration plant/process-specific burdens, hazardous waste incineration plant/CH/kg	ABB EPD
Regular waste to landfill	4.15E+02	kg	3317	process-specific burdens, residual material landfill/process-specific burdens, residual material landfill/CH/kg	ABB EPD
Energy					
Electrical energy	0.00E+00	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD
Vacuum mooring system	1.57E+04	kg			
Electrical motor mooring system	5.95E+02	kg			
Waste	2.26E+01	kg			
Regular waste to landfill	2.26E+01	kg	3317	process-specific burdens, residual material landfill/process-specific burdens, residual material landfill/CH/kg	ABB EPD
Energy					
Electrical energy	2.82E+01	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD

Table 8.27: End of life specific for the battery electric ferry, part 1

End of life battery electric					
Process	Amount	Unit	Arda ID	Arda name	Reference
2700kVA charge transformer	5.20E+03	kg			
Waste	1.52E+03	kg			
Hazardous waste treatment	0.00E+00	kg	3067	hazardous waste, for incineration/treatment of hazardous waste, hazardous waste incineration/CH/kg	ABB EPD
Hazardous waste process-specific	1.29E+03	kg	3073	process-specific burdens, hazardous waste incineration plant/process-specific burdens, hazardous waste incineration plant/CH/kg	ABB EPD
Landfill waste	2.34E+02	kg	3317	process-specific burdens, residual material landfill/process-specific burdens, residual material landfill/CH/kg	ABB EPD
11kV charging switchboard ferry	3.50E+03	kg			
Drive 11 kV charging switchboard ferry	2.39E+03	kg			
Waste	2.46E+03	kg			
Hazardous waste treatment	0.00E+00	kg	3067	hazardous waste, for incineration/treatment of hazardous waste, hazardous waste incineration/CH/kg	ABB EPD
Hazardous waste process-specific	2.28E+01	kg	3073	process-specific burdens, hazardous waste incineration plant/process-specific burdens, hazardous waste incineration plant/CH/kg	ABB EPD
Regular waste to landfill	2.44E+03	kg	3317	process-specific burdens, residual material landfill/process-specific burdens, residual material landfill/CH/kg	ABB EPD
Energy					
Electrical energy	0.00E+00	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD
1600kVA grid transformer	3.98E+03	kg			
Waste	1.16E+03	kg			
Hazardous waste treatment	0.00E+00	kg	3067	hazardous waste, for incineration/treatment of hazardous waste, hazardous waste incineration/CH/kg	
Hazardous waste process-specific	9.84E+02	kg	3073	process-specific burdens, hazardous waste incineration plant/process-specific burdens, hazardous waste incineration plant/CH/kg	
Regular waste to landfill	1.80E+02	kg	3317	process-specific burdens, residual material landfill/process-specific burdens, residual material landfill/CH/kg	
930kVA CVC transformer	2.70E+03	kg			
Waste	7.89E+02	kg			
Hazardous waste treatment	0.00E+00	kg	3067	hazardous waste, for incineration/treatment of hazardous waste, hazardous waste incineration/CH/kg	
Hazardous waste process-specific	6.67E+02	kg	3073	process-specific burdens, hazardous waste incineration plant/process-specific burdens, hazardous waste incineration plant/CH/kg	
Regular waste to landfill	1.22E+02	kg	3317	process-specific burdens, residual material landfill/process-specific burdens, residual material landfill/CH/kg	

Table 8.28: End of life specific for the battery electric ferry, part 2

End of life battery electric					
Process	Amount	Unit	Arda ID	Arda name	Reference
1600kVA ESS transformer	3.95E+03	kg			
Waste	1.15E+03	kg			
Hazardous waste treatment	0.00E+00	kg	3067	hazardous waste, for incineration/treatment of hazardous waste, hazardous waste incineration/CH/kg	ABB EPD
Hazardous waste process-specific	9.76E+02	kg	3073	process-specific burdens, hazardous waste incineration plant/process-specific burdens, hazardous waste incineration plant/CH/kg	ABB EPD
Regular waste to landfill	1.78E+02	kg	3317	process-specific burdens, residual material landfill/process-specific burdens, residual material landfill/CH/kg	ABB EPD
BlueDrive PlusC switchboard	3.90E+03	kg			
Drive BDPC switchboard port	2.31E+03	kg			
Waste	2.37E+03	kg			
Hazardous waste treatment	0.00E+00	kg	3067	hazardous waste, for incineration/treatment of hazardous waste, hazardous waste incineration/CH/kg	ABB EPD
Hazardous waste process-specific	2.20E+01	kg	3073	process-specific burdens, hazardous waste incineration plant/process-specific burdens, hazardous waste incineration plant/CH/kg	ABB EPD
Regular waste to landfill	2.35E+03	kg	3317	process-specific burdens, residual material landfill/process-specific burdens, residual material landfill/CH/kg	ABB EPD
Energy					
Electrical energy	0.00E+00	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD
11kV switchboard port	4.50E+03	kg			
Drive 11 kV switchboard port	3.09E+03	kg			
Waste	3.18E+03	kg			
Hazardous waste treatment	0.00E+00	kg	3067	hazardous waste, for incineration/treatment of hazardous waste, hazardous waste incineration/CH/kg	ABB EPD
Hazardous waste process-specific	2.94E+01	kg	3073	process-specific burdens, hazardous waste incineration plant/process-specific burdens, hazardous waste incineration plant/CH/kg	ABB EPD
Regular waste to landfill	3.15E+03	kg	3317	process-specific burdens, residual material landfill/process-specific burdens, residual material landfill/CH/kg	ABB EPD
Energy					
Electrical energy	0.00E+00	kWh	1159	electricity, medium voltage/market for electricity, medium voltage/NO/kWh	ABB EPD
Batteries					
Energy					
Energy for analysis, demolition and testing	0.00E+00	kWh	1124	electricity, low voltage/market for electricity, low voltage/NO/kWh	Mail Fredrik Andresen 05.02.20, generic for batteries
Transport					
Transport	1.77E+05	tkm	13905	transport, freight, lorry ¿32 metric ton, EURO6/transport, freight, lorry ¿32 metric ton, EURO6/RER/metric ton*km	Mail Fredrik Andresen 05.02.20, generic for batteries

C Additional results

C.1 Additional MariTEAM results

Identification of representative periods

The period in Figure 8.1 is clearly not representative as there are extreme outliers with irrational loads. The period in Figure 8.2 on the other hand has logical loads, but the crossings are not consistent with for instance the first crossing visible from the MariTEAM output having values close to zero for the battery data.

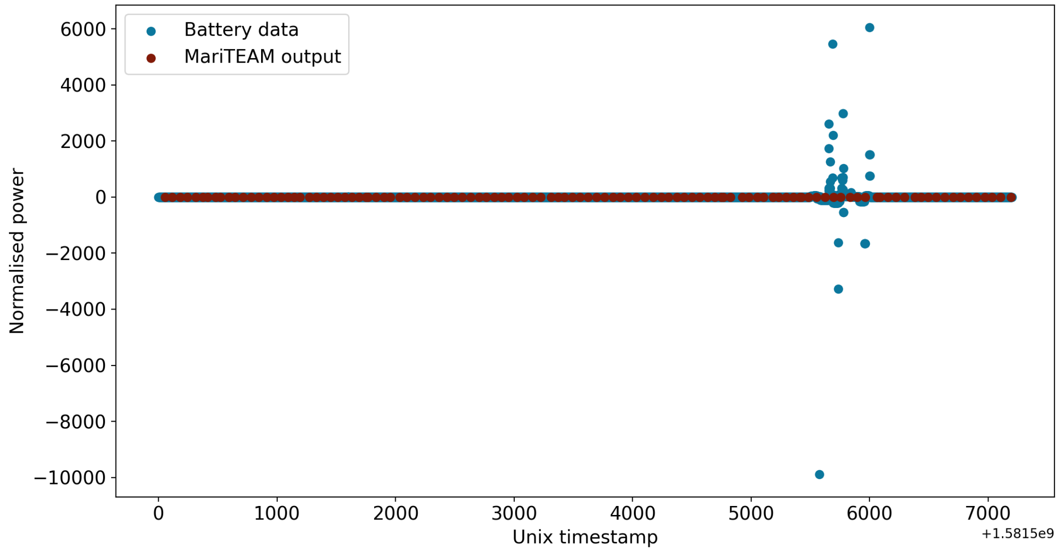

Figure 8.1: Battery data and MariTEAM output normalised on average power during a not representative period

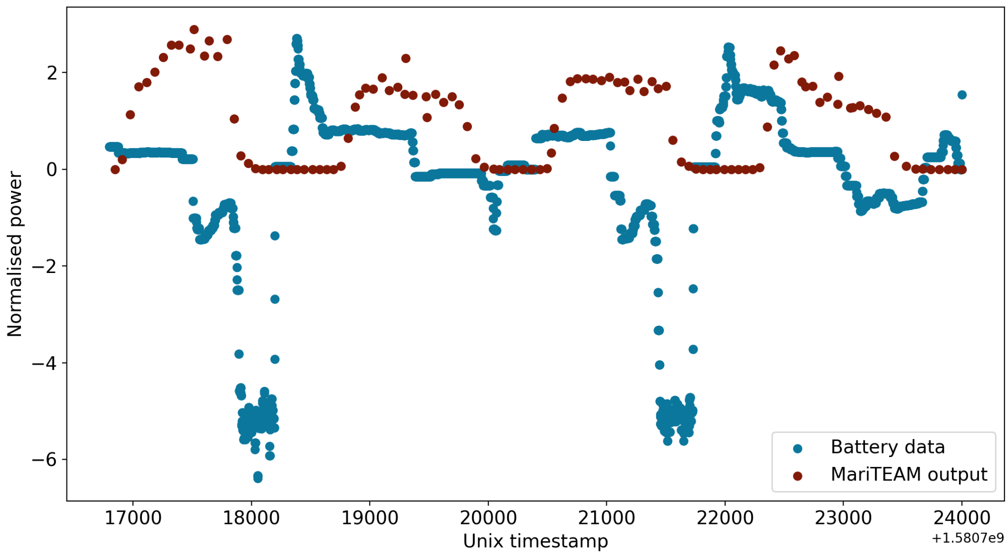

Figure 8.2: Battery data and MariTEAM output normalised on average power during a not representative period 2

From Figure 8.3, it can be observed that the battery data and the MariTEAM output are out of sync with a time delay. This result is found throughout the two-week time period considered, and is assumed not to affect the total energy consumption significantly.

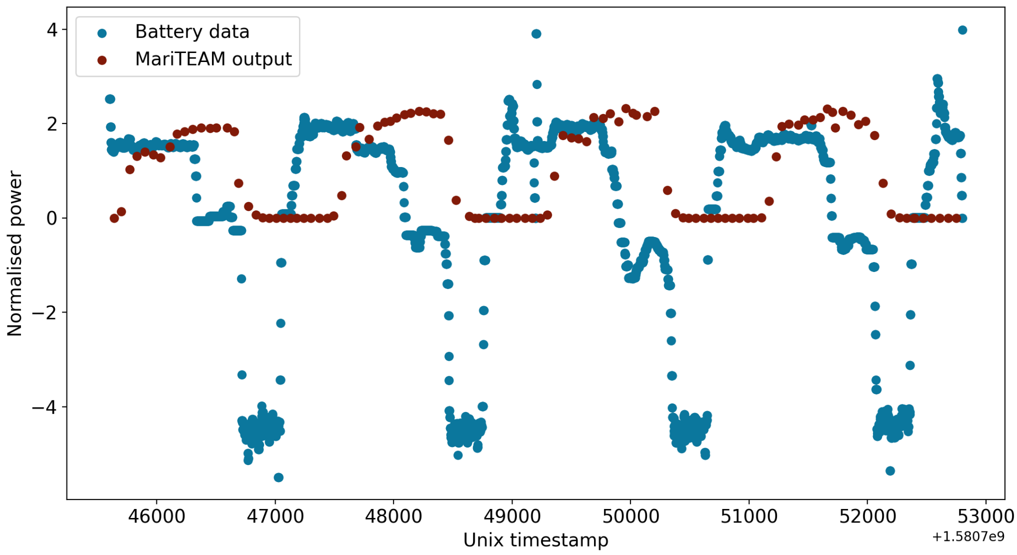

Figure 8.3: Battery data and MariTEAM data normalised on average power during a representative period

Table 8.29: Calibration results for test cases

Without cleaning

Calibration: Tuesday 04.02 12:00-14:00. Testing: Tuesday 04.02 11:00-15:00	
Load_adjust	1.05
Siemens/MariTEAM energysum 2 without load_adjust	1.01
Siemens/MariTEAM energysum 2 with load_adjust	0.96

Calibration: Tuesday 04.02 12:00-14:00. Testing: Tuesday 11.02 10:30-12:30	
Load_adjust	1.05
Siemens/MariTEAM energysum 2 without load_adjust	1.09
Siemens/MariTEAM energysum 2 with load_adjust	1.04

Calibration: Tuesday 11.02 10:30-12:30. Testing: Tuesday 04.02 11:00-15:00	
Load_adjust	1.09
Siemens/MariTEAM energysum 2 without load_adjust	1.01
Siemens/MariTEAM energysum 2 with load_adjust	0.93

Calibration: Tuesday 11.02 10:30-12:30. Testing: Tuesday 04.02 12:00-14:00	
Load_adjust	1.09
Siemens/MariTEAM energysum 2 without load_adjust	1.05
Siemens/MariTEAM energysum 2 with load_adjust	0.96

Calibration: Tuesday 04.02 11:00-15:00. Testing: Tuesday 04.02 12:00-14:00	
Load_adjust	1.01
Siemens/MariTEAM energysum 2 without load_adjust	1.05
Siemens/MariTEAM energysum 2 with load_adjust	1.04

Calibration: Tuesday 04.02 11:00-15:00. Testing: Tuesday 11.02 10:30-12:30	
Load_adjust	1.01
Siemens/MariTEAM energysum 2 without load_adjust	1.09
Siemens/MariTEAM energysum 2 with load_adjust	1.08

Calibration: Monday 03.02 16:00-18:00. Testing: Tuesday 04.02 12:00-14:00	
Load_adjust	1.08
Siemens/MariTEAM energysum 2 without load_adjust	1.05
Siemens/MariTEAM energysum 2 with load_adjust	0.97

Calibration: Monday 03.02 16:00-18:00. Testing: Tuesday 04.02 11:00-15:00	
Load_adjust	1.08
Siemens/MariTEAM energysum 2 without load_adjust	1.01
Siemens/MariTEAM energysum 2 with load_adjust	0.93

Calibration: Monday 03.02 16:00-18:00. Testing: Tuesday 11.02 10:30-12:30	
Load_adjust	1.08
Siemens/MariTEAM energysum 2 without load_adjust	1.09
Siemens/MariTEAM energysum 2 with load_adjust	1.01

Calibration: Tuesday 04.02 12:00-14:00. Testing: Monday 03.02 16:00-18:00	
Load_adjust	1.05
Siemens/MariTEAM energysum 2 without load_adjust	1.08
Siemens/MariTEAM energysum 2 with load_adjust	1.03

Calibration: Tuesday 11.02 10:30-12:30. Testing: Monday 03.02 16:00-18:00	
Load_adjust	1.09
Siemens/MariTEAM energysum 2 without load_adjust	1.08
Siemens/MariTEAM energysum 2 with load_adjust	0.99

Calibration: Tuesday 04.02 11:00-15:00. Testing: Monday 03.02 16:00-18:00	
Load_adjust	1.01
Siemens/MariTEAM energysum 2 without load_adjust	1.08
Siemens/MariTEAM energysum 2 with load_adjust	1.07

Calibration: Monday 03.02 17:00-19:00. Testing: Tuesday 04.02 12:00-14:00	
Load_adjust	0.97
Siemens/MariTEAM energysum 2 without load_adjust	1.05
Siemens/MariTEAM energysum 2 with load_adjust	1.08

Calibration: Monday 03.02 17:00-19:00. Testing: Tuesday 04.02 11:00-15:00	
Load_adjust	0.97
Siemens/MariTEAM energysum 2 without load_adjust	1.01
Siemens/MariTEAM energysum 2 with load_adjust	1.04

Calibration: Monday 03.02 17:00-19:00. Testing: Tuesday 11.02 10:30-12:30	
Load_adjust	0.97
Siemens/MariTEAM energysum 2 without load_adjust	1.09
Siemens/MariTEAM energysum 2 with load_adjust	1.12

Calibration: Monday 03.02 17:00-19:00. Testing: Monday 03.02 16:00-18:00	
Load_adjust	0.97
Siemens/MariTEAM energysum 2 without load_adjust	1.08
Siemens/MariTEAM energysum 2 with load_adjust	1.12

Calibration: Tuesday 04.02 12:00-14:00. Testing: Monday 03.02 17:00-19:00	
Load_adjust	1.05
Siemens/MariTEAM energysum 2 without load_adjust	0.97
Siemens/MariTEAM energysum 2 with load_adjust	0.92

Calibration: Tuesday 11.02 10:30-12:30. Testing: Monday 03.02 17:00-19:00	
Load_adjust	1.09
Siemens/MariTEAM energysum 2 without load_adjust	0.97
Siemens/MariTEAM energysum 2 with load_adjust	0.89

Calibration: Tuesday 04.02 11:00-15:00. Testing: Monday 03.02 17:00-19:00	
Load_adjust	1.01
Siemens/MariTEAM energysum 2 without load_adjust	0.97
Siemens/MariTEAM energysum 2 with load_adjust	0.96

Calibration: Monday 03.02 16:00-18:00. Testing: Monday 03.02 17:00-19:00	
Load_adjust	1.08
Siemens/MariTEAM energysum 2 without load_adjust	0.97
Siemens/MariTEAM energysum 2 with load_adjust	0.89

With SoC cleaning

Calibration: Tuesday 04.02 12:00-14:00. Testing: Tuesday 04.02 11:00-15:00	
Load_adjust	1.05
Siemens/MariTEAM energysum 2 without load_adjust	1.01
Siemens/MariTEAM energysum 2 with load_adjust	0.96

Calibration: Monday 03.02 17:00-19:00. Testing: Monday 03.02 16:00-18:00	
Load_adjust	0.97
Siemens/MariTEAM energysum 2 without load_adjust	1.08
Siemens/MariTEAM energysum 2 with load_adjust	1.12

Calibration: mandag 03.02 17-19, Testing: Tuesday 11.02 10:30-12:30	
Load_adjust	0.97
Siemens/MariTEAM energysum 2 without load_adjust	1.09
Siemens/MariTEAM energysum 2 with load_adjust	1.12

Model simulation and analysis of MariTEAM output

The extended periods with zero load in Figure 8.4 are periods where the ferry is not in operation.

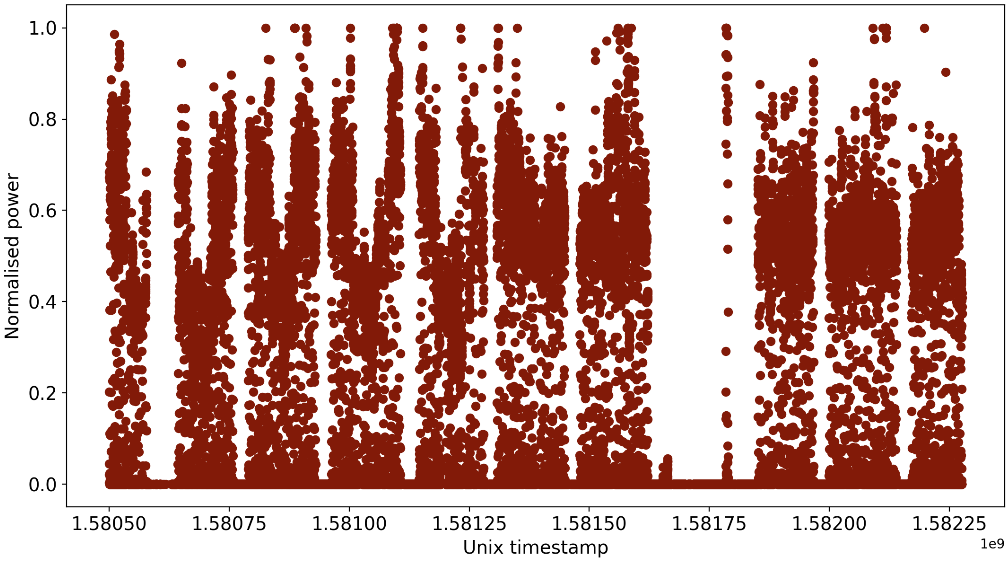

Figure 8.4: Load power profile in MariTEAM output for battery electric case

As evident from Figure 4.6 in Chapter 4 and Figures 8.5 and 8.2 below, CO_2 and NO_x emissions are the largest in terms of weight, followed by CO and OC. SO_x, EC and BC are relatively small.

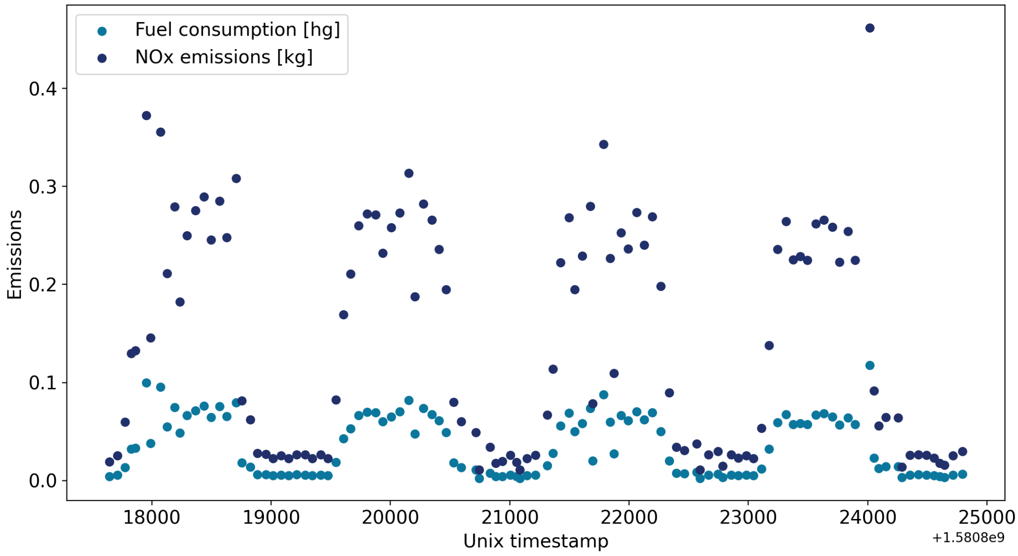

Figure 8.5: NOx emissions profile for sample crossings

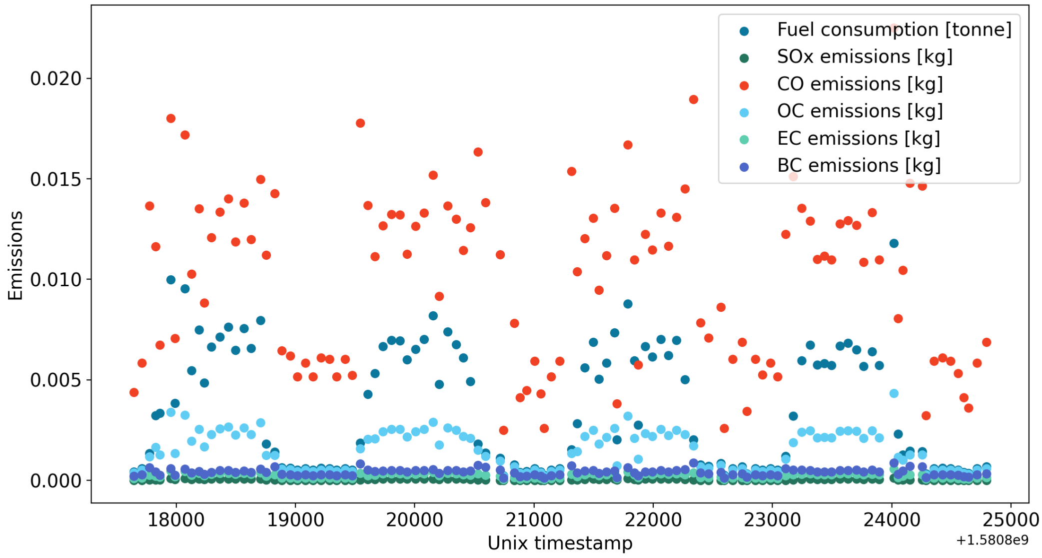

Figure 8.6: Remaining emissions profiles for sample crossings

C.2 Additional LCA results

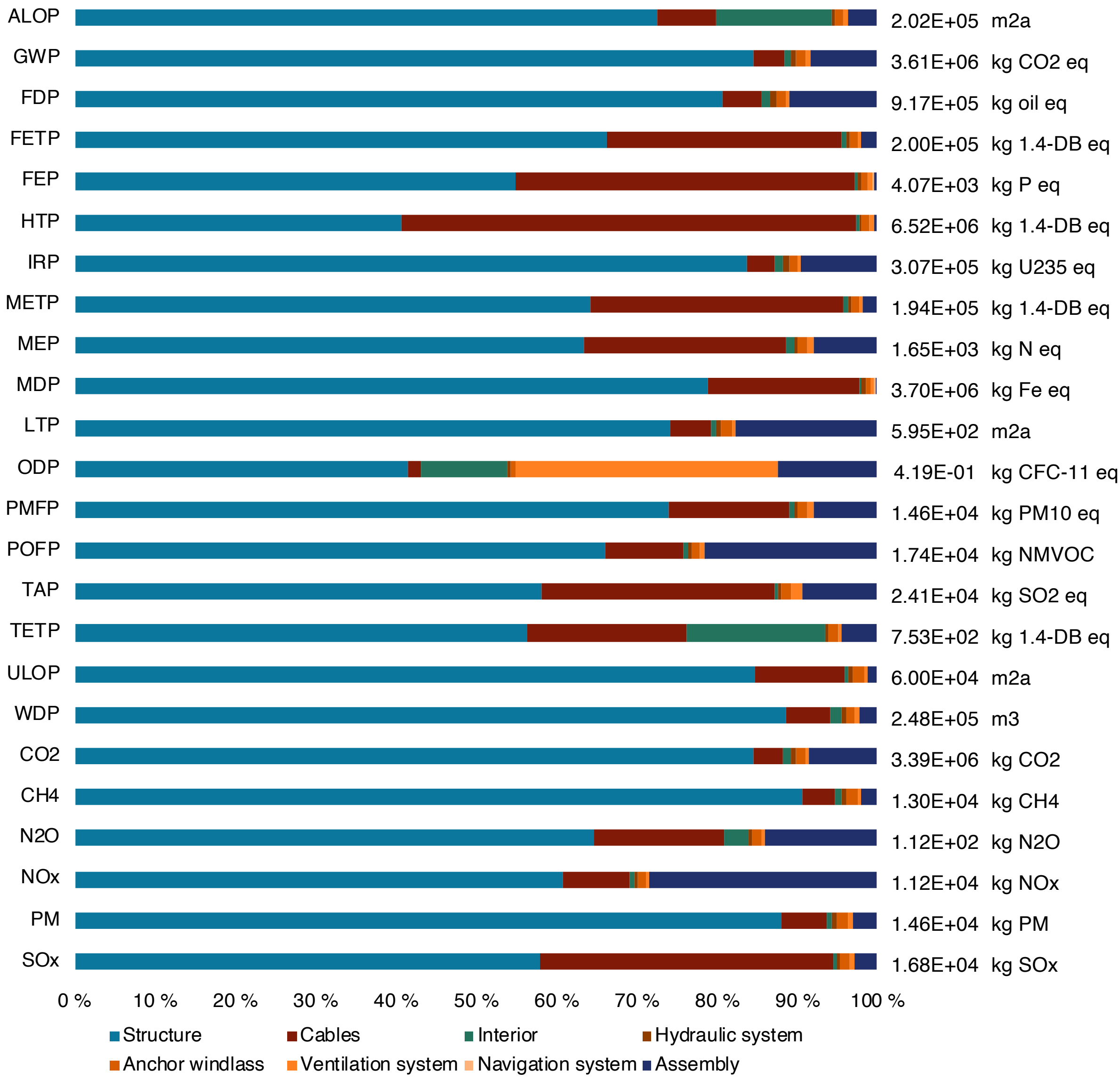

Figure 8.7: Distribution of LCA results from components in the battery electric ferry construction

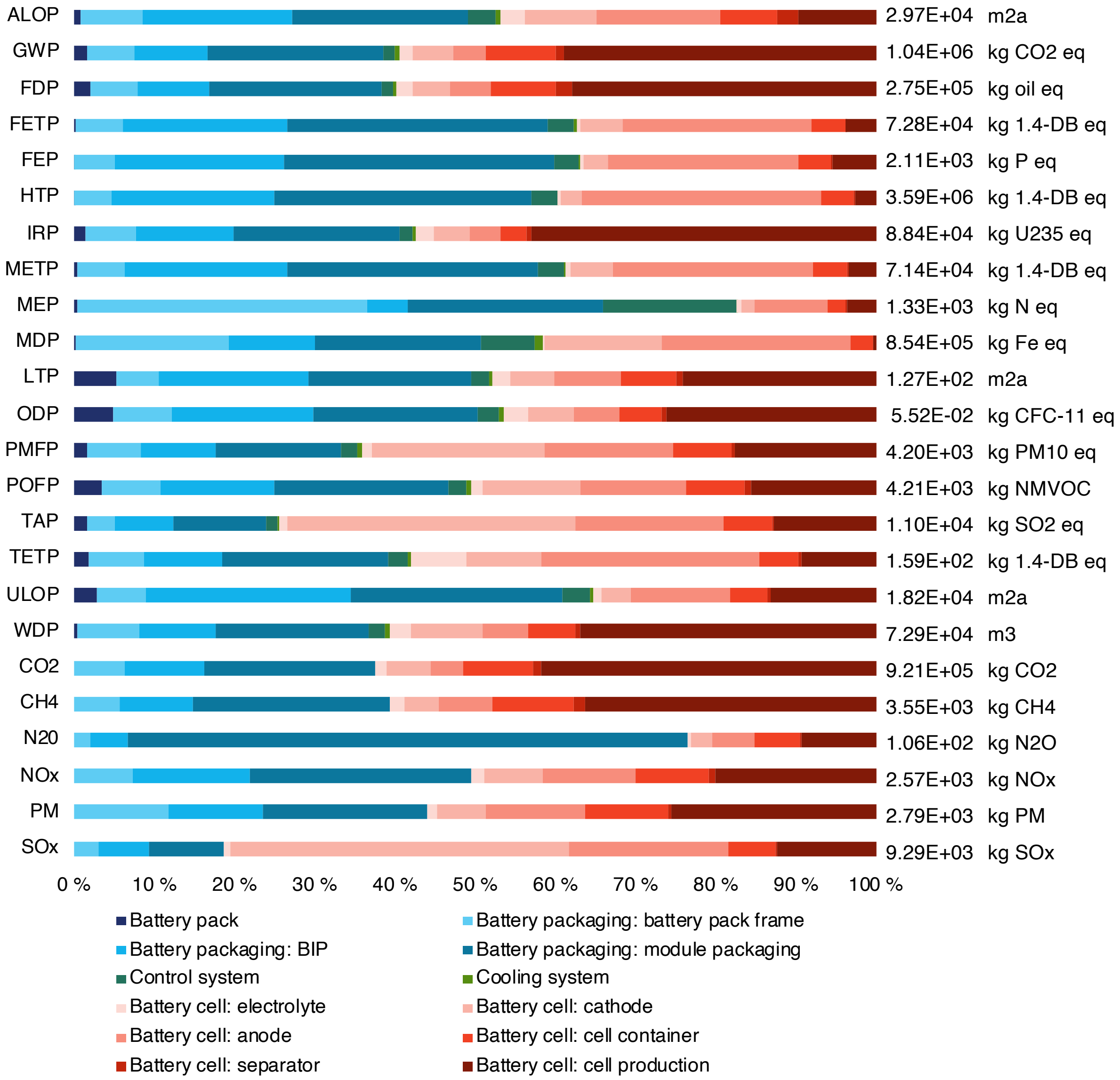

Figure 8.8: Distribution of LCA results from components in the shore battery production

Results per PKT

The PKT was calculated using Equation (8.8) inspired by Statens vegvesen (n.d.b), where C_P is the passenger capacity of the ferry, U_C is the capacity utilisation, and D_L is the total kilometres travelled by the ferry during its lifetime. The capacity utilisation was found for boat routes in Trøndelag in 2019 using SSB (2020).

$$PKT = C_P * U_C * D_L = 399 * 0.275 * 51,800 = 5,683,755 \tag{8.8}$$

The total kilometres travelled by the ferry during its lifetime was calculated using Equation (8.9). Here, $T_{O,\,year}$ is the total operating hours during one year, T_C is the time of one crossing including charging, D_C is the distance of one crossing and L_{year} is the ferry lifetime in years.

$$D_L = \frac{T_{O,\,year}}{T_C} * D_C * L_{year} = \frac{7,000}{30} * 7.4 * 30 \tag{8.9}$$

Table 8.30 presents the total results and the results per life cycle phase for the diesel electric ferry for one PKT.

Table 8.30: Total impacts and impacts from construction, operation and end of life for diesel electric ferry per PKT

Indicator	Unit	Total	Construction	Operation	End of life
ALOP	m2a	1.43E-01	4.32E-02	9.98E-02	2.19E-05
GWP	kg CO2 eq	2.67E+01	8.01E-01	2.59E+01	2.83E-03
FDP	kg oil eq	9.10E+00	2.13E-01	8.88E+00	3.54E-03
FETP	kg 1.4-DB eq	8.35E-02	5.19E-02	3.15E-02	1.24E-05
FEP	kg P eq	1.70E-03	1.12E-03	5.88E-04	2.07E-07
HTP	kg 1.4-DB eq	2.52E+00	1.84E+00	6.72E-01	2.60E-04
IRP	kg U235 eq	1.88E+00	7.28E-02	1.80E+00	7.18E-04
METP	kg 1.4-DB eq	7.65E-02	5.00E-02	2.65E-02	1.05E-05
MEP	kg N eq	1.29E-02	3.72E-04	1.25E-02	9.94E-07
MDP	kg Fe eq	9.31E-01	7.88E-01	1.43E-01	1.01E-04
LTP	m2a	9.10E-03	1.47E-04	8.95E-03	3.31E-06
ODP	kg CFC-11 eq	4.84E-06	9.18E-08	4.75E-06	1.90E-09
PMFP	kg PM10 eq	8.20E-02	3.21E-03	7.88E-02	9.84E-06
POFP	kg NMVOC	3.30E-01	3.80E-03	3.26E-01	3.02E-05
TAP	kg SO2 eq	2.09E-01	5.56E-03	2.04E-01	2.32E-05
TETP	kg 1.4-DB eq	2.04E-03	1.67E-04	1.87E-03	7.10E-07
ULOP	m2a	7.11E-02	1.44E-02	5.67E-02	2.64E-05
WDP	m3	1.97E-01	5.42E-02	1.43E-01	5.42E-05
CO2	kg CO2	2.63E+01	7.52E-01	2.56E+01	2.67E-03
CH4	kg CH4	1.75E-02	2.81E-03	1.47E-02	5.81E-06
N2O	kg N2O	9.75E-05	2.71E-05	7.03E-05	7.54E-08
NOx	kg NOx	3.15E-01	2.44E-03	3.13E-01	2.27E-05
PM	kg PM	8.97E-03	3.13E-03	5.84E-03	3.53E-06
SOx	kg SOx	3.24E-02	3.95E-03	2.85E-02	1.04E-05

Table 8.31 presents the total results and the results per life cycle phase for the battery electric ferry for one PKT.

Table 8.31: Total impacts and impacts for construction, operation and end of life for battery electric ferry per PKT

Indicator	Unit	Total	Construction	Operation	End of life
ALOP	m2a	9.01E-02	6.08E-02	2.93E-02	7.08E-05
GWP	kg CO2 eq	3.00E+00	1.29E+00	1.71E+00	5.57E-03
FDP	kg oil eq	8.06E-01	3.41E-01	4.61E-01	4.60E-03
FETP	kg 1.4-DB eq	1.35E-01	8.47E-02	5.07E-02	4.32E-05
FEP	kg P eq	2.43E-03	2.06E-03	3.70E-04	4.42E-07
HTP	kg 1.4-DB eq	3.78E+00	3.44E+00	3.40E-01	8.08E-04
IRP	kg U235 eq	8.59E-01	1.16E-01	7.42E-01	9.46E-04
METP	kg 1.4-DB eq	1.27E-01	8.22E-02	4.51E-02	5.07E-05
MEP	kg N eq	1.13E-03	9.10E-04	2.16E-04	1.26E-06
MDP	kg Fe eq	1.30E+00	1.19E+00	1.13E-01	1.89E-04
LTP	m2a	6.94E-04	2.09E-04	4.80E-04	4.21E-06
ODP	kg CFC-11 eq	3.12E-07	1.18E-07	1.91E-07	2.44E-09
PMFP	kg PM10 eq	7.02E-03	5.17E-03	1.84E-03	1.47E-05
POFP	kg NMVOC	8.72E-03	5.78E-03	2.90E-03	3.87E-05
TAP	kg SO2 eq	1.43E-02	1.05E-02	3.85E-03	3.03E-05
TETP	kg 1.4-DB eq	3.62E-04	2.47E-04	1.13E-04	1.29E-06
ULOP	m2a	3.38E-02	2.29E-02	1.05E-02	2.65E-04
WDP	m3	2.69E-01	8.82E-02	1.81E-01	9.93E-05
CO2	kg CO2	2.88E+00	1.19E+00	1.69E+00	5.34E-03
CH4	kg CH4	1.12E-02	4.48E-03	6.72E-03	8.54E-06
N2O	kg N2O	1.34E-04	7.21E-05	6.15E-05	1.94E-07
NOx	kg NOx	5.79E-03	3.65E-03	2.11E-03	2.77E-05
PM	kg PM	6.83E-03	4.54E-03	2.29E-03	1.03E-05
SOx	kg SOx	1.05E-02	8.02E-03	2.50E-03	1.46E-05

Table 8.32: Normalised results for batteries

Indicator	Unit	Ferry battery per kg	Ferry battery per kWh	Shore battery per kg	Shore battery per kWh
ALOP	m2a	1.03E-01	5.16E+00	1.36E-01	6.20E+00
GWP	kg CO2 eq	3.60E+00	1.80E+02	4.74E+00	2.16E+02
FDP	kg oil eq	9.62E-01	4.80E+01	1.27E+00	5.76E+01
FETP	kg 1.4-DB eq	2.55E-01	1.27E+01	3.36E-01	1.53E+01
FEP	kg P eq	7.37E-03	3.68E-01	9.72E-03	4.42E-01
HTP	kg 1.4-DB eq	1.25E+01	6.25E+02	1.65E+01	7.50E+02
IRP	kg U235 eq	3.10E-01	1.55E+01	4.08E-01	1.86E+01
METP	kg 1.4-DB eq	2.49E-01	1.24E+01	3.28E-01	1.49E+01
MEP	kg N eq	4.28E-03	2.14E-01	5.64E-03	2.56E-01
MDP	kg Fe eq	2.85E+00	1.42E+02	3.76E+00	1.71E+02
LTP	m2a	4.56E-04	2.28E-02	6.01E-04	2.73E-02
ODP	kg CFC-11 eq	1.93E-07	9.63E-06	2.54E-07	1.16E-05
PMFP	kg PM10 eq	1.46E-02	7.30E-01	1.93E-02	8.76E-01
POFP	kg NMVOC	1.45E-02	7.24E-01	1.91E-02	8.68E-01
TAP	kg SO2 eq	3.88E-02	1.94E+00	5.11E-02	2.32E+00
TETP	kg 1.4-DB eq	5.64E-04	2.82E-02	7.44E-04	3.38E-02
ULOP	m2a	6.42E-02	3.21E+00	8.47E-02	3.85E+00
WDP	m3	2.64E-01	1.32E+01	3.48E-01	1.58E+01
CO2	kg CO2	3.25E+00	1.62E+02	4.28E+00	1.94E+02
CH4	kg CH4	1.24E-02	6.21E-01	1.64E-02	7.46E-01
N2O	kg N2O	2.01E-04	1.00E-02	2.65E-04	1.21E-02
NOx	kg NOx	8.86E-03	4.42E-01	1.17E-02	5.31E-01
PM	kg PM	9.62E-03	4.80E-01	1.27E-02	5.76E-01
SOx	kg SOx	3.27E-02	1.63E+00	4.31E-02	1.96E+00

Table 8.33: GWP results normalised on each battery part

Battery part	Normalised GWP [$\frac{\text{kg } CO_2 \text{ eq}}{\text{kg battery part}}$] Ferry battery	Shore battery
Battery packaging	7	8
Control system	5	5
Cooling system	2	2
Battery cell	23	23

Table 8.34: Shore power sensitivity results

Indicator	Unit	Diesel electric	Battery electric	No shore power
ALOP	m2a	8.12E+05	-37%	-37%
GWP	kg CO2 eq	1.52E+08	-89%	-89%
FDP	kg oil eq	5.16E+07	-91%	-91%
FETP	kg 1.4-DB eq	4.74E+05	62%	63%
FEP	kg P eq	9.68E+03	43%	43%
HTP	kg 1.4-DB eq	1.43E+07	50%	50%
IRP	kg U235 eq	1.06E+07	-54%	-54%
METP	kg 1.4-DB eq	4.35E+05	66%	67%
MEP	kg N eq	7.33E+04	-91%	-91%
MDP	kg Fe eq	5.29E+06	40%	40%
LTP	m2a	5.16E+04	-93%	-93%
ODP	kg CFC-11 eq	2.75E+01	-94%	-94%
PMFP	kg PM10 eq	4.66E+05	-91%	-91%
POFP	kg NMVOC	1.87E+06	-97%	-97%
TAP	kg SO2 eq	1.19E+06	-93%	-93%
TETP	kg 1.4-DB eq	1.16E+04	-82%	-82%
ULOP	m2a	4.04E+05	-53%	-53%
WDP	m3	1.12E+06	37%	37%
CO2	kg CO2	1.50E+08	-89%	-89%
CH4	kg CH4	9.96E+04	-36%	-36%
N2O	kg N2O	5.53E+02	37%	38%
NOx	kg NOx	1.79E+06	-98%	-98%
PM	kg PM	5.09E+04	-24%	-24%
SOx	kg SOx	1.84E+05	-68%	-68%

EPD modelling, Ecoinvent 3.2 processes and lifetimes sensitivity analysis

A simplified sensitivity analysis was conducted to investigate the EPD modelling, uncertain Ecoinvent 3.2 processes and control system lifetimes. The objective of this sensitivity analysis was to ensure robust and representative modelling where modelling choices were unclear.

The sensitivity analysis of the EPD modelling was carried out by normalising the global warming results from the original analysis on the functional unit used in the EPD, and comparing this value to the global warming results from the EPD.

Regarding Ecoinvent 3.2 processes, the ones examined were cardboard in the drives, unclassified material from the EPD on drives, type of lorry used for transport, the additional material in the UPS and the battery in the UPS. Other paper processes alternative to kraft paper were examined for the cardboard. For the unclassified material from the EPD on drives, hot-rolled steel was used as an alternative to zinc. For lorry transport, Euro III, Euro IV and Euro V were assessed as well as the lorry size. The additional material in the UPS was replaced with cables and connectors and polyvinyl chloride, and the battery was replaced with a lithium ion battery and a NiMH battery.

The lifetimes of the control systems were altered to 20 years instead of 15, implying fewer control systems needed during the ferry lifetime.

For the interior, all components have reasonable results in the analysis, with GWP values close to the ones in the EPD. The only one with a significant variation is the Nordia 3-seater, which obtains a larger GWP value in this analysis than in the EPD. That may be because the EPD is modelled with 49% of the input materials being recycled, which lowers the impact. The drives, electric motor and generator are also controlled and their GWP results are similar to those in the EPDs.

It is found that the GWP values for the Ecoinvent 3.2 processes regarding cardboard in the drive with ReCiPe hierarchist modelling are rather low and do not vary significantly between the alternatives. Also, the cardboard only make up 0.7% of the weight of the drive, so the total sensitivity is found to be negligible. Modelling the unclassified material in the drive EPD as hot-rolled steel instead of zinc generally leads to reductions in impacts for the drives, except for MDP impacts that increase.

The GWP values for EURO3, EURO4, EURO5 and EURO6 lorries do not vary significantly, but the GWP values for lorries of different sizes do. The smaller the lorry, the higher the GWP per tonne kilometre. In this analysis, only the two largest sizes are used, because components to a large extent have a high weight or can be assumed to be transported together with other components from the supplier.

UPS impacts in all categories except WDP decrease when using polyvinyl chloride as additional material, and impacts increase in all categories when using cables and connectors. The use of a LIB instead of the NaCl battery in the UPS results in higher impacts in all categories except IRP, PMFP, POFP, TAP, TETP, N_2O and SO_x. The use of a NiMH battery results in generally larger impacts increases than the use of a LIB. Only IRP does not increase.

Impacts naturally decrease in all categories when the control system lifetime is increased, but this does not have a major effect on the total results.