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Life Cycle Assessment of a Battery Passenger Ferry

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Abstract

This thesis was conducted to find the environmental potential of a future all-electric passenger ferry which will operate between three locations in the “Indre Oslo-fjord”. The concept will contribute to reduce local and global emissions in urban areas where public transportation is a central part of the transportation system. The concept is owned and designed by the Norwegian maritime business cluster NCE Maritime CleanTech, located in Bergen.

The project is conducting the life cycle assessment (LCA) methodology to assess four scenario cases: Scenario 1 uses a conventional diesel combustion propulsion system. This scenario the reference scenario in comparison to the other scenarios. Scenario 2 uses batteries which are charged from the grid as propulsion system. Scenario 3 uses batteries which are charged by photovoltaics and charged by the grid as propulsion system. Scenario 4 also use batteries that are charged from the grid as propulsion system. In addition, this scenario is implemented with additional batteries, located at each charging station, which are supporting the grid during charging.

The LCA results showed that battery propulsion has potential to reduce the global warming potential (GWP), when compared to the reference scenario, both with and without additional charging batteries. The GWP payback time for the scenarios with electric propulsion was estimated to be 5 months, 6 months and 6,5 months for Scenario 2, Scenario 3 and Scenario 4 respectively.

The thesis concludes that battery electric propulsion can contribute to reduce the GWP and other air related emissions. Compared to the reference scenario, the scenarios with battery propulsion system have larger impact to several depletion and toxicity categories. However, as long as the GWP is the most important factor for transport planning, the final conclusion is that operating ferries with electrical energy is the best alternative in Norway, compared to the reference scenario.

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Abbreviations

AC – Alternating Current

BEV – Battery Electric Vehicle

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

DC – Direct Current

EPD – Environmental Product Declaration

EoL – End of Life

EV – Electrical Vehicle

FTP - Eutrophication Potential

GHG – Green House Gas

HTP – Human Toxicity Potential

ICV – Internal Combustion Vehicle

IPCC – Intergovernmental Panel on Climate Change

LCA – Life Cycle Assessment

LCIA – Life Cycle Impact Assessment

LIB – Lithium ion Battery

MCT – Maritime CleanTech

NO_x – Nitrogen Oxides

NTP – Nasjonal Transportplan

PKT – Person Kilometre Travelled

PMF – Particulate matter formation

POF – Photochemical Oxidant Formation

PV – Photovoltaic

PVDF – Polyvinylidene Difluoride

SO_2 – Sulphur Dioxide

SOC – State of Charge

SSB – Statistics Norway

UWS – Urban Water Shuttle

VKT – Vehicle Kilometre Travelled

1 Introduction

1.1 Motivation

The combination of increasing transportation and the growing climate change can be one of the main challenge the world will face the coming decades. The long-term results of climate change are among others global temperature increase, more extreme weather conditions and increased sea level. As a result of climate change, the Paris Agreement was defined and signed by 195 countries at the $21^{st.}$ United Nations Climate Change Conference in Paris in December 2015. This is the most ambitious global climate agreement, and the agreement set targets to reduce the greenhouse gas (GHG) emission and other air related emissions. Additionally, the agreement aims to keep the future global surface temperature increase within 2 ℃ [1]. If this agreement is intended to be met, the Intergovernmental Panel on Climate Change (IPCC) state that the global air emissions should be reduced by 40 to 70 percent by 2050 (compared to 2010 levels). If this is not achieved, the IPCC suggest to implement negative emissions within the end of this century, which will be more complicated and difficult [2].

As a result of the Paris Agreement, the Norwegian government has set target to reduce domestic emissions by at least 40% by 2030 compared to the 1990 level of emission. By reaching this goal, the transportation sector, which stand for 31 percent of the national emissions, has to implement more low emission technologies [2]. According to "Miljøstatus.no", which operates with data from the Norwegian Ministry of the Environment, the national GHG emissions have increased by approximately 25 percent in the period from 1990 to 2015. Transportation on roads are responsible for more than 50 percent of these emissions, while interior ship transportation are responsible for 17 % of these emissions [3].

In the biggest Norwegian cities, such as the city of Oslo, the public transportation sector is near its capacity. Despite this, the urban population is expected to expand the coming years, resulting in larger share of people travelling on roads. The consequence may greater environmental emissions, and more limited capacity on roads and in public transportation. To avoid over crowded routes and simultaneously reduce tailpipe emissions, the public transportation sector needs a sustainable expansion in the near future [4][3]. The major transportation propulsion system is still fossil related fuels, but in order to meet GHG emissions goals, new propulsion technologies with low tailpipe emission have to be considered [5].

Battery technology has the potential to mitigate the GHG emissions. The tailpipe emissions from battery propulsion technologies is zero, only dependent on the emissions from the electricity mix and the battery production itself [6]. As battery technology has improved in the last years, the price of the batteries has reduced [7]. This combination makes them attractive in almost all transportation systems, and the technology is slowly being introduced to both vehicles and vessels. The first all-electric car ferry was conducted in 2015 in Sognefjorden, Norway [8]. The experience of the ferry has generated positive results, and more ships with battery as propulsion will be built in the future [9].

The aim of this thesis is to investigate the environmental potential of an all-electric passenger ferry which operate between three locations in the Oslo-fjord, called Urban Water Shuttle

(UWS). The concept is owned by NCE Maritime CleanTech, a Norwegian maritime business cluster located in Stord and Bergen in Norway. The study will use life cycle assessment (LCA) to determine the environmental potential of the vessel. LCA is a methodology that can be used to determine the environmental impact on a system or a function's lifetime. The results of an LCA can be used as a document to compare several technologies with respect to the environmental impact [10].

The public transportation system in Oslo needs to be expanded, and the transportation capacity on the roads in Oslo are crowded. The aim of UWS is to move parts of the public transportation from the roads in the Oslo region to the sea. This is a solution which require a relatively small amount of infrastructure expansion. The aim of UWS is to reduce the air emissions such as carbon dioxide (CO_2), nitrogen oxides (NO_x) and particle matters from the combustion of fossil fuels [11].

1.2 Problem statement

The purpose of this master thesis is to carry out a LCA of the UWS. Based on the results of four different simulation scenarios, the potential environmental emissions will be calculated.

As the literature review will show, a wealth of previous LCAs on electrical vehicles have been published, but there is a research gap in the impact of battery electric vessels. Therefore, this thesis aims to fill this gap, and hence investigate the environmental load of a Norwegian passenger ferry. The results of the battery propulsion system will be compared to a conventional diesel combustion propulsion system.

A deeper description of the purpose and the objective of the thesis can be seen under the goal and scope definition in chapter 6.

2 Literature Review

This chapter presents the transportation situation in Oslo today and describes the expected future situation. This chapter also summarizes the results of previous LCA studies on electrical propulsion. As the UWS is a pilot project, the amount of published research in this topic are limited. The literature review will therefore concern LCA on other electric propulsion technologies, such as electrical vehicles, electrical buses and electrical propulsion on sea. Parts of the chapter is obtained from the energy research project performed in autumn 2016.

2.1 Transportation situation in Oslo

The public transportation in Oslo is used as case study in this thesis. The literature review looks briefly at the present and future situation in the city. This section is carried out to show that the public transportation sector needs to be expanded in order to face the future situation of growing population and transportation.

Much of the next paragraphs are based on the Norwegian government's National Transport Plan (NTP). NTP is the government's political schedule for making an effective and sustainable transportation system for the future. Much of Oslo's present- and future transportation situation are described in NTP. The NTP is released every fourth year, and the next publication for the period 2018-2029 was released in the spring 2017. The applicable version for when this thesis was written are the NTPs for 2014-2023 and 2018-2029. One of the main focuses of the NTP is to define methods to develop a sustainable public transportation system which can overcome the future population growth and environmental challenges. The goal of the report is according to NTP to "offer an effective, safe and environmental friendly transportation system which has the ability to cover the need for transportation and promote development" [5].

2.1.1 Present situation in Oslo

The public transportation in the Oslo-Area is discussed in [12], a report from a political consultation concerning the transportation situation in the city. The number of people travelling with rail related transportation and buses in Oslo has increased the last years, and is near its capacity limit. The capacity trouble propagates to other rail-based technologies, such as the tram and metro in Oslo. This generates bottlenecks in the busiest rail-tracks and affects the whole transportation system all over the city.

Another big transportation problem in Oslo is the road-related transportation. Much of both person- and freight transportation in the city takes place on roads. The combination of limited rail-capacity and the large utilization of roads may develop more crowded roads in the city [12]. This again generates long travelling time both with vehicles and buses, especially in rush hours in the morning and afternoon when people are travelling for work [4].

Approximately 26% of Oslo's population travels with public transportation. Most of the travelling are in conjunction with transportation to- and from work and school. The train system is the most utilized public transportation option, which stands for 55 % of the public transportation, followed by bus with 44 % and boat with 1 % [4]. The public transportation utilization in the city of Oslo is the largest utilization share of all the Norwegian cities. However, there is room for improvements in Oslo as well, both by expanding the existing transportation technologies, and by also developing new innovative transportation technologies. *Table 2-1* shows the distribution of people travelling with different transportation options in Oslo and Akershus in 2015. The table also shows the passenger km and seat km for the different transportation options. The given numbers for the train-transportation is only for the local train in Oslo, while the given bus numbers include the travellers between the Oslo region and Akershus region as well. The data are extracted from Statistics Norway (SSB) and statics extracted from “Akershus fylkeskommune”[13] [14] .

Table 2-1: Overview of the person transportation in Oslo and Akershus.

Description	***Boat***	***Bus***	***Tram***	***Subway***	***Train***
Persons travelling (in million)	4,4	141	54	95	39,6
Passenger km (in million)	26,7	1 127	174	570	1 011
Seat km (in million)	113	1 814	614	4 633	3 768
Capacity utilization	23,6 %	62,1 %	28,3 %	12,3 %	26,8 %

The table shows that the capacity utilization for bus is the largest with 62,1 percent, while subway transportation has the lowest utilization with only 12,3 percent. The remaining options operated with a capacity utilization between 20 and 30 percent.

2.1.2 Future situation in Oslo

Factors such as better economy, population growth, technology development, and increase of export and import of goods have impact on the transportation need in Norway [5]. In a report, “KVU Oslo-Navet”, the projected public passenger transportation requirements in Oslo and Akershus from 2015 to 2060 are presented to discover the challenge in future public transportation [4]. The report is based on the present population in Oslo and Akershus, and looks at the future population growth from 2015 to 2060. The Oslo-area includes 16 municipalities around the city and has a current population of approximately 1,6 million people. The population growth in the same area in 2030 is predicted to grow to 1,9 million, and 2,2 million in 2060. This will result in a growing need for public transportation services in the cities. In order to overcome these challengers, the public transportation has to be expanded, and new technology has to be utilized [4]. Despite the predicted population growth, one of the government’s goal is to limit the road-traffic to zero growth [4]. According to the NTP for 2018-2029, the zero-growth target will be achieved by making people to choose public transportation, bicycle and walking, rather than using private vehicles [2]. The results of this goal will according to NTP cut the CO_2 emission from approximately 2,5 million to 1,5 million ton annually [5]. The outcome is intended to reduce environmental air emissions and the road-related vehicles, and hence both meet the environmental concerns and reduce the road capacity [2].

Data from 2004 to 2009 shows that the growth in transportation with vehicles in Oslo was zero in this period. Data from the same period shows that the use of public transportation has increased from 21% to 25% in Oslo. In Akershus, the private vehicle transportation has increased in the same periode, but not as much as the population growth indicate. The public transportation utilization has expanded from 9% to 11% in the period. The reason for more people chose public transportation is explained as a combination of more toll for driving private vehicles and the improvement in the public transportation sector (in terms of cheaper travelling and better mobility). In order to continue this trend and reduce the cost of infrastructure maintenance, the government propose to focus on utilizing new transportation related technology when designing the future infrastructure and public transportation. Making people to select public transportation when travelling will according to NTP be performed by making it more expensive to driving private vehicles in the future [5].

In order to reach the goals described previous in this section, it is desired that the transportation sector has to expand in a sustainable direction. This requires that the amount of alternative energy systems, such as biodiesel and electrification increases [5]. The experience from previous alternative energy storage system as propulsion in the transportation sector should be considered for future transportation design.

2.2 Emissions from Norwegian shipping

In a report from DNV GL in [15], the fuel consumption, CO_2-, SO_X- and NO_X- emissions from vessel operating in the Norwegian waters were assessed in the year 2013. In total, 6 700 vessels were operating in the Norwegian waters in 2013. Approximately 500 of these are passenger- and car ferries. The calculations are performed by specific data regarding engine capacity and purposes of the different vessels. The total fuel consumptions from the vessels were determined to be approximately 2,3 million tons, with 7 million ton of CO_2 emissions produced. Approximately 55 % of the fuel consumption and emissions originated from domestic fleet. The main contribution from the domestic fleet originated from passenger transport ferries operating in Norway. The remaining emissions in the Norwegian water originates from foreign vessel (22 %), transit traffic (16 %) and from vessels operating on quay (7 %).

2.3 LCA on electrical vehicles

Many authors have published research papers of the environmental impact of battery electric vehicles (BEV) and lithium ion batteries (LIB). Zackrisson et. al. have in [6] performed an LCA on LIB in plug-in hybrid electric vehicles (EV). The paper's focus is the production phase and the operation phase of the batteries. The results showed that the battery production has the largest environmental impact. This was reflected when modelling with both European and Scandinavian energy mix. When modelling with Chinese energy mix, the results showed that the operation phase has more emissions than the emissions from the battery production phase. The findings in Zackrisson et. al.'s report corresponds well to the results from the authors in

[16], [17] and [18], where EVs are compared to internal combustion engine vehicles. The results from these studies depends on where the electricity has its origin as well.

These results are well illustrated in *Figure 2-1, Figure 2-2* and *Figure 2-3* obtained from [6]. The figures describes the environmental influence on five impact categories. The battery operation, battery production and transport to recycling with three energy mixes (European, Scandinavian and Chinese) are presented. The five categories are emissions on global warming potential (CO_2), photochemical smog (ethane), eutrophication (PO_4), acidification (SO2) and ozone depletion (CFC11). In all cases, the "transport to recycling" phase has a minor impact.

Figure 2-2 shows the environmental potential during operation in Europe. The figure shows that the battery production has slightly more emissions on all categories, expect in the global warming, where the battery operation has the biggest impact. *Figure 2-1* describes the environmental impact on the batteries when operating in Scandinavia. The battery production has the biggest impact on all categories, followed by the battery use. When operating in China, shown in *Figure 2-3*, the highest impact originates from the user of batteries. Battery production has the biggest impact on Eutrophication and Ozone depletion.

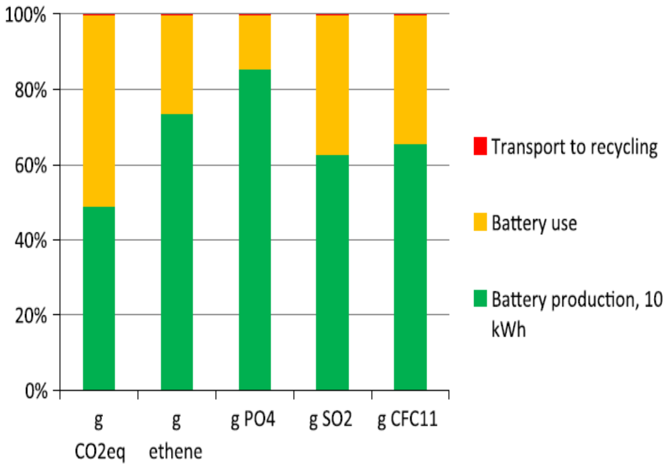

Figure 2-2 Environmental impact from a battery life operating in Europe [6].

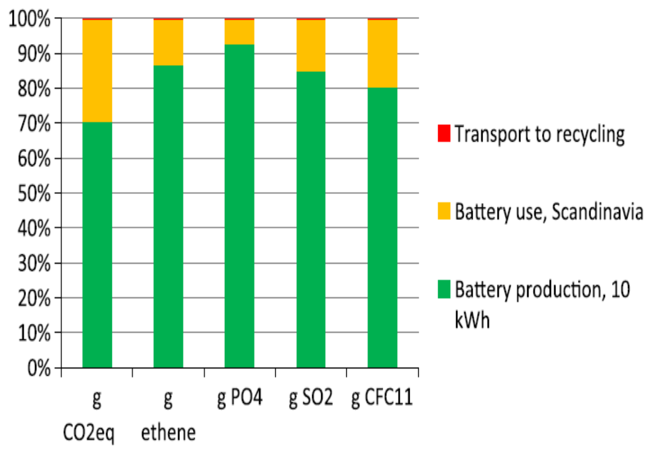

Figure 2-1 Environmental impact from a battery life operating in Scandinavia [6].

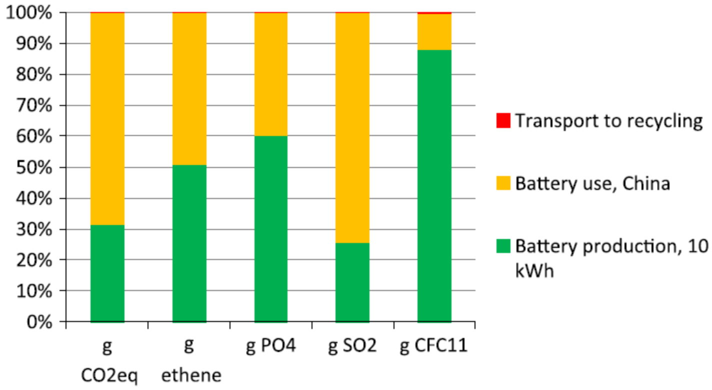

Figure 2-3 Environmental impact from a battery life operating in China [6].

Hawkins et. al. reported in [19] a comparative LCA between a BEV and an internal combustion vehicle (ICV). The production of the vehicles, batteries, and engines was conducted in the study. The vehicles were designed with the same shell, while the components and energy demand needed for an ICV and a BEV was based on a Mercedes A-series and a Nissan Leaf respectively. The BEV was tested with three different electricity mixes: Average European electricity mix, electricity originated from a coal power plant and electricity generated from natural gas.

Results showed that the use phase of the EV was contributing the largest emission on GHG emission. However, the results show that powering the vehicle with European average electricity mix gave lower GHG emissions compared to electricity generated from coal. Summed up, BEV show slightly better results in terms of GHG emission when powered with European electricity mix, followed by natural gas. Powering the BEV with coal increased the GHG emissions worse than ICV.

The results for the BEV in categories on human toxicity potential (HTP), eutrophication potential (FEP) and fresh water ecotoxicity potential showed to contribute larger impact in these categories than the ICV. The authors explained that the extra production rate for the battery increases the toxicity potential by 180 % to 290 % compared to the contribution for the ICV in the same categories. The high impact of FEP and HTP is explained by the high mining activity in extraction of the needed metals for the batteries.

2.4 LCA of public passenger transport systems

This subsection presents LCAs of different public passenger transportation systems. The awareness of emissions from transportation in cities should be reflected in order to limit the GHG emissions and other air pollutant gases. This subsection will start with a comparison of different technologies in passenger transportation, followed by assessments of more electric and hybrid technologies in the public transportation.

A hybrid LCA of passenger transportation of cars, buses, rails and aircrafts was conducted by Chester and Horvath in [20]. They performed an LCA which include energy consumption and air pollutant from the four transportation technologies with focus on production, infrastructure, and fuel. The production phase includes the manufacture of vehicles, train and aircraft with the needed propulsion systems. The infrastructure contains road-, track-, station-, and airport construction. The functional unit in the life cycle comparison was per person kilometre travelled (PKT), but vehicle kilometre travelled (VKT)was used as well. With PKT as a functional unit, the sensitivity simulation showed that the results are sensitive to the passenger occupancy. The results indicated that GHG emissions were highest during operation for vehicles and aircraft, while rail has higher emissions during infrastructure production, compared to its operational emissons. For SO_2 and NO_x emissions, the contribution mainly originated from the electricity production. Therefore, most of the contribution from rail is during its operation, while most of the emissions from road and air options are in conjunction to the electricity use during its production. Another interesting finding in the study was that during off peak, i.e. travelling between the rush hours, the transportation had largest impact per person travelled. The emission per person will therefore vary significantly during the day, where the morning- and afternoon rush will experience the lowest emissions. The PKT functional unit results are therefore dependent on the passenger occupancy, and not that sensitive to technology emissions.

The Chester and Horvath study was only an assessment of the four transportation systems, and which system is the best option depends on the passenger occupancy and the time of the day they are operating. Therefore, no conclusion regarding the best option is drawn. Nevertheless, suggestion for low emission technologies such as battery propulsion are proposed. The next section will therefore assess electric propulsion in buses.

Madrid in Spain is one of the cities that has been studied with different fuels in buses. Antonio et. al. have in [21] investigated the environmental potential and compared four different fuels for powering buses. The four fuels are hydrogen, hybrid diesel-electric, battery, and diesel. In the case of battery propulsion, the authors performed the study with different Spanish electricity mixes from the year of 2008 to 2030. The amount of renewable energy in the Spanish electricity grid was assumed by the authors to increase until 2030, where wind energy is expected to have the biggest expand.

Regarding the GHG emission, the results showed that the battery electric bus was the best fuel alternative during operation phase. However, the overall conclusion was that the battery bus was the propulsion technology with the highest life cycle GHG emission, followed by the hydrogen bus and hybrid bus. The reason for the high GHG emissions in the battery electric bus was explained by the maintenance process and that they could not meet the requirements in the automotive transport sector.

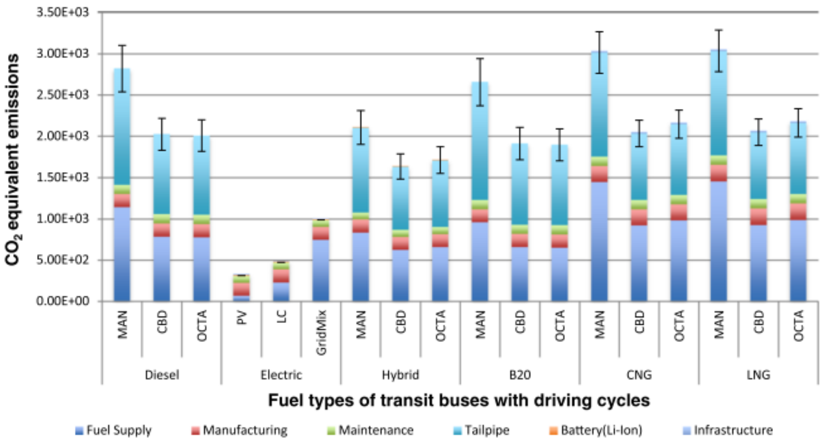

Figure 2-4: GHG emission results from Ercan et al's study on different fuel options in buses [22].

Another LCA study on buses was performed by Ercan et. al. in [22] where the goal was to investigate different fuels in public buses. Battery electric bus was one of the options, and the bus was tested with different electricity mixes and compared to a conventional combustion engine bus. The study include production, maintenance, operation, infrastructure, three LIB replacement, and different electricity mixes. The electricity mixes were the average US electricity mix, low carbon electricity mix and clean renewable energy from photovoltaics. The battery electric bus performed the lowest CO_2 emission of all fuel alternatives within all three electricity mixes. This is explained in *Figure 2-4*. As can be seen, the electricity generated from the photovoltaic resulted in the lowest CO_2 emission, while the average grid mix showed to have higher emissions. The highest impact in GHG emissions is generated from diesel, CNG, biodiesel and LNG.

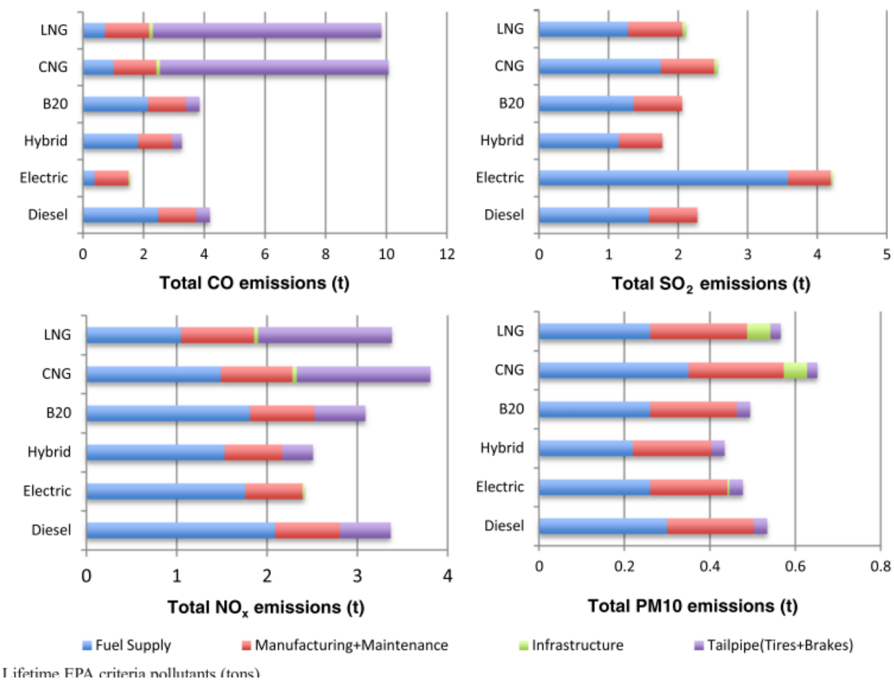

Figure 2-5: Comparison of different fuel alternative and its impact on CO, SO_2, NO_x and PM_{10} [22].

Despite the low GHG emission for the battery technology, the battery electric bus was sensitive to SO_2 and water use during electricity production. *Figure 2-5* shows the impact on categories such as carbon monoxide (CO), Sulfur dioxide (SO_2), NO_x and PM_{10}. The figure show that the battery electric bus proved the least impact in CO emisssion. The PM_{10} and NO_x emissions in the battery are more or less average compared to the other fuel options. LNG, CNG and diesel shows more or less average results in all categories in the figure except in CO emissions, where LNG and CNG has more than twiced emissios compared to the other fuel alternatives.

The authors in the papers found it hard to conclude with one specific fuel due to varying results within the different impact categories. However, the battery powered bus performs on an average or lower level compared to the other options with respect to environmental burdens.

2.5 LCA on battery and hybrid vessels

MS Ampere operates between Lavik and Oppedal, and was in 2015 the world's first battery electric car ferry[8]. Annelise B. Kullmann reported in [8] a comparative LCA between MF Ampere and MF Oppedal, a conventional diesel combustion ferry. They operate between the same crossing and are therefore comparable. MS Ampere is a catamaran hull, built in aluminium for low resistance and lightweight. MF Oppedal is a one hull ship, build in steel. The author's objective was to present the impact on several environmental categories, and get an analysis of the total environmental impact of the ferries.

The results from Kullmann's study correspond to the results found in many of the previous LCAs of EVs. MS Ampere has less GHG emissions during its operation phase, compared to the operational emissions for MF Oppedal. In the case of toxicity impact groups, the author found that MF Ampere has more emissions compared to MF Oppedal, which was associated by the author to have its origin from the copper use in the power grid and the chemicals in the batteries. Additionally, it was found that the operation-phase of both ferries had the largest amount of emissions. The aluminium for the hull had large impact on categories regarding Metal depletion. The battery production of MS Ampere was found to have significant influence in categories regarding ecotoxicity of land areas and human toxicity.

A life cycle assessment of batteries in the maritime sector was performed by Lasselle et. al. in [23]. The authors aim was to find the environmental cost (payback time) of using batteries in a hybrid propulsion vessel and in an all-electric ferry. The battery solution was compared to a conventional combustion engine solution. The authors were mainly focusing on the emissions to GWP and NO_X. The vessels were assumed to be powered by Norwegian electricity mix.

The results from the study showed that the environmental payback time for the hybrid solution in terms of NO_x is 0,3 months and 1,5 months for GWP. For the all-electric ferry, the payback time was 1,4 month and 0,06 month for GWP and NO_x respectively. The limitation from the study was the energy consumption during production of the battery, which was an uncertain factor. However, the results did not change in the sensitivity analysis where the environmental CAPEX (the environmental impact from production) was increased tenfold

The energy efficient design index (EEDI) is a measure of the total CO_2 emissions per transported ton mile [24]. For ships, it is required and desirable to achieve an EEDI as low as possible, both from an economical- and from an environmental perspective. M. A. Øverleir has in [24] researched a hybrid system in a general cargo ship, in order to meet the required EEDI. The idea is to combine battery energy storage and diesel generation on ships. Normally in such ships, the emissions from engines is high when the propulsion load is low, while the emission decreases as the load increases. In order to minimize the total emissions, the energy from the battery is intended to cover the energy need during low load, and during high power fluctuation peaks. This technology makes the combustion engine to operate more or less at a constant efficient operation point.

The author concluded that the hybrid system has a potential to increase the total energy efficiency for the ship. In addition, the system has beneficial results in reducing the amount of load variation. It also decreased the local and global air emissions, and noise and vibrations from the engine was reduced. The author found that the overall efficiency is better for the hybrid system, compared to a conventional combustion system.

The findings in the study of M.A. Øverleir corresponds well to the findings in a similar study performed by Lindstad et. al. in [25]. Batteries were implemented as a hybrid system in supply vessels where pollutant, economics and climate impacts were assessed. The results showed that taking hybrid propulsion into use in supply vessel can contribute to reduce local and global emissions. However, the results are very dependent of the fuel prices. The investments of combining batteries and engines in new building vessels shows to have a payback time of 5 years, compared to 10-15 years if rebuilding an existing combustion engine vessel to a hybrid vessel. The reason may be explained by the huge investment in replacing existing main engines (and generators) with batteries.

2.6 Summary

UWS shuttle is a pilot project which is in its “planning-stage”. The literature review is therefore based on similar existing technologies. The experience from electric propulsion in vehicles and urban transportation in cities are useful when implementing battery technology in the transportation sector. MS Ampere has been in operation for approximately two years, which means that much experience from the battery technology at sea can avoid several issues and difficulties in the UWS.

The results from most of the studies on battery propulsion in cars, buses and vessels are similar in many cases. For instance, in the extraction and production of the materials, the production of batteries has higher emissions compare to the operation phase. This results in a higher environmental contribution from the production of a battery propulsion technology compared to the production of conventional combustion technologies. In the operation phase, it is clear that the grid-mix has a significant impact on the overall environmental impact of the vessel.

The previous work done on battery powered technology is useful for road transport but there is a research gap in electric water vessel transport, particularly passenger ferries. Part of the studies on electric road transportation can be related to electric water vessel transport, but many factors also differs between them. Therefore, this study will keep that in mind and focus on the electric transport on the water by considering an electric passenger ferry which operates in the Oslo fjord.

As presented previously, the road- and railway capacity are limited, while the maritime public transportation constitutes only 1% of the travellers in Oslo. Additionally, the future public transportation must meet strict local and global emissions requirements, and more people will use the public transportation sector. This thesis will therefore consider these demands, and assess if an electric passenger ferry can meet the future transportation needs and environmental requirements.

Different charging technologies and methods are factors which have high potential to increase the charging efficiency. The high load on the electricity grid is important to consider when planning high energy demand technologies such as UWS. Efficient charging and power conversion is important to consider to save on energy consumption and costs.

On-board energy production will be considered in this study as well. Producing a significant share of the energy consumption could potentially reduce the grid-load and in an environmental perspective, it can be a significant factor.

3 Theoretical Background

3.1 Battery technology

The battery technology has been improved the last years due to better battery-components. In addition, the prices for the components have been reduced making them attractive in low- and high capacity electrical devices such as laptops, vehicles and ships. The most used batteries today are LIBs [7].

3.1.1 Battery theory

Figure 3-1 shows the basic function of a battery. Batteries stores electrical energy as chemical energy and vice versa through redox reactions. They consist of one or more electrochemical cells. Each individual cell is built-up of two electrodes (anode and cathode) immersed in at least one electrolyte solution wherein they are separated by a separator. The separator is ion conductive, while electrons are blocked. The material of the electrodes is different so that they dissolve differently, depending on their standard potential (electrochemical series of metals), in the electrolyte solution. Electrons remain in the electrode. If an external circuit connects the electrodes, the electrons start flowing to balance the different electron density between them and form an electric current. The electrode where the oxidation (gives electrons to the external circuit) takes place is called anode; where the reduction takes place is called cathode (receives electrons). The circuit is closed by the migration of ions between the electrodes through the electrolyte passing the separator (ion current). This process describes the discharging reaction. For charging, the process is reversed [26] [27].

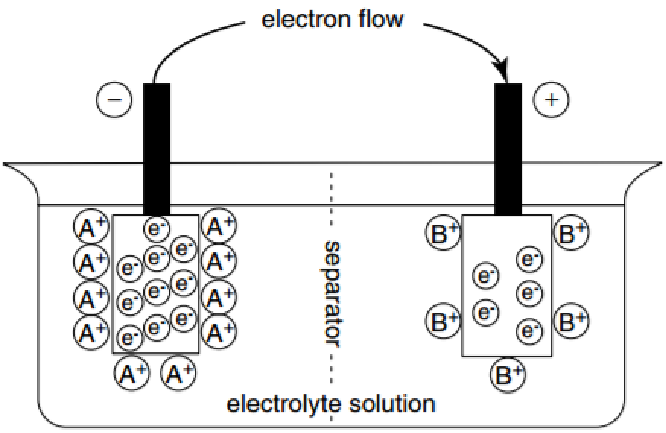

Figure 3-1: Basic operation of a battery with the anode, cathode and electrolyte [26].

3.1.2 Chemical reactions and energy conversion

As stated, the electrodes in batteries consists of different active materials with different standard potential, measured in voltage (V). The electrodes are made up of a composite of the active material and a binder material, which keep the structure of the active material together. The binder should have high conductivity so that the electrons are easily transported to the active material [28]. The potential difference of the two electrodes defines the characteristic terminal voltage of a cell. The anode reduction potential is negative, while the cathode reduction potential is positive. The reduction potential is listed in the electrochemical series of metal and can be used to calculate the standard cell potential in a battery, as shown in equation 3.1 [29].

$$Standard\ cell\ potential = Oxidation\ potential + Reduction\ potential \qquad (3.1)$$

If the emitted electrons of the oxidation partner are transferred to those of the reduction partner, it is referred as a redox reaction. Through such a redox reaction, the maximum theoretical energy released in a battery can be calculated by the change in Gibbs free energy described in equation 3.2.

$$\Delta G° = -nFE° \qquad (3.2)$$

Where;

- $\Delta G°$ is Gibbs free energy [J]
- n is the amount of electrons in the reaction
- F is the Faraday constant [C/mol]
- $E°$ is the standard potential [V]

The free energy makes the electrons to flow in an external circuit. However, during the chemical redox reaction, energy is released as heat losses to the surroundings. The losses occurs due to three different polarizations in the battery; activation polarization, ohmic polarization and concentration polarization [29] [27]. Activation polarization is the energy needed to convert or transfer the electrons from the electrodes through the external circuit. Ohmic polarization is the energy drop from the impedance in the components in the cell. The impedance is calculated from the resistance in the contact-area between the electrodes and the current collector, the electrolyte, and from the active electrode materials. The ohmic polarization is given by ohm's law, and is proportional to the circuit current as described in equation 3.3 [29].

$$U = RI \qquad (3.3)$$

Where;

- U is the ohmic polarization in voltage [V]
- R is the resistance [Ω]
- I is the current flow in the circuit [A]

Concentration polarization changes with the current flow in a circuit. It is the electrolytic concentration change between the electrolyte and the electrodes, i.e. in the interface of the reactants and products in the reaction. As the battery is discharged, the amount of ion from the electrolyte is reduced at the electrodes, resulting in an increased concentration polarization. *Figure 3-2* describes the three polarization processes during one discharge cycle [29].

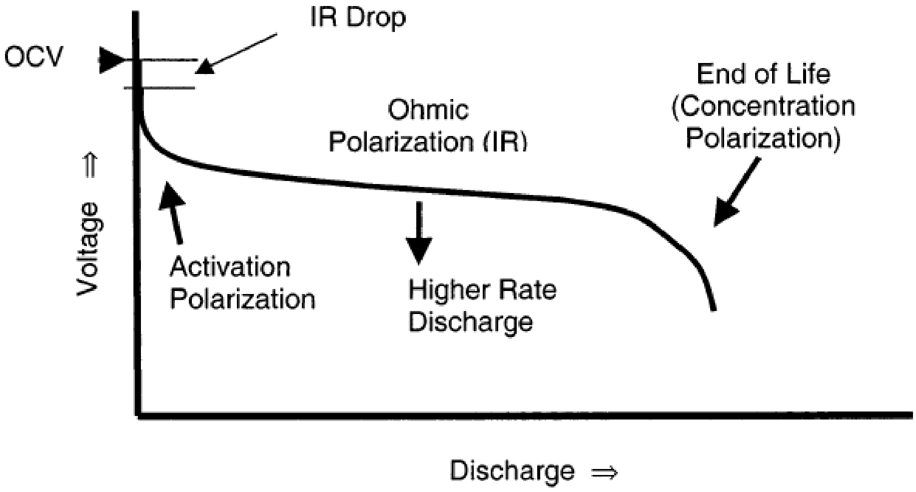

Figure 3-2: Representation of activation polarization, ohmic polarization, and concentration polarisation [27].

3.1.3 Electrolyte

The electrolyte aims to conduct ions between the electrodes. Therefore conductivity in the electrolyte is important. Reducing the electrolytic resistance and maximizing the contact between electrode and electrolyte will limit the ohmic polarization. The electrolyte must be stable in contact with the separator and electrodes to avoid chemical reactions between them. However, the stability range changes with the cell potential and temperature in the battery, which may cause unwanted safety issues. Therefore, the choice of electrolyte is an important factor in battery design. Electrolytes are divided into solid electrolyte, aqueous electrolyte, and non-aqueous electrolyte with different stability-voltages. Aqueous electrolytes have the highest conductivity and is only stable within a voltage of 1,23 V (called electrochemical stability window). Non-aqueous electrolytes have a reduced dielectric constant compared to aqueous solutions, which increase the ion-pair formation. This reduces the conductivity in the electrolyte. The stability window of non-aqueous electrolytes is approximately 4,6 V [27].

3.1.4 Capacity

Specific energy and specific power are important terms in battery theory. Specific energy is a measure of the capacity of the battery, measured in Wh/kg. The battery capacity determines the amount of electric energy that is available in the battery. It is a measure of the amount of charge within a cell and is given in ampere hours (Ah). Ampere hours can be converted into Watthours by the product of cell potential and Ampere-hours shown in equation 3.4 [29] [27];

$$Capacity\ [Wh] = Ampere\ hours\ [Ah] \times Cell\ potential\ [V] \tag{3.4}$$

Specific power is a measure of the available power of a battery to charge or discharge. It is measured as power per weight of the active material, W/kg [27].

The specific energy and specific power are dependent on the active materials used in the electrodes.

3.1.5 Lithium-ion batteries

The basic operation of a LIB is shown in *Figure 3-3* overleaf. Ions are transported in the liquefied electrolyte while electrons flow through an outer circuit during discharging. For charging, the reaction is reversed [7].

The two electrodes in a LIB is built up of different active materials. One of the electrode (cathode during discharge) is a lithium-based material that easily is oxidized during discharge. When the battery is charging, the reaction is reversed, and the same electrode is reduced and hence operating as anode. The most used lithium-based composites are lithium cobalt oxide ($LiCoO_2$), lithium nickel oxides and lithium manganese oxide ($LiMn_2O_4$), where the ratio between the atoms changes in order to optimize the capacity and stability of the materials. Lithium iron phosphate ($LiFeP_4$) is a material with high capacity even after long life time. This has made them attractive in many electric devices. In comparison to cobalt and nickel, iron is less expensive and less environmental toxicity [30].

The active material and the current collector in the electrodes must have high conductivity to transport electrons to and from the active material. The current collector should contain a material which do not react with the electrode material. In LIBs, copper is frequently used as the anode's current collector, while aluminium is a widely used current collector material for the cathode [28].

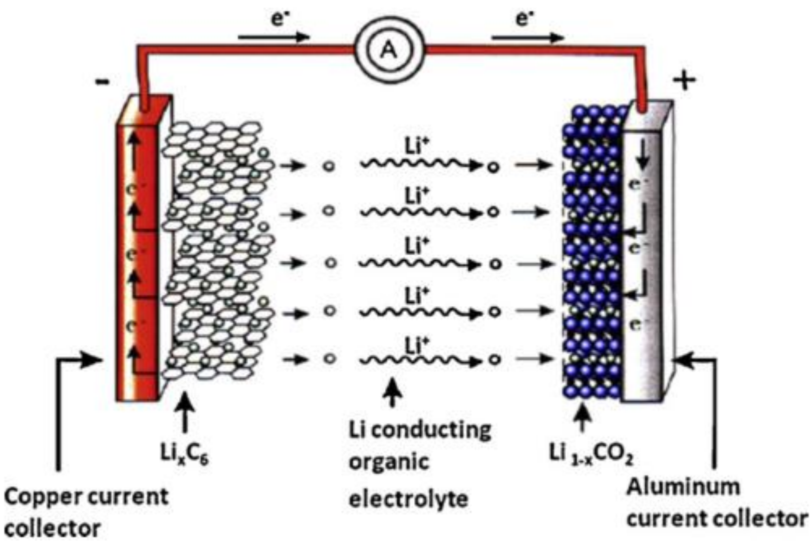

Figure 3-3: Representation of a typical lithium-ion battery where the transport of lithium ion and electrons is described [31].

Using lithium in both electrodes would theoretically increase the capacity of a LIB. Nevertheless, the use of lithium on both cathode and anode would result in short circuit and danger of firing between the electrodes due to a potential growth of reactive dendrites in the separator. This may cause in a volume expansion and hence contact between the electrodes. Therefore, other material types rather than lithium are used. Carbon or graphite is materials that are used on the electrode that undergoes the oxidation. This can avoid metallic lithium growth and volume expansion in the cell [30].

The electrolyte in LIBs is an organic solution containing lithium salts. The electrolyte is immersed in the electrodes, and contains a membrane separator in order to avoid contact between the electrodes. The membrane is ion conductive, while electrons are blocked [31] [30].

3.2 Photovoltaics

Photovoltaic (PV) produce electrical current from the photons in light. They are designed with semiconductor technology which are doped with a material of one more or one less electron than the semiconductor material [32]. The next section will describe the operation of PVs.

3.2.1 Semiconductors

The most used semiconductor in PVs is silicon. Semiconductor works as insulators in low temperatures, and conductors at elevated temperatures. This can be explained by the band model, shown in *Figure 3-4*. A semi conductive material has fulfilled its valence band in room temperature, and the electrons are bounded in strong covalent bindings. If the temperature increases (hence the energy), some electrons will break from the covalent bindings, and reach the conductive band, where they are free to move. The gap between the valence bond and conductive bond is called the forbidden gap. In order to reach the conductive band, the electrons need more energy than the forbidden gap energy, E_G, shown in the figure. If the energy is less than E_G, the electrons will drop back to the valence band. When one electron reach the conductive band, it will leave a hole in the valence band. A hole is a positive charge carrier, and new electrons can occupy the hole. This will make the hole to propagate together with the electrons [32].

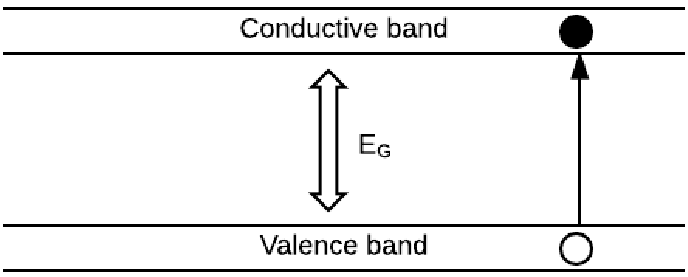

Figure 3-4: The figure shows a schematic of how electrons behave in semiconductor. An electron (black circle) emits from the valence band to the conductive band, and leaves a hole in the valence band (white circle). The figure is extracted from [32].

3.2.2 P-doping and n-doping

Doping of semiconductor can increase the efficiency of PVs. The silicon atom has four electrons in the outer shell, and is bounded with four other silicon atoms through covalent bindings. By doping silicon with an atom containing one more electron in the outer shell, the model will get an abundance of one electron. This electron is less bounded to the silicon atom, which means that the energy needed to reach the conductive band for the electron is lowered. This type of semiconductor doping is called negative doping (n-doped). Positive doping (p-doped) is when a silicon atom is combined with another atom containing one less electron in the outer shell. One more hole is then generated in the valence band, and electrons are free to occupy the hole [32].

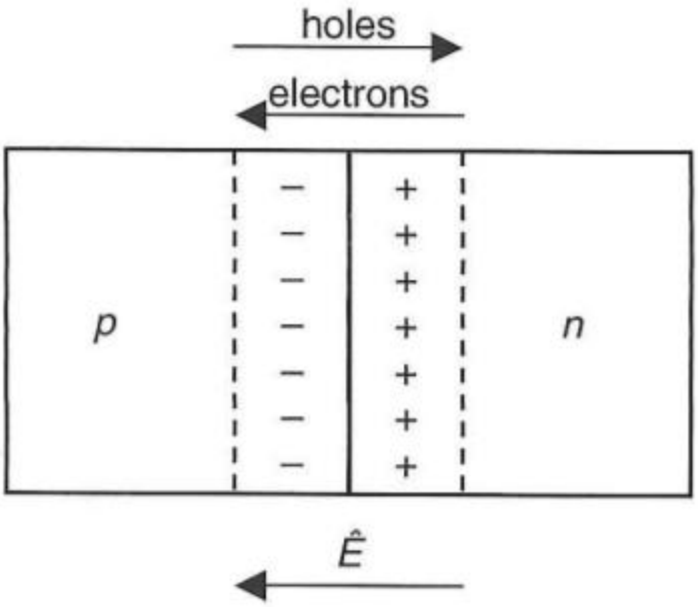

Figure 3-5: The figure shows the flow of electrons and holes when a p-doped and n-doped material are combined [32].

Combining the n-doped and p-doped materials will result in a p-n-junction. The electrons and holes will move freely between the merging of the doped materials. This will generate an electric field, E in the junction, which stops the flow of electrons and holes. The electric field generates a voltage potential in the junction, V_{bi}. The phenomena is explained in *Figure 3-5*. If connecting an external voltage source to the p-n-junction, the electric field and voltage across the junction will decrease and current will flow in the circuit [32].

3.2.3 PV in operation

The operation of PVs are similar to the operation in a p-n-junction. The n-doped and p-doped materials in silicon are combined in a PV. Photons from sunlight reaches the PV and releases an electron from the valence band if the photon energy is higher than the gap energy, E_G. An electron-hole pair is generated i.e. current, and travels in an external circuit. However, if the photon energy is less than E_G, or if the electron gives away its energy to other electrons, a recombination can occur. Recombination is a phenomenon where electrons and holes recombines in the valence band. Electrons can lose its energy in the conductive band, combine with a hole in the valence band and release a photon. Recombination is loss of energy and decreases the PV's efficiency [32].

The theoretical average energy production of a PV is calculated based on the irradiance to the PV module, shown in equation 3.5.

$$E = H * A * \eta * PR \tag{3.5}$$

Where:

- E is the annual energy produced by the PV [kWh]
- H is the irradiance to the PV module [kWh/m^2]
- η is the PV efficiency
- PR is the performance ratio (0,8 used in this thesis)

3.2.4 Losses and efficiency

As mentioned in the previous section, recombination reduces the overall efficiency of PVs. Another important loss in PVs are optical losses. Optical losses occur due to blocking of sunlight in the top contact of the PVs, high reflection on the surface or reflection in the rear of the PVs. Different methods, such as increasing the absorption in the cells (both on the surface and on the rear of the cell) and decreasing the surface cover can avoid some of the absorption. Resistance in all surface contact is another factor that decreases the overall efficiency of PVs. [32]. The efficiency of a PV module is defined as the ratio between the incoming solar energy and the utilized energy by the PV, as described in equation 3.6 [33].

$$\eta = \frac{P_{max}}{P_{in} * A} * 100\% \tag{3.6}$$

Where;

- η is efficiency
- P_{max} is the maximum produced power of the PV [W]
- P_{in} is the incoming irradiance [W/m^2]
- A is the area of the PV module [m^2]

Typical efficiency for a PV today is 13-19%. However, researches has reached an efficiency of 24-25% in some silicon PVs under standard test conditions (cell temperature of 25 ℃, irradiance of 1000 W/m^2 and air mass 1,5). The theoretical limit in efficiency for PVs today is 30 % [32].

3.2.5 PV in vessels

The environment at sea is more varied compared to the environment onshore, and different aspect should be considered when using PVs on vessels. Weather conditions such as wind, humidity and salt can result in damage to components in the PVs. Therefore, installation of PVs in vessels should follow marine protection standards in order to avoid problems such as corrosion and short circuiting. These are efforts which may cost additional investments, and should be considered in a potential design [34].

The energy production of on-vessel PVs will vary through the day, where the vessel is located and the tilt angle of the module. The PVs can be installed either in a fixed position, dynamic positioning or horizontal. Fixed tilt installation is a solution which can resist the extreme weather conditions. However, PVs with fixed tilt angle cannot utilize all the irradiations during a day. By utilizing dynamic positioning, the tilt angle can automatically be adjusted according to the solar irradiation. Such a system includes many rotating and moving parts which needs regular maintenance and replacements, and hence more unpredictable costs. Another possible solution is a horizontal PV installation. Horizontal mounting is beneficial concerning the aerodynamic and weather conditions of the vessel. The biggest problem with such a system is cooling and self-cleaning [34]. In literature, it is recommended with a tilt angle of more than 10° in order to have some kind of self-cleaning of dirt [32].

Shading of cells is another problem in vessel-installed PVs [34]. Partly shading, often called hot spot, of cells in a module can have serious results. In case of shaded cells in a module where the cells are connected in series, the shaded cells can dissipate the generated current by the "good" cells. This may result in short circuiting and overheating, which can destroy the modules such as melting or cracking of the glass. However, hot spot can be avoided by including bypass diodes in the installation [32].

4 Methodology

This chapter explains the LCA methodology which is used in this thesis. The last part of the chapter describes how the data collection was performed, and all the assumption considered in the thesis.

4.1 LCA methodology

The methodology to be used in this thesis is LCA-method. LCA is a useful tool when comparing the environmental impact on several technologies and products. An LCA can consider the environmental impact of a product or process from its production to its end of life (EoL), called cradle-to-grave. Cradle-to-grave include the full life cycle of the product from its extraction of raw materials to manufacturing, usage and EoL [10]. The ISO 1440 and ISO 14044 standards are the basis of the methodology of LCA [35] [36]. They are used to describe the procedure for performing an LCA in this chapter.

LCA is built up of four life phases, which are shown in *Figure 4-1*. The four main phases in an LCA are; goal and scope definition, inventory, life cycle impact assessment, and interpretation. The figure show that the phases are an iterative process, where new information is continuously collected [35]. A deeper description of these phases follows in the next pages.

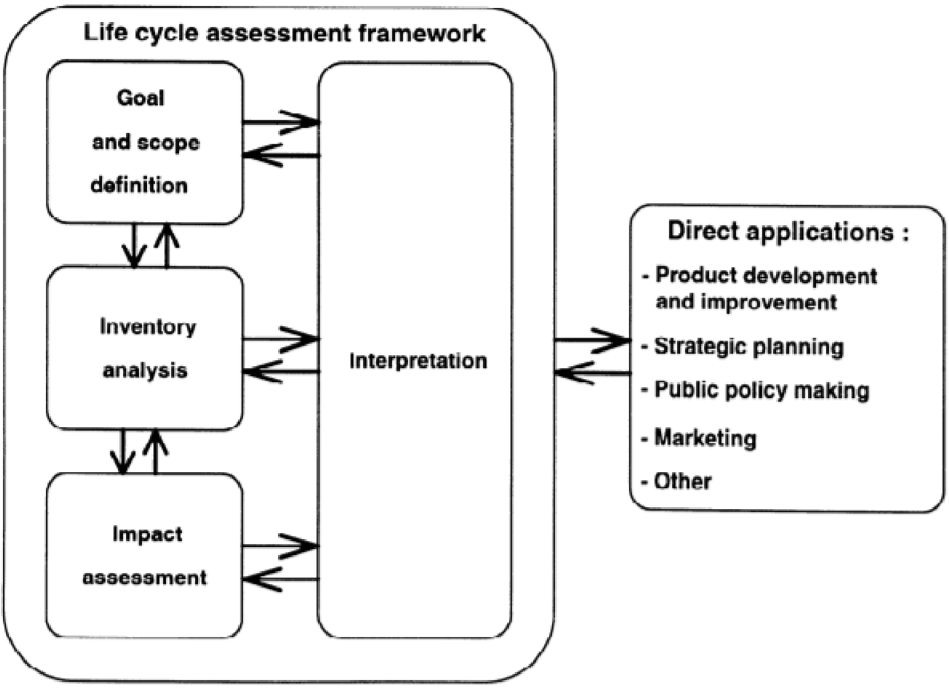

Figure 4-1: Life Cycle Assessment framework [35].

4.1.1 Goal and scope

When performing an LCA, the first step is to define a clear goal and scope definition. The goal of a LCA describes the purpose of the study, the reason for doing it, and for whom the work of the study is carried out. The reason for doing the study should be explained in a detailed description of strength and weakness of the product to be study. This section should also describe where it is room for improvements, where most of the emissions are contributed, and what would be the consequence of the product [10].

The scope of the study is carried out when the goal is defined. The scope describes how the LCA is to be carried out. The function of the product should be defined, and all the simplifications and limitations of the study must be shown. Preparing the system in a flow chart is an useful method when defining the scope [35]. Flow chart is a systematic overview of the system and describes the environmental impact from one functional unit [8].

The functional unit is a reference unit used to compare the emissions from different flows, and reflects the function of the product. The functional unit is the same for the different processes in the study in order to make the results comparable [10].

System boundaries are used to limit the study, and decide which parts of the system that are included. The system boundary should describe the different unit processes in the study and which elements are included. This process should be decided based on the goal and scope definition, the audience, limitations and assumption, and cut-off criteria. A description of the data and its quality is further important to understand the quality of the results [35].

Allocation in LCA is useful in the system boundary process. It is used to divide inputs to and outputs from a product [36]. During a process, it is often used several inputs, or generated more than one output [35]. How to share the environmental impact on these inputs and outputs is decided with allocation.

The allocation process is described by the ISO 14044 standard in three steps. The first step is to try to avoid allocation. This is performed by either dividing the process into several sub processes, and collecting more data for the input and output for these sub processes. Another option is system expansion, where all the functions to the co-product of the system are included. The second step is to perform allocation (if it could not be avoided) by dividing the inputs and outputs between the products based on how they quantitatively- and physically change in the process. Step three concern if physically changes cannot be used in the allocation. Other products, such as economical values can then be used in the allocation [36].

Types of LCA studies

Attributional- and consequential LCA are the two most used LCA methods. The difference between the two depends which time horizon the LCA is performed for. Attributional LCA uses data from the past in order to assess the environmental impact on a product. The consequential LCA looks at the future change and the future environmental consequence of the product [37].

4.1.2 Life cycle inventory

The aim of the inventory analysis is to make a model of the system which will be studied. This process includes the data collection and the calculations related to these data. The inventory analysis is a iterative process as more information of the system is collected [35]. The inventory is according to Baumann and Tillman performed in the following steps; flow chart design, data collection and calculations [10]. The next paragraphs briefly describe the three phases.

The flow chart is defined with respect to the system boundaries in the goal and scope definition. A simple flow chart can be made when the goal and scope are defined, and then expand it when more data are available [10]. The purpose of a flow chart is to show a detailed overview of the system. A flow chart should include all processes which are performed through the system's life cycle. The energy and mass flow between the process should be included as well. If materials used in the system are recycled, this should be shown in the flow chart [10].

The second step is to collect all the relevant data required in the study. This part can be time consuming, and it can be a huge challenge to find the right data. Before starting the data collection, the author of the LCA-study should get to know what kind of data which are needed. Both qualitative and numerical data should be searched for. Qualitative data are data which describes the technology and where the processes takes place. Numerical data are data which describes the inputs and outputs to the process, such as emissions in the system [10].

The third and last step of the inventory analysis is to use the flow chart and the collected data to perform the needed calculations. All data should be validated in order to confirm that the data correspond to the data quality requirements. The data should further be normalized to the activities and processes, in order to make them fit to the functional unit [36].

Foreground and background data

Foreground and background systems in LCA indicates where the system belongs. Foreground systems are the processes that has the main focus in the study, and its data collection related to that. The background systems are all other processes, such as raw material extraction, material production, energy flow in the foreground processes, etc [10]. Ecoinvent is a background database, which is much used in LCAs. Ecoinvent is based on average processes around the world, and is therefore a useful database to use in case of lack of data. According to Ecoinvent's webpage, they are the world's leading LCA database [38].

4.1.3 Life cycle impact assessment

In the life cycle impact assessment (LCIA), the results from the inventory phase is used to assess the environmental potential of the study, making it simple to compare the outcome to other studies. This is performed by sharing the inventory data on specific environmental impact groups [35]. The LCIA phases is divided into three mandatory processes [36];

1. Choice of impact categories, category indicators and characterization models. This process should reflect the goal and scope definition.
2. Classification - define which impact categories the different LCI results should concern.
3. Characterisation – calculation of the results.

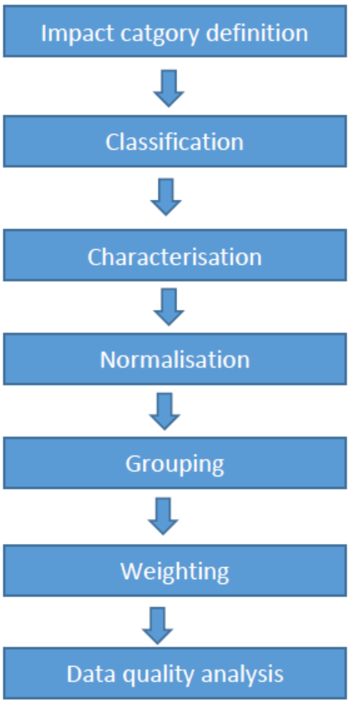

Figure 4-2: Typical procedure in the LCIA. The figure is inspired of the authors in [10].

The procedure used in the LCIA is described in *Figure 4-2*. The LCIA starts with the three mandatory process described previous. An introduction of the different impact categories that stays in focus in the study is the first step. The inventory results are further classified into the different impact categories. The characterisation phase includes the calculation of the load on each category, where equivalency factors are used in the calculations. The results from the characterization are used to normalize the values to a reference value, and sorted to the results into location and priority of the emission. The two last steps of the LCIA procedure are weighting and data quality analysis. Weighting is classification of the importance of the impact, compared to the other environmental impacts. Data quality analysis is a further analysis of the data, which assess the weakness and strengthens of the data. This phase increase the quality of the impact results [10].

ReCiPe

Different LCIA-methods are used in LCA studies. One of the most used method is called ReCiPe, and is used in the classification phase of the LCIA. The ReCiPe method is build-up of 18 midpoint impact categories shown on the left side in *Table 4-1*. The midpoint categories show the direct impact on different environmental loads. Each category is briefly described in the table. To better understand the impact of a LCA, these 18 midpoint categories are further converted into three endpoint indicators. The three endpoint indicators are human health, ecosystems species and resources surplus cost [39] [40].

Table 4-1: ReCiPe method used in LCA. The midpoint categories are shown and described in the figure.

	Midpoint categories	***Description***
LCI Results	Ozone depletion [kg CF-11 eq.]	Ozone prevent ultraviolet radiation, and is therefore vital for life on earth [40].
	Human toxicity [kg 1,4DBC eq.]	Emissions of toxic substances can indirect reach human through food chain and risk of health [40].
	Ionising radiation [kBq U_{235} eq.]	Radiation from radioactive materials, resulting in human health concerns [40].
	Photo chemical ozone formation [kg NMVOC eq.]	Pollutants from NO_x and hydrocarbons, resulting in human heath [10].
	Particulate matter formation [kg PM_{10} eq.]	Pollutants of small particles from acid, metals, chemicals, soil and dust, resulting in human health [40].
	Climate change [kg CO_2 eq.]	Impact on the radioactive force in the atmosphere, resulting in heating of the earth. Emissions from CO_2, CFC, nitrous oxides [10].
	Terrestrial ecotoxicity [kg 1,4DBC eq.]	Emissions of organic solvents, heavy metals, and pesticides [10].
	Terrestrial acidification [kg SO_2 eq.]	Emissions of SO_2, NO_x, HCL and NH_3. These pollutions forms H^+ ions [10].
	Agricultural land occupation [m^2 year]	Amount of agricultural land occupation. May result in damage to ecosystem [40]
	Urban land occupation [m^2]	Damage to ecosystem due to land occupation in a process [40].
	Natural land transformation [m^2]	Damage to the ecosystem due to transformation of land in a process [40]
	Marine ecotoxicity [kg 1,4DBC eq.]	Emissions of organic solvents, heavy metals, and pesticides [10].
	Marine eutrophication [kg N eq.]	Emissions of high content of nutrients, such as nitrogen and phosphorus [10].
	Freshwater eutrophication [kg P eq.]	Emissions of high content of nutrients, such as nitrogen and phosphorus [10].
	Fresh water ecotoxicity [kg 1,4DBC eq.]	Emissions of organic solvents, heavy metals, and pesticides to water [10].
	Fossil resource depletion [kg oil eq.]	Resources containing hydrocarbons. Includes volatiles like methane, or liquid petrol, and non-volatile materials [40].

	Minerals depletion [kg Fe eq.]	Depletion of metals and other minerals through mining activity [40].
	Water depletion [m^3]	Measures the amount of water used in the process [40].

4.1.4 Interpretation

The life cycle interpretation involves using the results from the LCI and LCIA to make decisions and conclusions. The interpretation should start with an identification of the results, followed by an evaluation phase, and finally draw conclusions, discuss limitations and recommendations from the study [36]. The interpretation have to recognise that the results from the LCA is just an identification of the potential emissions, and not the actual future emissions [35].

In the identification phase, the results from the LCI and LCIA are used to describe the significant issues. Significant issues can be energy and emissions data, and impact categories, and they are in accordance to the goal and scope. [36].

The goal of the evaluation is to make the results from the study reliable. This is often performed by conduction sensitivity analysis. Such an analysis is used to identify and assess how a product respond to a small change in one or several inputs. Finally, the conclusions can be drawn, the limitations can be identified and recommendations can be identified [36].

4.2 Data collection method

The data used in the thesis is collected via different methods. In order to get a result that can be related to the real life operation of the ferry, it was desirable to get as much data as possible from manufactures, companies, and previous research papers. Nevertheless, data which was not available from these sources were collected from the background database, Ecoinvent version 3.3. Ecoinvent 3.3 is integrated in the simulation software, Simapro. The data in Ecoinvent are based on average values, and is a great representation if data are missing [38]. However, to get the LCA results closer to the real life processes, most of the data should be collected directly from manufactures.

The data for the batteries has its origin from the companies DNV GL and Grenland Energy. The data are based on production information from Grenland Energy.

Data for the boat structure, hull, energy consumption, and route information were collected in conversation with the business cluster, NCE Maritime CleanTech (MCT). The data for the different parts of the vessel originates from several companies. The aluminium intended to be produced by “Norsk Hydro” in Norway. The remaining design and construction of the vessel is performed by the Norwegian shipyard, Fjellstrand AS.

Implementation of PVs is a supplement to the thesis, and is tested as a scenario assessment. The data for the extraction- and production processes of the PVs were obtained from Linjord’s report, which is master thesis from UiA on an LCA of PV integrated in roof tiles [33].

4.2.1 Assumptions

Photovoltaics

In this thesis, several assumptions have been made, mainly in the design and calculation of PV modules. The area-occupation of PV modules can be huge, and should be considered during planning of a solar power plant. Nevertheless, area occupation is not considered in this thesis i.e. the actual location of the panels is not treated.

Other assumptions regarding PV module design is listed below:

- The online calculator PVGIS (theoretical calculator for PV systems) is used to determine the irradiance in Indre Oslo-fjord. These data are used for theoretical calculation of electricity production, and no practical measurements is performed [41].
- Economic- and area limitations are not considered.

Diesel engine

In the case of diesel engine scenario (described in chapter 6), it was assumed that the energy consumption for the diesel engine is based on the calculation for the electrical propulsion system. A typical diesel-motor-efficiency was therefore considered.

Charging

It is uncertain if the grid capacity in Sætre, Fagerstrand and Aker brygge can handle a charging power of 1 MW. An attempt was made to contact Skagerak Energi to get information regarding this challenge, but the needed information was not received. It is therefore assumed that the capacity in the three areas satisfies a charging power of 1 MW without supporting batteries located at each port for maintaining a constant charging. DNV GL has performed a study on possible ferry crossings suitable for battery propulsion [42]. The needed upgrade in the electricity at each crossing were identified as well. 12 % of the areas do not need grid-upgrade to implement battery propulsion. Sætre, Fagerstrand and Aker brygge were not mentioned in the study, but based on the results from DNV GL, the assumption of not designing additional batteries is reasonable. However, a scenario analysis was made with additional on-shore batteries for charging. The calculation of these batteries is based on the charging batteries on MS Ampere.

5 Manufacturing

This chapter describes the manufacturing processes of batteries, aluminium and PVs. The chapter aims to present the different processes in order to get a better understanding of the results of this LCA.

5.1 Battery production

With experience from previous studies, the production of batteries is one of the component which contributes most to the LCA impacts. An introduction to the production process of LIB is shown in the next sections.

5.1.1 Extraction of lithium

Lithium is an element used in among other lithium-ion batteries. The biggest lithium reserves are found in Argentina, Bolivia and Chile, where approximately 70 % of the global reserves are stored. Another big lithium producer is China. The primary sources of lithium are found in minerals, clays and brines. The most lithium containing minerals are spodumene, petalite and pegmatite [43].

Extraction from minerals

Two methods are usually used in the extraction of lithium from minerals; alkaline digestion and acid digestion. Acid digestion is a process which includes sulfation-roasting with lepidolite and water leaching. This can give a high concentration of, for example, lithium carbonate, depending on the mass ratio between the reactance and the roasting temperature. Acid Digestion is performed by adding an acid to the mineral, for instance sodium carbonate, roast it and perform water leaching [43].

Alkaline digestion is a method where the ores are calcined together with limestone normally at high temperatures from 820℃ to 1050℃. The outcome of this process is a calcine which is crushed and milled, before water is added. The resulting lithium hydroxide is then mixed with hydrochloric acid, and lithium chloride are formed. The chemical process is described as follows [43]:

$$Li_2O\ Al_2O_3\ 4SiO_2 + CaCO_3 \rightarrow Li_2O + CaO\ Al_2O_3\ 4SiO_2 + CO_2$$

By changing the reactant and roasting temperatures in the two processes, it is possible to extract different purities of lithium. However, the different processes with other reactants will not be presented here.

Extraction from brines

Approximately 66% of the lithium reserves on the earth are stored in brines. However, due to a time-consuming extraction process, only 8% of the extracted lithium originates from brines. The full process of lithium extraction from brines is described by the block diagram in *Figure*

5-1. The method starts with solar evaporation of the brines over a year. This process, forms crystallized potassium, magnesium chloride and sodium. After the evaporation process follows a refining process purifies the lithium metal. Roasted calcium carbonate is then added to the evaporated lithium in order to separate the magnesium hydroxide ($Mg(OH)_2$) from the lithium chloride. The resultant in the process is lithium carbonate, ready to be implemented in lithium ion batteries. There are several concerns regarding lithium extraction from brines. The process is time consuming, and the process contributes to a high share of water consumption. In addition, a lot of waste is generated during the process [43]. There are several methods in lithium extraction from brines, but these will not be presented in this thesis. However, further reading can be found in Meshram et al's report in [43].

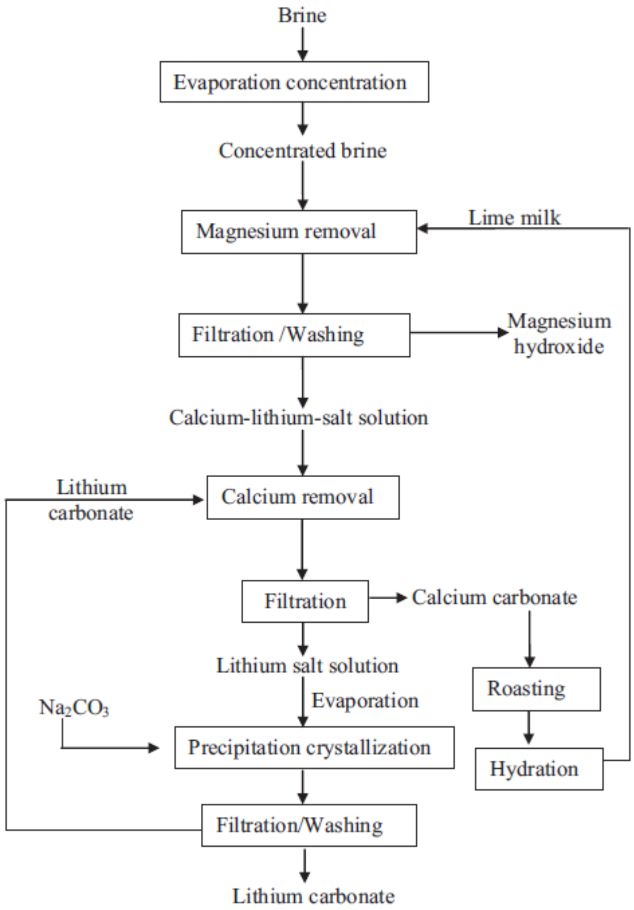

Figure 5-1: The process of lithium extraction from dry lakes and brines [43].

5.1.2 Electrode manufacturing

The electrodes in LIBs are made by mixing the active material and a binder into a slurry, before coating the slurry with a current collector.

The cathode is mixed with the active material (lithium oxide), a binder such as polyvinylidene difluoride (PVDF) and a conductive carbon based material, such as graphite. The lithium oxide and the carbon material are mixed together in a dryer. The lithium oxide and the carbon are then combined with the binder in a ball mill and stirred. This is an important process that can influence the battery performance [44].

The anode mixing process is the same as for the cathode, only with different materials. The active material in the anode is graphite or carbon, and a binder such as PVDF can be used in the mixing process. PVDF is a great binder when combining the carbon and current collector together. Unlike the ball mill used in the mixing process for the cathode, a planetary mixer is used for the anode mixing process. The planetary mixer has two or three blades located on different axes, in order to get a best mixing result as possible [44].

The electrodes are then coated with a thin layer (normally 15 to 300 µm) of current collector. Aluminium is used as current collector for the cathode and copper is used for anode. Automatic controlled coating machines are used to get an optimal size of the electrodes and to ensure that all the components fit together in the batter assembly. The coating is then compressed and dried, before slitting is performed to make them suit for the different electrodes [44].

5.1.3 Battery cell assembly

Cylindrical cells and prismatic cells are the most common types of fabrication in lithium ion batteries. In high capacity, such as electrical vehicles, prismatic cells are most commonly used. Therefore only the production of prismatic cells will be briefly introduced here.

The cell assembly process starts with mounting the anode, cathode and separator in a winding machine. The machine is formed as a flat paddle and operates automatically with high precision. Constant pressure by the winding machine is crucial in order to avoid leakage and gap in the assemble [44].

The cell is further dried in a drying room to remove eventually moisture in the cell. The cell is then filled with the electrolyte by a pump and vacuum device which ensures that the electrolyte is filled in the porous structure in the electrodes. High contact area between the electrolyte and electrodes secure that the battery will operate in an optimal manner [44]. The electrolyte filling has to be performed in a dry room in order to avoid chemical reactions between the electrolyte and water [45]. The cell is further added a mechanism that cut the current if the temperature or pressure in the battery exceeds a certain pre-set value. The cell assembly and the electrolyte filling mechanism are then sealed [44].

5.1.4 Formation

The last step in the manufacturing process of lithium ion batteries is the formation process. The formation process activates the active materials in batteries. The cell assembly is mounted when the battery is discharged. In the formation process, the charge of the battery start with a low current and increases gradually. This is performed to suite the solid electrolyte interface, which is a protective layer on the anode during normal operation. Cell voltage and capacity are logged during the formation. These data can be used to separate cells with different cell voltage and capacity for different application [44] [45].

5.2 Aluminium production

Aluminium is extracted both from primary resources and secondary resources. Primary extraction is a process which converts bauxite to aluminium. Secondary process is recycling or re-melting of used aluminium. Further reading regarding primary- and secondary aluminium production follows in the next sections

5.2.1 Primary production

According to Norsk Hydro, the primary aluminium process starts with the extraction of bauxite from mines [46]. Bauxite is an ore that contain 50% aluminium, while the remaining part is water and other pollutions [47]. The bauxite is transported from the brines to the refinery and washed with water to purify the bauxite from clay and mud. The bauxite is further milled and transported to the refinery. In the refinery, aluminium oxide is extracted from the bauxite. This is performed by adding the bauxite to a pre-heated solution with lye and caustic soda. The aluminium oxide is then dried to a white powder which is further sent to the metal plant [46].

The oxygen in the aluminium oxide is removed by processing the aluminium oxide in an electrolyser, which contains an anode and a cathode. The anode is made of a carbon-based material which react with the oxygen in the aluminium oxide. Current is added to the electrodes and the anode reacts with the oxygen, and forms CO_2. The resultant is molten aluminium in liquid form [46] [47].

The liquefied aluminium is alloyed and then processed in the casting plant. The casting plant is a process that forms the purified aluminium into small bolts or billets [47]. What is performed further depends on the area of use [46].

5.2.2 Secondary production

Secondary aluminium production or recycling, is a process which can have huge energy savings. Approximately 4 kg of bauxite, 7,5 kWh of electricity and 2 kg of chemicals are saved when 1 kg of aluminium is recycled. The total amount of recycled scrap aluminium in the world is 4,5 million ton per year [48].

The aluminium is re-melted in a rotating furnace together with a huge amount of salt. The most used salt in the process is sodium chloride (NaCl) and potassium chloride (KCl). The salts are combined in a mixtures with cryolite. The mixture has a melting point lower than the aluminium. When the temperature increases, the salt mixture melts and forms a coating on the aluminium which protects against oxidation [48]. The process is showed in *Figure 5-2*.

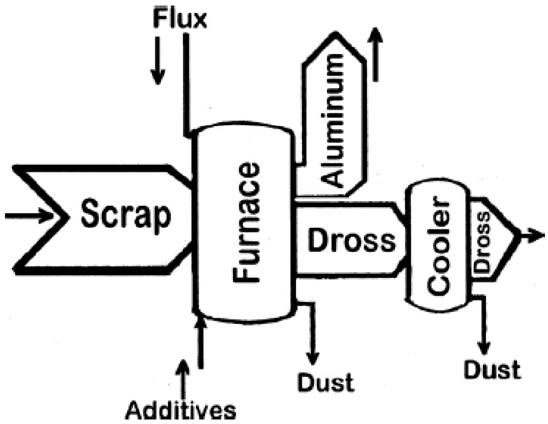

Figure 5-2: Recycling process of Aluminium [48].

As explained by the figure, the products from the heating process in the furnace is aluminium, dross and dust. The dross still contains 12-20% of aluminium which can be extracted in a new process. However, aluminium extraction from dross is rarely performed [48].

The dross process starts with a separation of dust and metals. Metals are stronger than other components in the dross, which makes them easy to separate when crushed in a mill. The metal is extracted and melted in a rotating furnace, where the aluminium is purified. The additional resultants are dust and huge amount of salt cakes. The dross and salt cakes are classified as high toxic waste, and should therefore be treated rather than transported to the landfills [48].

5.3 Photovoltaic production

Different technologies and methods are available in manufacturing of PVs. In this thesis, the "Elkem solar process" is considered in the extraction of silicon. According to Elkem Solar, the Elkem solar process only uses 25% of the energy consumption compared to conventional processes, such as the Siemens process. In addition, Elkem solar are located in Kristiansand which use Norwegian electricity. This makes the silicon purification process more clean due to the high share of renewables in the Norwegian energy mix [49]. The Elkem solar process starts with a metallurgical process where the silicon is purified from quartz rocks. The rocks are fed into a high temperature furnace together with carbon rich materials. The oxygen in the SiO_2 reacts with the carbon and forms CO_2 gas, while purified silicon can be extracted on the bottom of the furnace. The silicon is further purified in the following steps to extract solar grade silicon: Slag treatment, leaching, solidification and post treatment [50].

The solar grade silicon is crystallized and doped in a process called Czochralski process. The silicon is first molten, before the temperature are stabilized at approximately 1400 ℃ to get the silicon crystalized. The silicon crystals are then cut into pieces to make them fit into the solar cell assembly [33]. The last process is the manufacturing of the cells. The cells are optimized for electricity production. The p-n-junction is created, and texturing are performed on the cells in order to maximize the absorption of light and minimizing the reflection of light [32].

5.4 Energy mix

Energy mix is an important factor in many manufacturing processes. It refers to the source of primary energy generation in different countries. The primary energy sources can vary from fossil fuels, nuclear energy and renewable energy. The energy mix is a term that is used in electricity production, heating process and transportation. Most of the present average urban energy generation has its origin from fossil fuels. The Norwegian energy mix is mostly from renewable energy sources, such as hydro power [51]. *Table 5-1* show the electricity and heat production in Norway for 2015. In addition, the amount of imported and exported energy are shown in the table. The data are extracted form SSB [13].

Table 5-1: Electricity generation in Norway in 2015 [13].

Production	***Amount [GWh]***	***Share [%]***
Total	144 511	100
Hydro power	138 450	95,8
Heat	3 546	2,5
Wind power	2 515	1,7
Import	7 411	-
Export	22 038	-

6 Project Information

This chapter describe the concept of the project. Initially, the urban water shuttle will be described, followed by energy calculations. The last part of the chapter shows the life cycle inventory of study.

6.1 Introduction to the technology

UWS is a project owned and designed by NCE Maritime CleanTech (MCT). The concept is to build a battery electric passenger ferry, shown in *Figure 6-1*, that can operate in coast-line cities where public transportation is needed. The ferry can contribute to reduce local and global air emissions in these cities. In addition, minimal amounts of infrastructure expansion are needed for sea transportation, which makes it relatively cheap to implement. The UWS aims to expand the public transportation in urban areas, as well as contributing to reducing the future air emissions.

Figure 6-1: Urban Water Shuttle. The figure is obtained from Maritime CleanTech [52].

The size of the vessel is an important factor. MCT has designed two vessels with different passenger capacity depending on the route of operation: One vessel with 125 PAX and one with 194 PAX. The option which is studied in this thesis is the 125 PAX vessel. This vessel is 26 meters long and nine meters wide, with a capacity of 125 passengers. The vessel is designed with a operation velocity of 20 knots. A vessel with higher operation velocity requires a heavier weight and larger size [11].

The case study of the 125 PAX vessel is operating in the "indre Oslo-fjord" between three departures, shown in *Figure 6-2*. The route Sætre – Fagerstrand - Aker brygge is approximately 29 710 meters long (or 15,51 nautical miles) one way. The total travelling time with the UWS is approximately 1 hour and 10 minutes one way. It is assumed that the vessel can manage at least two roundtrips of this route per day. The number of trips can be optimized when the vessel is set in operation in the future. The lifetime of the UWS is 30 years, resulting in a total travelling distance of 325 324,5 km per lifetime if operating every day for 30 years. The vessel will not be delayed by charging, which is prevented by optimizing the charging process during boarding on all ports.

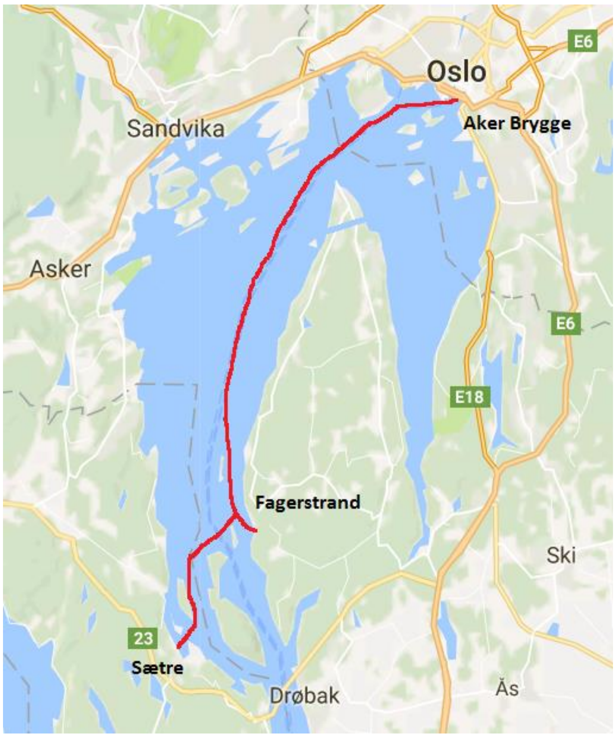

Figure 6-2: The planned route of the UWS in the Indre Oslo-fjord. The ferry will have three departures: Sætre, Fagerstrand and Aker Brygge, shown with a red line.

A simple block diagram of the electrical grid of the UWS is described in *Figure 6-3*. The diagram is a typical sketch of an electrical system in a vessel. The electrical components are connected to a DC-bus which distributes the energy on the vessel. The vessel-battery is charged from the grid with a transformer, which lowers the voltage from the grid-level to an acceptable charging voltage for the battery. A converter converts the alternating current (AC) current to direct current (DC) before the battery is charged. The engine on board the vessel is assumed to operate with an AC motor (as in MS Ampere). This requires another converter, which convert DC voltage to AC voltage between the DC-bus and the propellers. The batteries can be powered both from the electrical grid and from the PV produced power, described later in this chapter. The arrangement is a complex system consisting of converters and inverters to maintain a stable and continuous energy flow. The figure is based on information of the electrical grid used in MS Ampere. This information was extracted during a visit to NCE Maritime CleanTech and MS Ampere in October 2016.

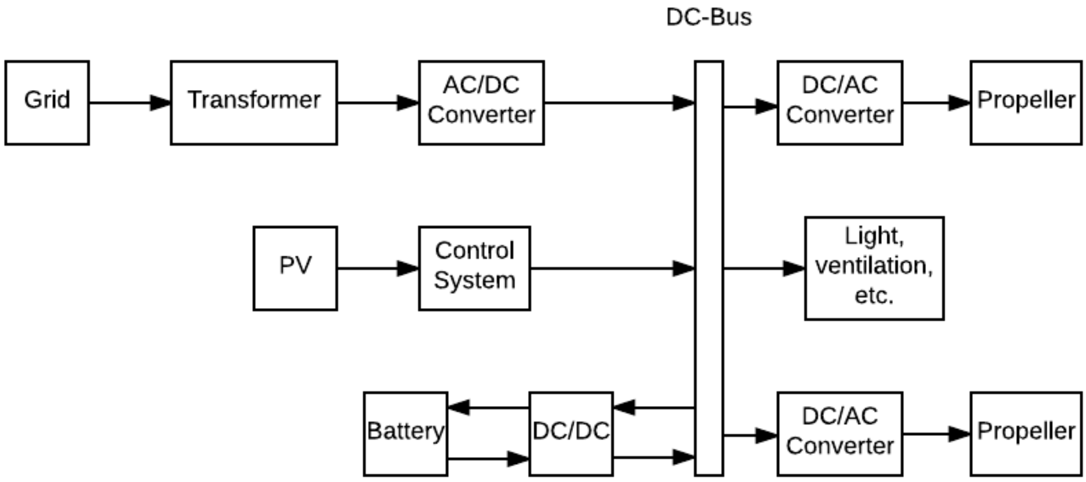

Figure 6-3: System description of the intended electrical system in the UWS.

6.2 Goal and scope

The current study aims to analyse the environmental impacts if implementing a high-speed passenger ferry powered by electricity from LIB. The goal of the study is to investigate if electric propulsion in high-speed passenger ferries is a better solution compared to conventional diesel combustion engines, with respect to the environmental impacts. The study is a cradle-to-grave study, i.e. the environmental impact from the material extraction, material production and operation to its EoL is considered. The EoL treatment is not considered in this thesis. The study will further assess and compare the environmental potential between different technologies to power the UWS, such as PVs and diesel.

The project is a case study of a possible introduction of the UWS in the Indre Oslo-fjord, where the environmental goal is to reduce local and global air emissions. Therefore, the main focus in this study is to assess the air emissions such as CO_2, NO_X, SO_X and particle matter (PM).

The outcome of this thesis can be used as a document of the environmental potential of electrical passenger ferries. It can be used to compare different types of public transportation system in the future. As the goal of the government is to expand public transportation connections in an environmentally friendly manner, the results in this study can be valuable in selecting transportation option.

6.2.1 Functional unit

The functional unit in this thesis is emission per person kilometre travelled (PKT). This is a functional unit which is used in similar LCA studies, and comparison between studies is therefore easy. By using PKT as functional unit, the results can simply be recalculated to other functional units, such as emission per lifetime.

The PKT functional unit was calculated based on the average Norwegian capacity utilization in buses as shown in the equation.

$$\text{PKT} = \text{total travelled km per lifetime} \times \text{Person capacity} \times \text{capacity utilization} \qquad (6.1)$$

The person capacity is the maximum number of persons that can travel with the public transportation technology. For the UWS, the person capacity is 125 persons. The capacity utilization is based on the average Norwegian relationship between the seat-km (the amount of km all seats travels) and the passenger-km (amount of seat-km utilized by persons) with bus, boat and train. According to SSB, the seat-km in Norway for 2015 was 26 927 015 km and the passenger-km was 8 751 258 [13]. Hence, the capacity utilization was estimated to be;

$$Capacity\ utilization = \frac{Passenger\ km}{seat\ km} = 32{,}5\ \%$$

6.2.2 Flow chart and system boundaries

Figure 6-4 shows a simplified system flow chart of the vessel's lifetime. The material extraction-, production- and use- phases are described in the figure. This is the most important phases of the vessel's life time. Specific data regarding transportation is considered where data were available for extraction. Average transportation values were used in case of lack of specific data.

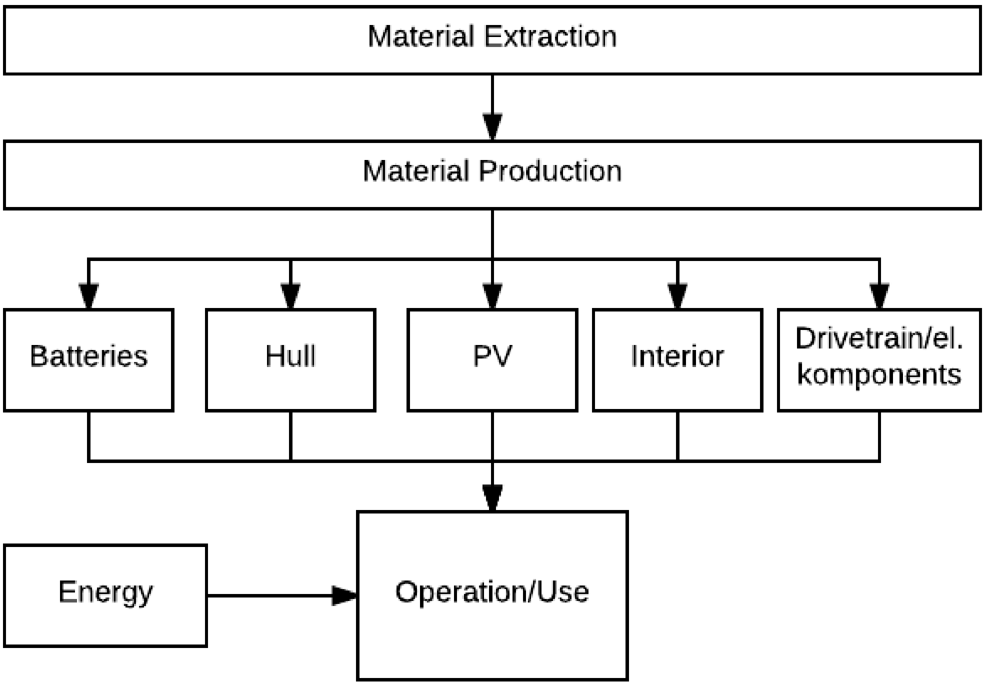

Figure 6-4: Simplified flow chart of the UWS's lifetime.

The study considers that the vessel operates in the city of Oslo in Norway. Norwegian electricity mix is therefore used in the operation phase of the vessel. However, all materials used in the manufacturing phase are not extracted and produced in Norway. The materials' production location is described later.

The lifetime of the vessel is assumed to be 30 years. The lifetime can be longer, but the same lifetime is assumed in MS Ampere and used in this study. The lifetime of the batteries is according to DNV GL 10 years per battery package. This requires at least two replacements of the battery.

In the boat production, most of the components used to produce the vessel are included i.e. components regarding batteries, hull-material, PVs, electrical components and drivetrain. Data regarding energy consumption, transportation and material type from its raw material extraction to its production is collected if it was possible to get. Missing data is based on average values extracted from the Ecoinvent database. The choice of the different materials in the UWS can cause large impact on the results of the LCA, and is therefore an important factor to consider. MCT has defined much of the materials which will be used in the UWS, while information which is not available from MCT are collected from previous research work. Data for the LIBs were obtained from the companies Grenland Energy and DNV GL.

6.2.3 Limitations

One important simplification is the estimation of the total amount of aluminium used in the vessel. The amount of the aluminium for the hull and superstructure is a rough estimation. It was difficult to determine the exact amount of aluminium as the vessel is not built yet. However, the same amount of hull-material is used in all four scenarios, meaning that the aluminium amount is insignificant in the comparison by the scenarios. Nevertheless, the individual results may be affected of this rough estimation.

6.2.4 Scenario description

The thesis will assess four different scenarios. The first scenario considers a ferry operating with conventional diesel propulsion. This is a simplified scenario that use the same vessel structure as the other scenarios, except components related to the electrical propulsion. The energy consumption for a diesel engine is estimated based on the energy consumption for the electrical engine in the UWS. The data is further implemented in a diesel engine-model in the Ecoinvent database and simulated with the same hull material as the UWS. This scenario is used as a reference in comparison to the other scenarios.

The second scenario is where the UWS is powered with Norwegian electricity mix and electrical propulsion. The UWS is designed per this scenario, which means that this scenario is the most important case.

The third scenario is assumed as a system with batteries powered by energy from the grid and PV-produced energy. The PVs are located two places, namely on the roof of the UWS and near the charging stations. The purpose of this scenario is to investigate if it is environmentally beneficial with onsite energy production on the UWS.

The fourth scenario examines the situation if the grid capacity is not large enough for the charging situation with 1 MW. An attempt was made to get information on the grid capacity in Sætre, Fagerstrand and Aker brygge, but it proved to be hard to get. Therefore, it is assumed in Scenario 4 that additional batteries are needed to assist the charging operation at each port.

The different scenarios are listed below:

- Scenario 1: Conventional diesel combustion ferry.
- Scenario 2: UWS powered directly from the Norwegian grid.
- Scenario 3: UWS with roof mounted PVs and PVs mounted on each port.
- Scenario 4: UWS powered from the grid and additional batteries located at each port for supporting the grid during charging.

6.2.5 Simapro

Simapro v8.3.0.0 Faculty is used as modelling- and simulation software in this project. Simapro is the most used software in LCA simulations. The software has Ecoinvent version 3.3 as build-in background database and use the standardisations in LCA [53].

6.3 Energy and battery calculations

The main energy demand for the UWS is for the propulsion. The calculations are based on the route Sætre-Fagerstrand-Aker Brygge, and are assuming that the batteries are charged at all stops. The needed propulsion power is calculated by MCT and are based on a tested water resistance and propulsion coefficient for the vessel when the velocity is 20 knops. The energy consumption includes a 20% safety margin in case of days with extreme weather conditions such as wind and waves. The 20% margin also includes electricity used for light, ventilation, etc. on the vessel. The outcome of the calculation is drawn in the operational profile of the distance Sætre-Aker brygge, shown in *Figure 6-5*. The operational profile describes the amount of time in the different operating power-levels of the UWS for the trip Sætre-Fagerstrand-Aker Brygge.

Some energy losses in the transmission when charging the batteries is considered in the energy calculations. The efficiency in the power electronics is assumed to be 95 % for converters and transformers, and 95 % for the battery [54] [23] . The calculated energy values are listen in the end of this chapter.

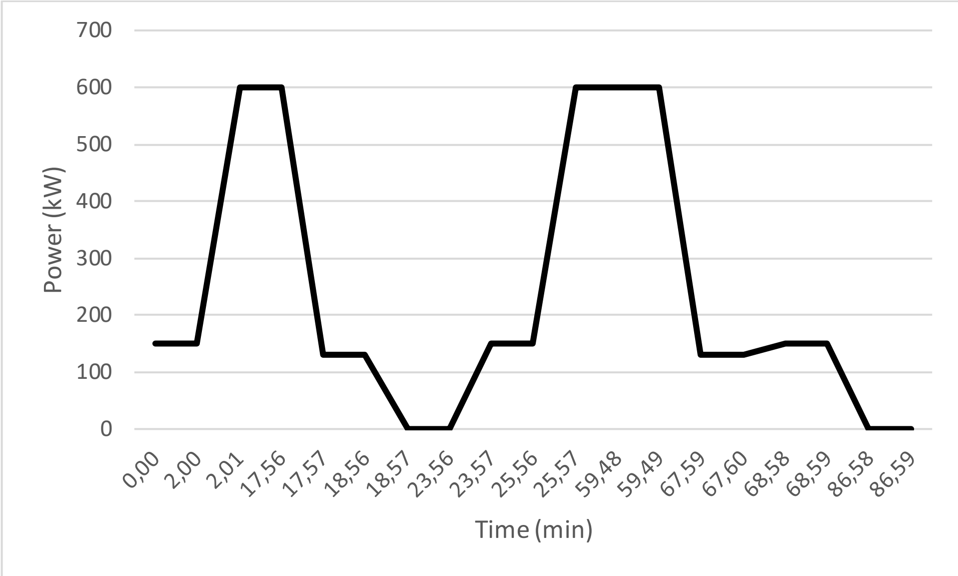

Figure 6-5: Operational profile for the UWS for the distance Sætr-Aker Brygge.

The calculation of the energy consumption also assume that the vessel is fully weight-loaded i.e. 69 ton. The weight calculation includes:

- 3 ton electrical engine plus 12 ton battery package.
- 125 passengers a 75 kg. plus 5 kg. luggage.
- Remaining weight is the vessel-structure.

In order to achiev the UWS's energy need, it was estimated a minimum on-board battery capacity of 720 kWh. *Figure 6-6* shows the battery's state of charge (SOC) for two round-trips with UWS. Two round-trips is defined as two times the distance Sætre-Fagerstrand-Aker Brygge-Fagerstrand-Sætre. As shown in the figure, the available energy in the battery decreases continuously from 100 % at maximum SOC to approximately 7% at its minimum SOC. Optimal operating range of batteries in electrical vehicles is according to "Battery university" between 30-80 % when they are new. This is the most efficient operating range of the battery, and the least stress range. By maintaining this range as long as possible, the lifetime of the battery is expected to be longer. As the battery get older, the operating rang will expand beyond the upper- and lower limit due to degradation [7]. According to Ellingsen et.al. the expected life time of a battery that is 100 % discharge is approximately 1 000 charging cycles, while 50 % depth of discharge can reach 5 000 cycles during its lifetime [54]. Based on this information, it should be considered to over-dimension the battery capacity to at least 15-20% of its minimum SOC, and not charge the battery to 100 % SOC. This is not considered in this study as the battery capacity is estimated by NCE MCT.

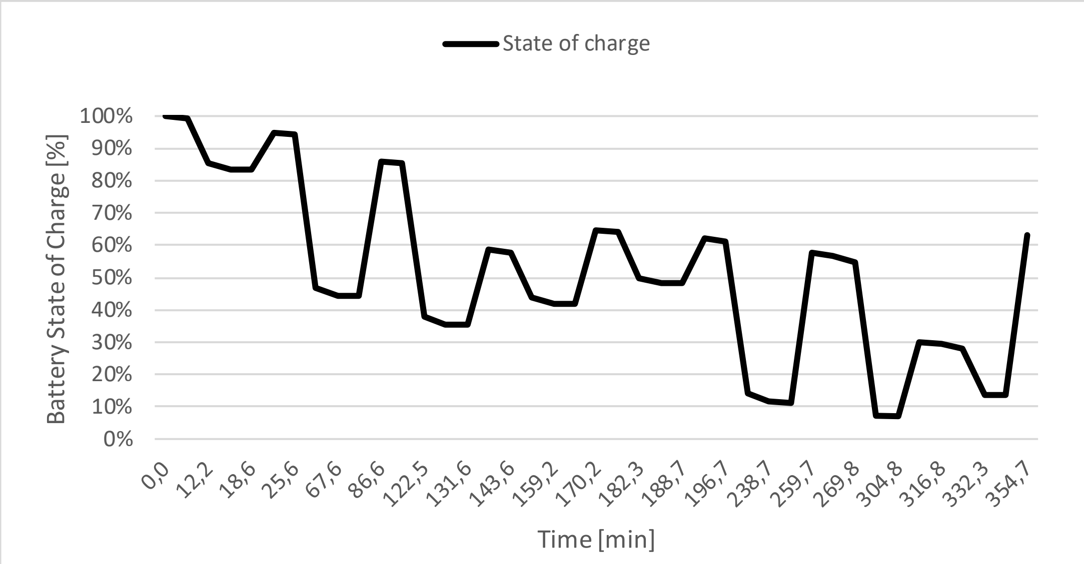

Figure 6-6: Battery state of charge in two round-trips with the UWS.

6.3.1 Calculation of additional batteries (Scenario 4)

In addition to the battery at the UWS, it is assumed in Scenario 4 that additional batteries are implemented for supporting the grid during charging operation. This assumption is based on the experience from MS Ampere, where the grid is too weak to only charge the on-board battery directly from the grid. The general Norwegian grid is weak and under-dimensioned, which mean that the scenario is important to include in the study [8]. Another opportunity, rather than using additional batteries, is to expand the grid capacity. According to Kullmann's research, the distribution between charging from grid and charging from batteries is 20% and 80% respectively with a 1MW charger [8]. This distribution will change according to the available grid capacity in the area, but due to lack of information, the same distribution as in MS Ampere is assumed in Scenario 4.

Table 6-1: Minimum required power at each port.

Port	*Minimum total energy need (kWh)*	*Energy powered from grid (kWh)*	*Energy powered from batteries (kWh)*	*Estimated battery capacity (kWh)*
Sætre	356,7	71,34	285,4	570
Fagerstrand	166,7	33,34	133,4	266
Aker brygge	333,3	66,67	267	533
Total				1369

The batteries that are located at each port should be designed according to *Table 6-1*. The data are estimated based on the previous described assumption. The estimation of the battery capacity is determined with respect to the maximum SOC limit of 80 % and minimum SOC limit of 30%, described previously. There will be an insignificant energy loss in the transmission from the on-shore battery to the off-shore battery, but this is not included when designing the on-shore batteries.

6.3.2 PV measurements

Ahead of the PV calculations, a goal was set of producing at least 10% of the energy consumption by the PVs. The energy production corresponds to the daily energy consumption for the UWS. As much as possible energy should be generated on the roof of the UWS, while the remaining energy is assumed to be produced by modules located near the ports of the UWS. The needed area for PV-installation on each location is calculated based on the amount of produced energy needed to meet the goal of 10%.

Roof mounted PVs

The energy production on the roof of the UWS is based on the irradiation in Indre Oslo-fjord, extracted from PV GIS. PV GIS is a free online solar calculation, which can be used to estimate the irradiation on a specific location [41]. The energy production is therefore a calculated estimation, which may differ from a real case scenario. The PVs are integrated on the roof of the vessel and is assumed to be mounted horizontal to the roof, i.e. the tilt angle is 0˚. This will limit the energy production, especially in the winter months, where the sun angle is decreased with an angle, Ɛ with respect to the equinox, as shown in *Figure 6-7*. The opposite occurs in summer solstice, resulting in an increase of Ɛ with respect to equinox [32].

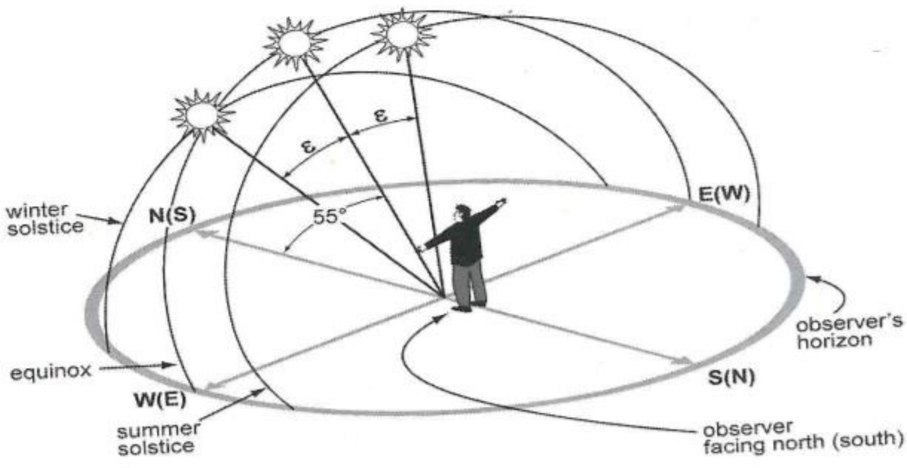

Figure 6-7: Description of the sun's path in winter- and summer time [25].

The available roof area for PV installation on the UWS is assumed to be 240 m^2. Utilization of other surface areas such as walls for more PV-installations is possible in the future. The PVs are assumed to produce power dynamically through the day. This is achieved by using the produced energy directly (without storage) when the vessel is in operation. In periods when the vessel is docked, the PV modules produces energy to the battery located on board. This means that the PVs can produce energy the whole day, and hence maximize the utilization of the modules.

The following data were implemented in PV GIS for the PV installed at the UWS:

- P_{peak}=37,5 kW_P
- η= 14%
- Tilt angle= 0˚
- Crystalline silicon, building integrated.

A typical produced peak power for a 1,6 m^2 crystalline PV cell is according to literature approximately 250 W under standard test conditions [55]. Normalizing for 240 m^2, a total power peak production of 37,5 kW is assumed in the calculations. The average daily irradiance to the modules where measured and used in the calculations of average daily energy production. Equation 3.5 was used to perform the energy calculation. The daily average energy distribution through a year is described in *Figure 6-8* for the PV modules on the vessel (black) and for the land mounted modules (blue). The average energy production is shown with dotted lines for the two cases. Due to the low production in the winter months, the average energy production is far from the peak production in June. An overview of the calculations can be found in Appendix B.

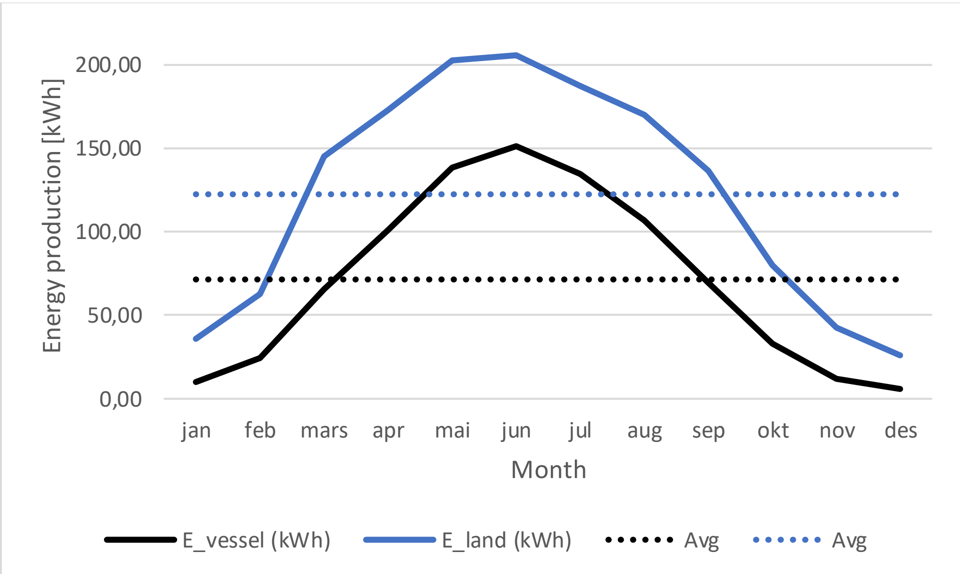

Figure 6-8: Daily energy production-distribution for one year in Oslo fjorden. Black line is energy production from vessel module, blue line is energy production from land mounted modules. The dotted lines are the average energy production of vessel- (black) and land (blue) modules.

Land mounted PVs

In order to meet the 10 % energy goal, a total energy production of the land mounted PVs is calculated to 122 kWh per day. This value gives a required area of 330 m^2 for PV installation. This gives 110 m^2 installation on each location. The energy is used to charge batteries which are located at each port. The data which was plotted in PV GIS is:

- P_{peak}=37,5 kW_P
- η= 14%
- Tilt angle= 44˚
- Crystalline silicone, free standing.

As a summary, *Table 6-2* shows a distribution of the energy produced from the grid and from the PVs in Scenario 3.

Table 6-2: Sum-up of energy production from PVs

Energy Generation	Energy production (kWh)
On site PVs	71,5
Land based PVs	123
Grid	1746

For the on-shore PVs, it is needed a battery for energy storage. These batteries were designed with respect to the production of the PVs and the SOC limits described previous. Three batteries with a capacity of 82 kWh each were estimated.

6.3.3 Diesel engine calculations (Scenario 1)

As mentioned in the assumption-section, the energy consumption for the diesel engine is calculated based on the UWS's energy consumption with electrical engine. A typical diesel engine efficiency of 55 % was considered when calculating the energy consumption. This is a little higher than was reported by Lasselle et. al, which assumed 40 % efficiency for a diesel engine [23].

6.4 Inventory

The qualitative inventory describes the processes in the cradle-to-grave LCA. It explains the type of materials used in the different components in the UWS, and where it is extracted and manufactured. A summary of the data quantity can be found in the end of this sub section. The Inventory of all parameters in this thesis can be found in Appendix C, Appendix D and Appendix E.

6.4.1 Hull and superstructure

The weight of the vessel is an important factor in the design process. By minimizing the weight, the energy consumption can be decreased significantly, which is the reason for building the UWS in aluminium. Aluminium is a strong metal with insignificant maintenance and long life time. Compared to steel, which is used in most conventional ferries today, aluminium is approximately 33 percent lighter [11].

The aluminium is assumed to be manufactured by the Norwegian company, Norsk Hydro. They will produce and deliver the needed aluminium for the hull and superstructure, and accept the aluminium for recycling when the vessel has reached its EoL.

Norsk Hydro extract bauxite from mines in Alunarte in Brazil, and transport it to the refineries through pipelines. The bauxite is converted to aluminium oxide in the refinery and further transported to the aluminium smelters located in different locations in Norway [46]. The energy consumption and emissions related to the bauxite extraction and refinery process is the same independent where the process is performed. However, the emissions associated to the energy consumption in the aluminium smelters depends on where the smelters are located. The data regarding extraction of bauxite is therefore based on average values. The energy used in the smelters are based on Norwegian conditions.

The transportation of bauxite, aluminium oxide and processed aluminium to the customers was hard to find. Therefore, average global transportation from Ecoinvent is used for this purpose.

6.4.2 Batteries

The manufacturing process of the batteries is described in Chapter 4. The specific data of the battery package in this study is given by Grenland Energy and DNV GL. The battery pack is built-up of battery cells, modules, sub-packs and strings.

A battery cell is an assembly of anode, cathode and separator. Lithium nickel manganese cobalt oxide (NMC) is the active material of the cathode, with aluminium as current collector. The anode is a composite of copper as current collector, and graphite as active material. The cells are connected in series and parallel in modules and capped with aluminium as cover. The modules are then combined in sub packs and strings in series. To form one battery pack, the strings are connected in parallel to get the desired output. 104 battery cells is needed to form one module, 9 modules are needed for one sub-pack , and 6 sub-packs are needed to make one string [23]. An image of a complete battery pack is shown in *Figure 6-9*, which is obtained from the battery in MS Ampere.

The battery inventory also includes the energy consumption during manufacturing. In addition, the total travelling distance from its production-location in China (Assumed) to its operation site in Norway with ship and lorry are included. Chinese electricity mix in the production phase is therefore utilized. The lifetime of the batteries is 10 years, which means that two replacements of the batteries are included in the analysis.

Figure 6-9: Battery pack in MS Ampere. Cells are connected in modules, sub packs and strings. The image is taken on visit to MS Ampere in October 2016.

6.4.3 Photovoltaics

The PVs are not the main focus in this study. It is however interesting to observe the impact of onsite energy production from PVs in scenarios. The data of the PV modules is extracted from a master thesis from UiA 2016 by Torjus Linjord. The thesis is an LCA on an integrated PV in the roof tile [33].

The manufacturing process in Linjord's report is assumed to be the same as in this thesis. The energy demand, transportation and materials in the manufacturing process are extracted from the thesis. The manufacturing process contains the following process: Silicon solar grade (Elkem process), silicon ingot, silicon wafer and PV cell manufacturing. The purification in the solar grade silicon is assumed to be performed at Elkem solar in Kristiansand. The remaining part of the manufacturing of the PV cells is assumed to take place in Germany. Shipping with boat from Kristiansand to Hirtshals in Denmark, and transportation with lorry from Hirtshals to Prenzlau in Germany is therefore assumed.

The lifetime of the PV modules is between 20 to 30 years. Therefore, replacement of the PV modules is not included in the study. However, the efficiency of the cells may decrease when operating with a long lifetime [33].

6.4.4 Electricity mix

The electricity mix which is utilized in the production phase is assumed to originate from each production location.

The energy consumption for the operation phase in the UWS is assumed to originate from the Norwegian electricity mix.

6.4.5 Engine

The UWS is intended to run on electricity from LIB, where the propulsion is achieved by an electric engine. Electrical engines can reach an efficiency of 90 to 95%, and requires less maintenance compared to a conventional diesel engine. Data regarding material extraction and production processes for the electrical motor is extracted from a 250 kW motor data sheet obtained from ABB [56]. The motor has a lifetime of 25 years, which means that 1,2 replacements are needed to fulfil the vessel's lifetime.

In comparison between electric- and combustion propulsion, a diesel engine is selected based on the energy consumption of the UWS. The energy consumption of a diesel engine can simply be calculated by considering the electric engine's energy consumption, and normalize it for the diesel engine with respect to efficiency. A diesel electric generating set is selected from the EcoInvent database and used in the simulation.

6.4.6 Drivetrain and electrical components

In this thesis, the drivetrain in the vessel includes the power electronics which maintain a constant power flow to the propulsion in the vessel. One of the most important power electronic devices are converters and transformers. The converter converts AC current to DC current when charging the batteries, or vice versa when discharged from the battery. The data of the converters were extracted from DNV GL, and can be seen in Appendix C.

Transformers in the vessel are used to rais or lowering the voltage-level from the electricity grid to an acceptable battery charging voltage-level. At least one transformer is therefore needed at each charging location. Expected lifetime of a transformer can be 30 to 50 years if low average load and temperature is maintained [57]. The transformer's data collection has its origin from DNV GL. The current study assumes that the production is performed by Møre Trafo AS which is a company producing transformers in Norway [58].

The amount of cables in the UWS is assumed to be the same amount as in MS Ampere. This assumption is taken mainly due to lack of information of the UWS's electronic system. The inventory of the cables is extracted from DNV GL.

6.4.7 Charging and grid capacity

The charging is intended to be performed at every stop. This means that a charging station is required on all three terminals where the UWS plans to stop. The charging stations have a maximum power delivery of 1 MW. Whether the grid has enough capacity to distribute this amount of power is uncertain. As described previously, the current study assesses the charging process in two scenarios (Scenario 2 and Scenario 4).

Another method which is suggested for UWS is a battery-exchange system. This is a method where batteries are located on each port. Rather than charging the on-board batteries of the vessel, spent batteries are exchanged with fully charged batteries located at the ports. Taking this technology into operation could have a potential to decrease the battery capacity and hence the weight and energy consumption on-board of the vessel. This charging method is not assessed in this study, but should be considered in future work.

6.4.8 Mooring

As energy saving in the vessel is important, it is desirable to avoid excess energy consumption during docking. Normally, ferries use propel-propulsion as mooring during operation of boarding. However, to reduce the energy consumption, the quay is implemented with a vacuum-system for mooring, as shown in *Figure 6-10*. The figure is an image of the mooring system used in MS Ampere, which was taken on a visit to the ferry in October 2016.The system keeps the vessel in position when connected to quay, and is powered by the electricity grid. A similar system is expected to be used in the UWS.

Figure 6-10: The mooring system which is used in MS Ampere, and is expected to be used in the UWS. Photo is taken by Tobias Einberger.

The materials needed to produce the mooring system, MoorMaster 400 is based on a datasheet given by the manufacture, Covatec. It provides safe, secure and automatic vacuum mooring between the quay and the vessel with a maximum holding force of 40 kN [59]. The MoorMaster has a peak power of 17 kW. The energy consumption is estimated based on the peak power, and the amount of time of charging the vessel, shown in Appendix A. The EPD of MoorMaster can be found in [60].

6.4.9 Interior

The interior which are included in this study is the number of seats. The inventory for the seats is extracted from "EPD-Norge", the Norwegian EPD foundation, and includes all the materials to produce the seats. The transportation to Norway and production location is not given in the EPD. Therefore, global average market data from the background database is used in the simulation. In total 125 seats are needed for the UWS, and the lifetime is 15 years, which means that one replacement of the seats is needed. The inventory of the seats is shown in Appendix C, and is based on the EPD in [61]

6.5 Quantitative inventory

This subsection summarizes the quantitative inventory used in this study. The specific data are listed for each scenario in tables in the next pages. A full and more detailed inventory list from Simapro is listed in Appendix C, Appendix D and Appendix E.

Table 6-3 lists the materials used to manufacture 1 m^2 of a PV panel in Scenario 3. A detailed overview of the PV inventory is shown in Appendix D. The Appendix show the manufacturing procedure of the silica sand, solar grade silicon, silicon ingot, silicon wafer and solar cell. In total, it is needed 570 m^2 for the PV installation.

Table 6-3: Inventory for material for production of 1 m^2 PV cell.

Product	*1 m^2 of PV cell*	*Unit*
Silica sand	4,02	kg
Solar grade silicon	1,07	kg
Silicon ingot	0,885	kg
Wafer	1,06	m^2

Table 6-4 and *Table 6-5* show the battery specifications. The distribution of battery capacity used in the four scenario cases is listed in *Table 6-4*. As shown in the table, the capacity has large variations depending on the scenario. The composition of the cells, modules, sub-packs and stings in the different scenarios are shown in *Table 6-5*. The distribution is normalized according to the battery capacity from *Table 6-4*. A full inventory of the battery is listed in Appendix E.

Table 6-4: Total battery capacity in each scenario.

Scenario	*Battery capacity*	*Unit*
1	0	kWh
2	720	kWh
3	720+3 batteries of 82	kWh
4	1369	kWh

Table 6-5: Inventory for production of one battery pack in the UWS for each scenario.

Product	*Amount (case 4)*	*Amount (Case 3)*	*Amount (Case 2)*
Cell	289 536 Cells	134 784 Cells	99 840 Cells
Module	2784 Modules	1 296 Modules	960 Modules
Sub-Pack	348 Sub-packs	162 Sub-Packs	120 Sub-Packs
String	58 Strings	27 Strings	20 Strings

Table 6-6 shows the inventory for the structure of the vessel for Scenario 2, 3 and 4. The hull, superstructure, engine, drivetrain and electrical components, interior, and mooring are described in the table. As described in the limitation section, the amount of aluminium in the hull is a rough estimation. The amount of aluminium in the hull and superstructure is assumed to be the same in all scenarios. *Table 6-7* shows the inventory for the UWS in Scenario 1. Most of the parameters are the same in the scenarios except that electrical components and electrical engines are not considered in Scenario 1. A detailed inventory list of the mooring device, transformer, converter, engine seats and cables are shown in Appendix C.

Table 6-6: Inventory of the vessel's structure for Scenario 2, 3 and 4.

Description	***Amount (per lifetime)***
Hull + superstructure (aluminium)	20 066 kg
Seats	125 x 2 (lifetime of 15 years)
Transformer	3
Converter	2x5= 10 (lifetime of 15 years, 5 converters)
Engine	2 x 300 kW (lifetime of 25 year gives 1,2 engines)
Cables	262,3 kg

Table 6-7: Inventory of the vessel's structure for Scenario 1.

Description	***Amount (per lifetime)***
Hull + Superstructure (aluminium)	20 066 kg
Seats	125

Table 6-8 shows the energy consumption of the UWS for the different simulation scenarios. The data are listed as per day and for one lifetime of 30 years. The diesel consumption is larger than the electrical consumption due to the poor efficiency in conventional diesel engines. In Scenario 3, the energy from the PVs is subtracted from the total energy consumption of the UWS. The energy losses in the battery and converter in Scenario 3 is added to the grid production to get an equal energy balance between the scenarios.

Table 6-8: Inventory of the UWS's input energy consumption per day for each scenario.

Product	*Per day*	*Lifetime*	*Unit*	*Scenario*
Diesel	3 527,6	38 627 618,2	kWh	1
Grid	2 149,8	23 540 376	kWh	2
PV on roof	71,5	782 925	kWh	3
Land mounted PV	123	1 346 850	kWh	
Grid	2014+31,5 (losses from PVs)	22 98541,1	kWh	
Grid	2240,32	24 531 550,5	kWh	4

7 Results

This chapter presents the results from the LCA. The chapter will initially present the individual results from each scenario. Further, the four scenarios will be compared to each other, followed by a sensitivity analysis of several parameters.

7.1 Life cycle inventory analysis

7.1.1 Scenario 1

The environmental impact from Scenario 1 on the midpoint categories in the ReCiPe method is expressed in *Figure 7-1*. The boat production, operation and other impact factors are shown in the figure. The results are based on EvoInvent's diesel generation unit as power propulsion system, as described previously. The numbers on the right side of the figures describe the total amount of emissions in each category measured in per PKT.

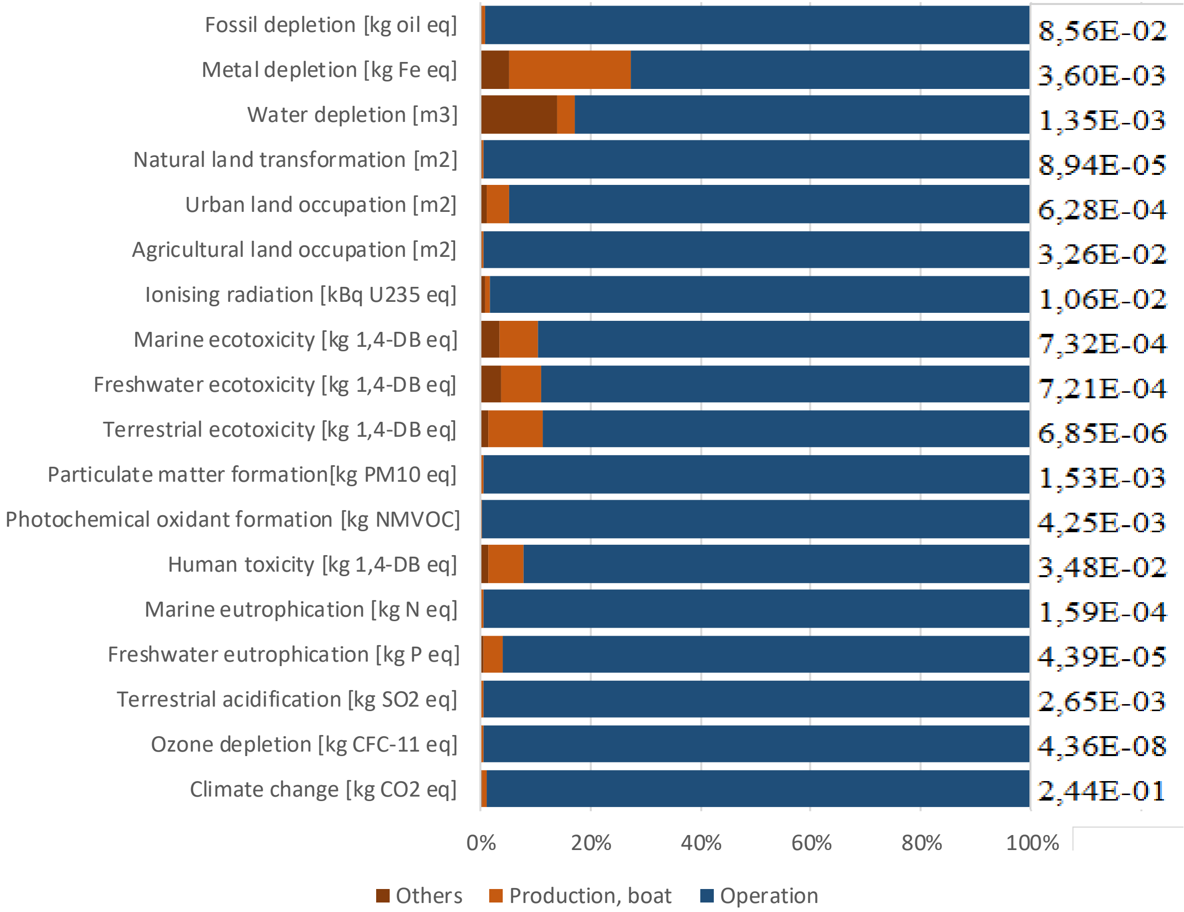

Figure 7-1: Impact results from Scenario 1 with per PKT as functional unit.

Figure 7-1 shows that the impact from the operation phase of the UWS is the largest on all impact categories. The impact from the other groups is insignificant in most of the categories. Emissions to freshwater eutrophication, human toxicity and terrestrial ecotoxicity have some contribution from the boat production. However, the emission from the operation phase is more than 90 % larger than the boat production in these groups. The reason for the high contribution from the operation phase can be explained by the high emissions from the refining and combustion of diesel.

The impact on freshwater ecotoxicity, marine ecotoxicity, water depletion, human toxicity and metal depletion is affected by all the three life-phase groups. Nevertheless, the operation-phase stands for the largest impact, followed by boat production and other impact related factors. The influence from the boat production is mainly due to the amount of aluminium used in the hull and superstructure. The remaining categories are very sensitive to the operation phase.

7.1.2 Scenario 2

Scenario 2 is the most important scenario in this thesis because most of the inventory are suited for this case. The main focus will therefore be on this scenario. *Figure 7-2* shows the impact results on the ReCiPe midpoint categories from Scenario 2. The battery production, boat production, operation and other impacts are displayed in the figure. The group named “others” contains impacts from factors which do not fit in one of the other groups, such as material and operation of the mooring device. This group has the lowest emissions on all categories. The overall impact from this group seems therefore to have limited influence on the presented results.

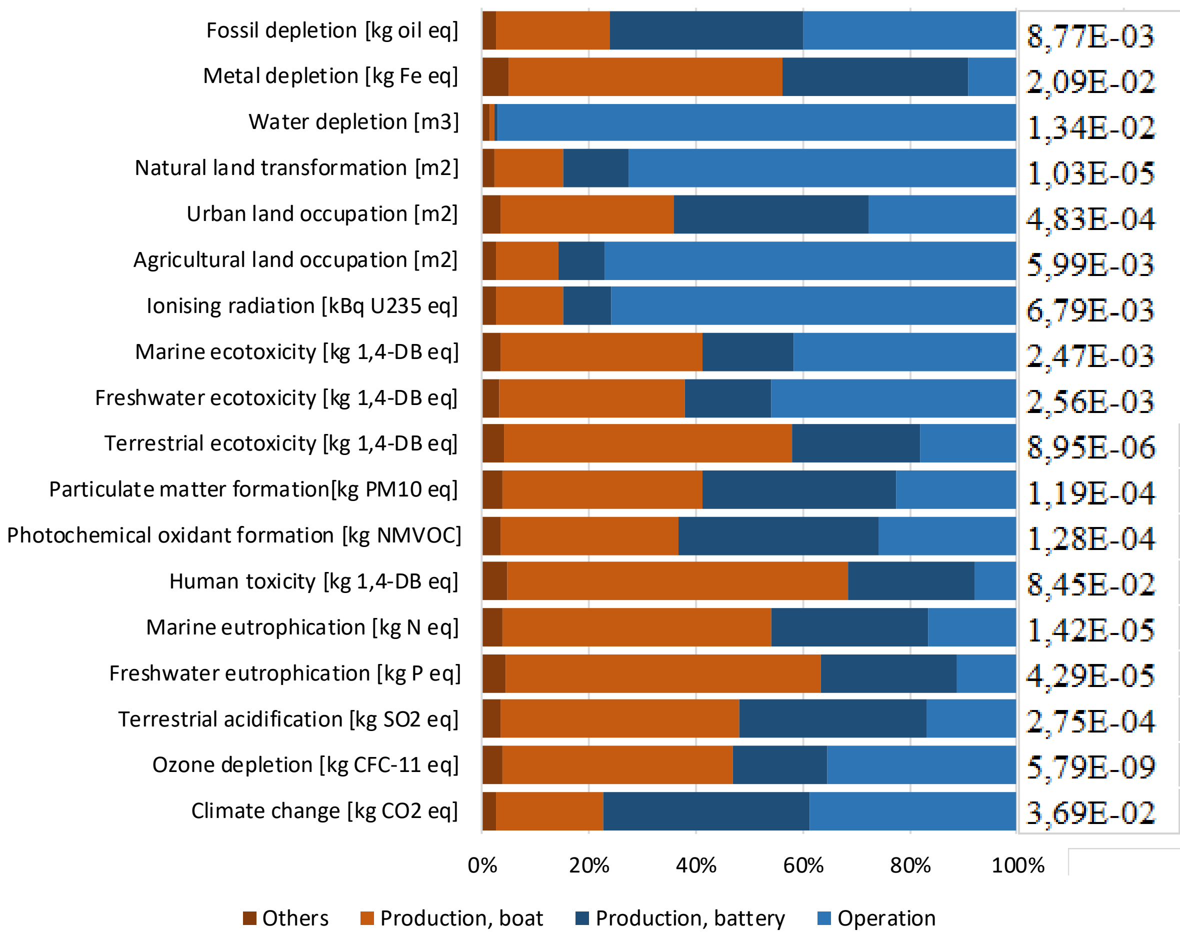

Figure 7-2: Emissions from Scenario 2 on the 18 midpoint categories with per PKT as functional unit.

Figure 7-2 shows that the battery production, boat production and operation phase have the largest impact to all categories. The battery production and the operation have equal impact on climate change, followed by the boat production phase which has 19% less emissions in this category. The boat production phase has the largest impact on ozone depletion, particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, terrestrial ecotoxicity, and metal depletion. In these categories, the battery production follows as the second largest contribution, except in the emissions on ozone depletion. In this category, the operation phase has the second largest contribution. In photochemical oxidant formation, the highest emissions originate from the battery production, which stand for 38% of the emissions. The battery production also has large emissions to urban land occupation, metal depletion, particulate matter formation, photochemical oxidant formation and fossil depletion with 35% to 36% contribution.

The operation phase has on average low emissions on many categories regarding direct air emissions. However, it is shown that the operation is one of the largest contributor to climate change and ozone depletion. The figure also shows that the operation phase has the highest impact on freshwater ecotoxicity, marine ecotoxicity, ionising radiation, agricultural land occupation, natural land occupation, water depletion and fossil depletion.

The boat production stands for a significant share on freshwater ecotoxicity, marine ecotoxicity and urban land occupation. In metal depletion, this group represents 51% of the impact. The reason can be related to the processes of extraction of bauxite and production of aluminium used for the hull and superstructure.

As stated, the global warming potential (GWP) in *Figure 7-2* shows that battery production, operation, and boat production have the highest emissions on this impact category. The operation phase is an interesting parameter to further assess, in order to see how much this parameter contributes to the overall results on GWP. Therefore, the operation phase is one of the parameters which will be assessed in the sensitivity analysis. The battery production and boat production is deeper analysed in the next paragraphs. The results of these analysis will determine which additional parameters should be studied in the sensitivity analysis.

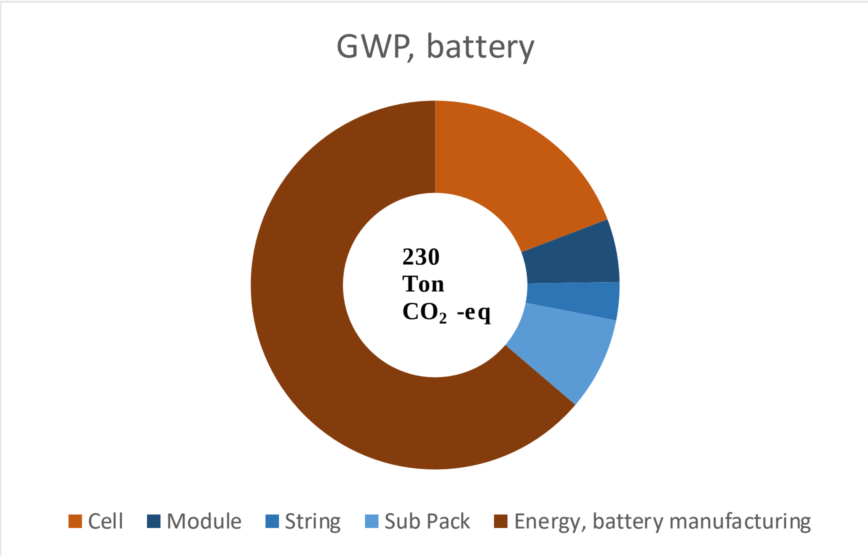

Figure 7-3:GWP analysis of the battery on the UWS.

The analyse of the GWP on the battery is shown in *Figure 7-3*. The energy for the battery manufacturing has the largest impact on GWP with a contribution of 63,75% of the GWP. The reason of the large emission from the energy consumption can be explained by the large amount of energy used during the coating process of the battery cell. This energy has its origin from China, which has large emissions of CO_2 emission due to its fossil fuel dominating energy mix.

The battery cell has a significant impact on the GWP as well. The parameters in the cell which are contributing most to the GWP are shown in *Figure 7-4*. The lithium for the cathode and lithium hexafluorphosphate in the electrolyte have the largest emissions to the GWP. This may originate from the mining activity in extraction and purifying the lithium from mines or salt lakes. The lithium content in the battery cell is therefore interesting to assess in the sensitivity analysis.

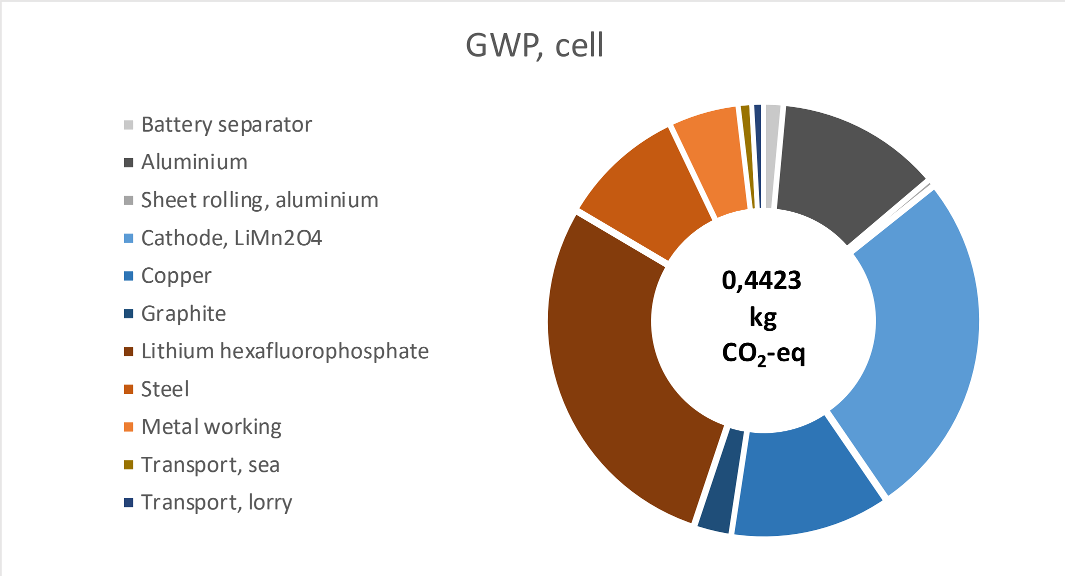

Figure 7-4: Analysis of the GWP of one battery cell.

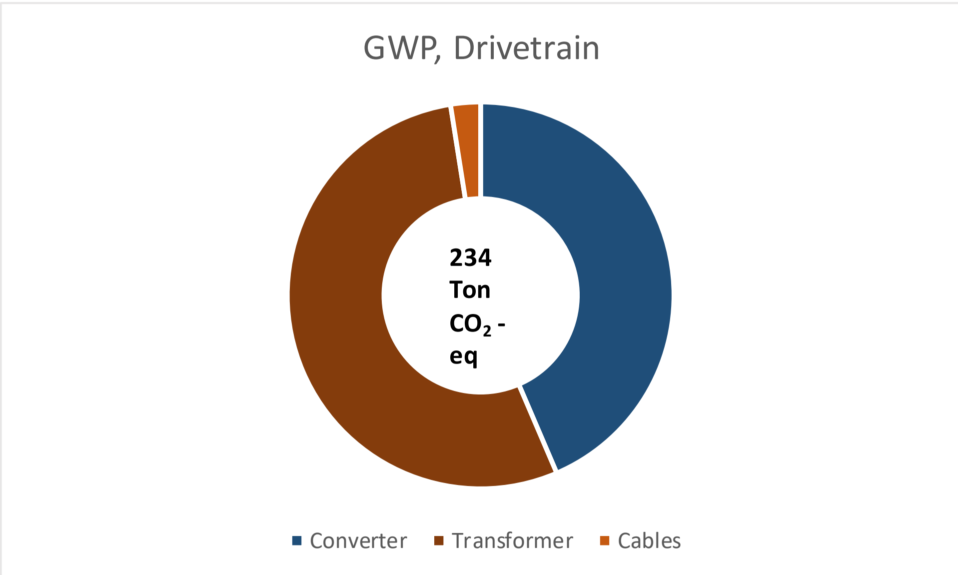

Figure 7-5: GWP form the drivetrain in the UWS

From the analysis of the boat production, it was shown that the drivetrain stands for the biggest impact. Within the drivetrain, it is shown in *Figure 7-5* that the transformers represents the biggest impact for the drivetrain, followed by the converters and cables. It should be noted that the share between the number of transformers and converters used in the study is not the same. However, further analysis on the transformer was performed to see which parameter has the highest contribution to GWP.

The results from the analysis of one transformer is shown in *Figure 7-6*. Copper is very sensitive in the results, which are more than 50% of the emissions to GWP. The second largest emissions are from metal working on copper with more than 20% contribution. This means that the overall impact from copper stands for more than 70 % of the GWP emissions from the transformer. This parameter will therefore be analysed in the sensitivity analysis as well.

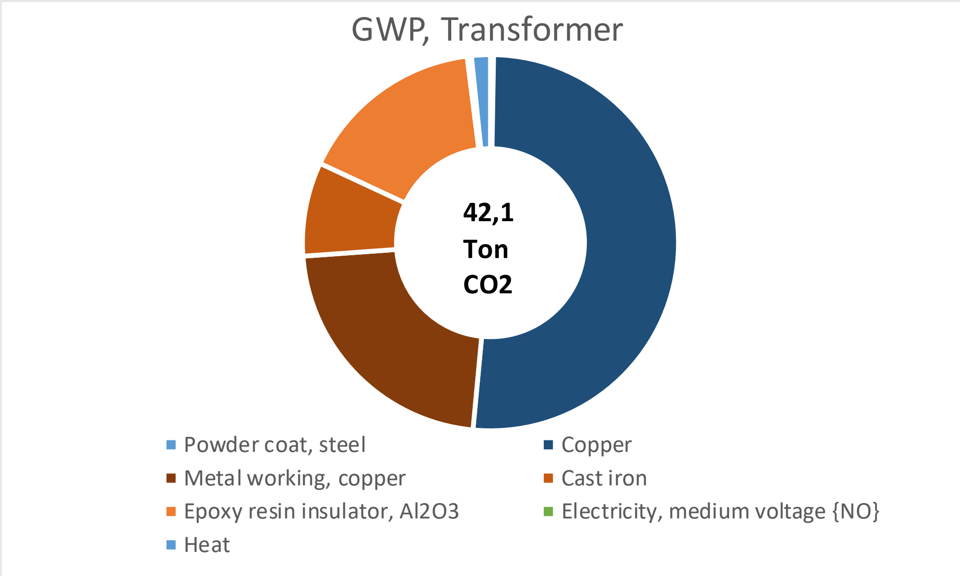

Figure 7-6: GWP of one transformers in the UWS

7.1.3 Scenario 3

Figure 7-7 shows the impact results from Scenario 3. Scenario 3 incudes the PV modules and the energy production from the modules.

Figure 7-7 displays that the battery production has the largest impact on climate change, terrestrial acidification, photochemical oxidant formation, particulate matter formation, urban land occupation and fossil depletion. The large contribution from the batteries on climate change is due to the Chinese energy mix used in the production phase of the batteries. The boat production has the largest emissions on ozone depletion, freshwater eutrophication, marine eutrophication, human toxicity and metal depletion. In addition this group has a significant impact to marine ecotoxicity.

Climate change is mainly dominated by the operation and battery production. The impact from the PVs are low in almost all categories, except in terrestrial ecotoxicity, where the contribution is the largest of all groups with 38%.

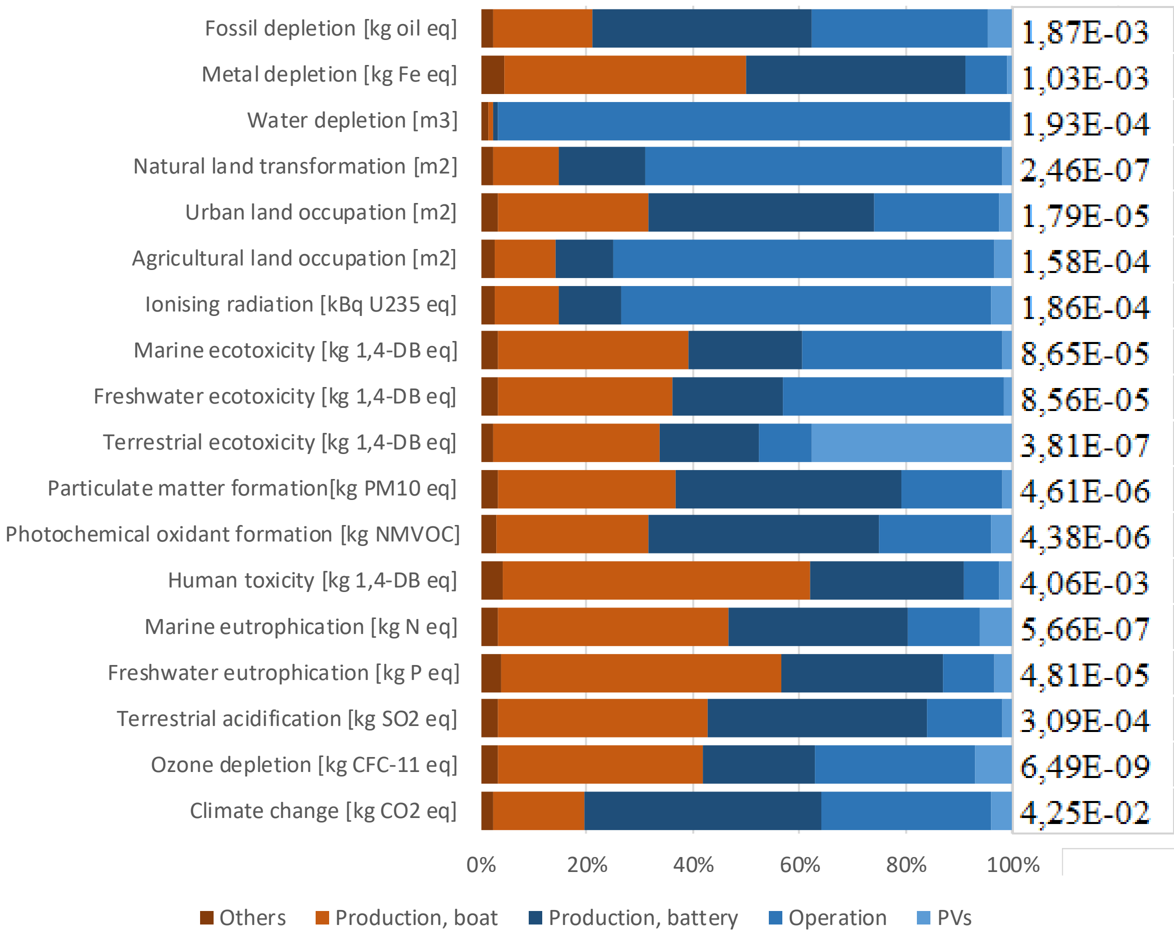

Figure 7-7:Impact results from Scenario 3 with per PKT as functional unit.

The operation phase use Norwegian electricity mix, which shows to be very sensitive to midpoint categories like ionising radiation, agricultural land occupation, natural land occupation, and water depletion. The emissions from the operation phase in these categories varies between 70% to over 96%. The impact on water depletion is the largest with 96% of the emissions from this group. In addition, the operation phase represents approximately 30% of the emissions to ozone depletion and climate change as well.

In urban land occupation, metal depletion and fossil depletion, the figure shows that the boat production and the battery production have the largest contribution. The operation phase also has a significant impact on this category, with only 5% less emission than the boat production.

7.1.4 Scenario 4

Figure 7-8 shows the result on the midpoint categories for Scenario 4. Scenario 4 has a larger amount of battery capacity due to the additional batteries located at each port for the charging assistance. This is reflected in the results, as shown in the figure. The battery production stands for a significant contribution to all the impact categories. In climate change, the battery production stands for 58% of the emissions, followed by operation and boat production with 27% and 13% contribution respectively. The battery production also has the highest impact on urban land occupation, metal depletion, fossil depletion, terrestrial ecotoxicity, particulate matter formation, photochemical oxidant formation, human toxicity, marine eutrophication, freshwater eutrophication, terrestrial acidification, and ozone depletion. In these three categories, the boat production and operation follows as the two next groups with the second and third largest emissions.

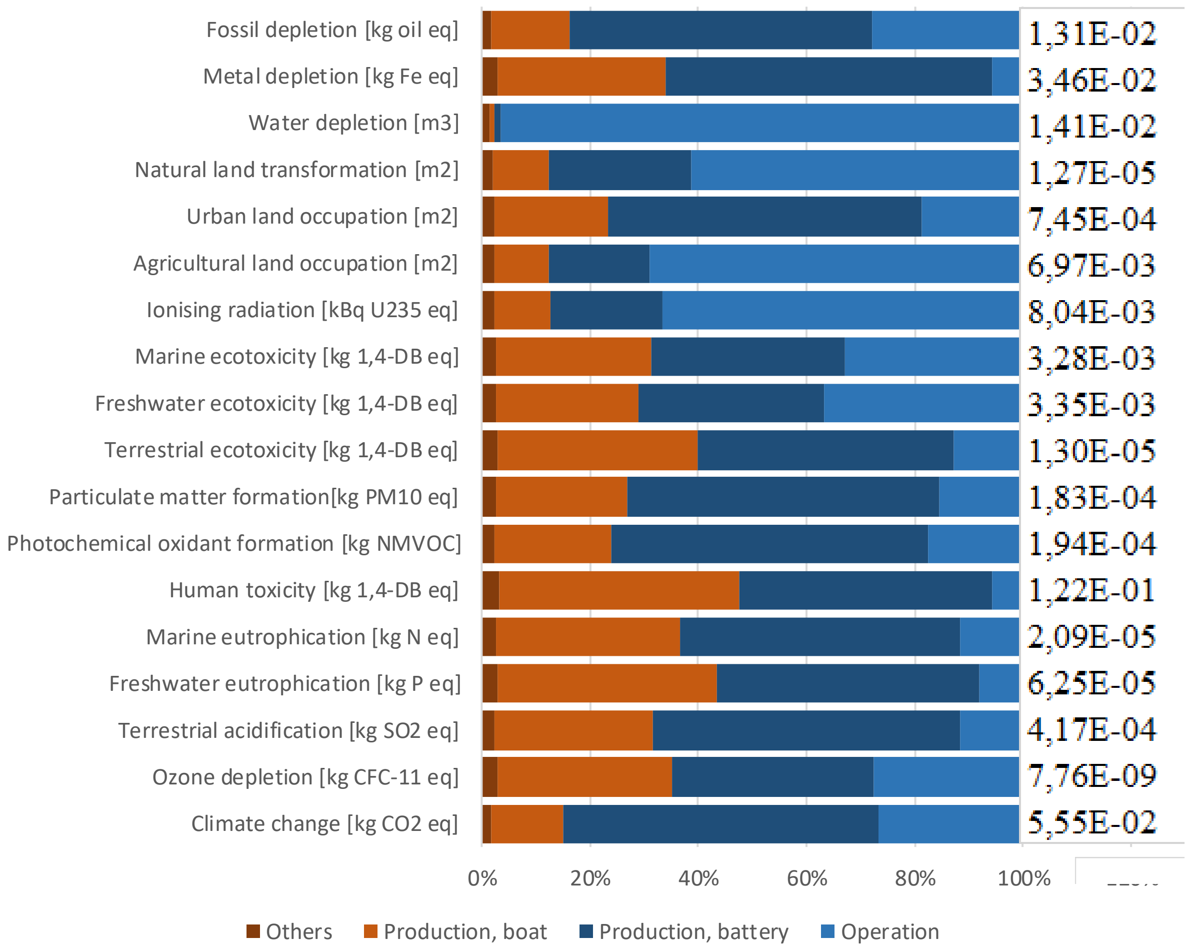

Figure 7-8:Impact results from Scenario 4 with per PKT as functional unit.

It is shown that the operation phase stands for a large share on ionising radiation, agricultural land occupation, natural land occupation, and water depletion. The contribution from this group is more than 65% in all these categories, and as large as 96% of the impact on water depletion. The emissions on freshwater ecotoxicity and marine ecotoxicity are approximately shared equally between boat production, battery production and operation.

The boat production has its largest impact to human toxicity freshwater eutrophication and terrestrial ecotoxicity, where the contribution varies between 37% to 44% of the emissions. In the remaining categories, the boat production has an impact that varies from 10% to 35 %, except in water depletion, where the impact is more or less insignificant. The group, others, has very small impact on all categories.

7.1.5 Comparison between the scenarios

Figure 7-9, *Figure 7-10* and *Figure 7-11* shows the midpoint category comparison between the four scenarios. The results are presented in relation to each other where the scenario with the largest impact in an impact category is represented by 100 %. The other scenarios are represented in relation to the largest contribution category, making it easy to determine the best alternative in the different impact categories. All scenarios are plotted with PKT as functional unit. The figures show that the diesel combustion ferry has the highest contribution in most of the midpoint categories.

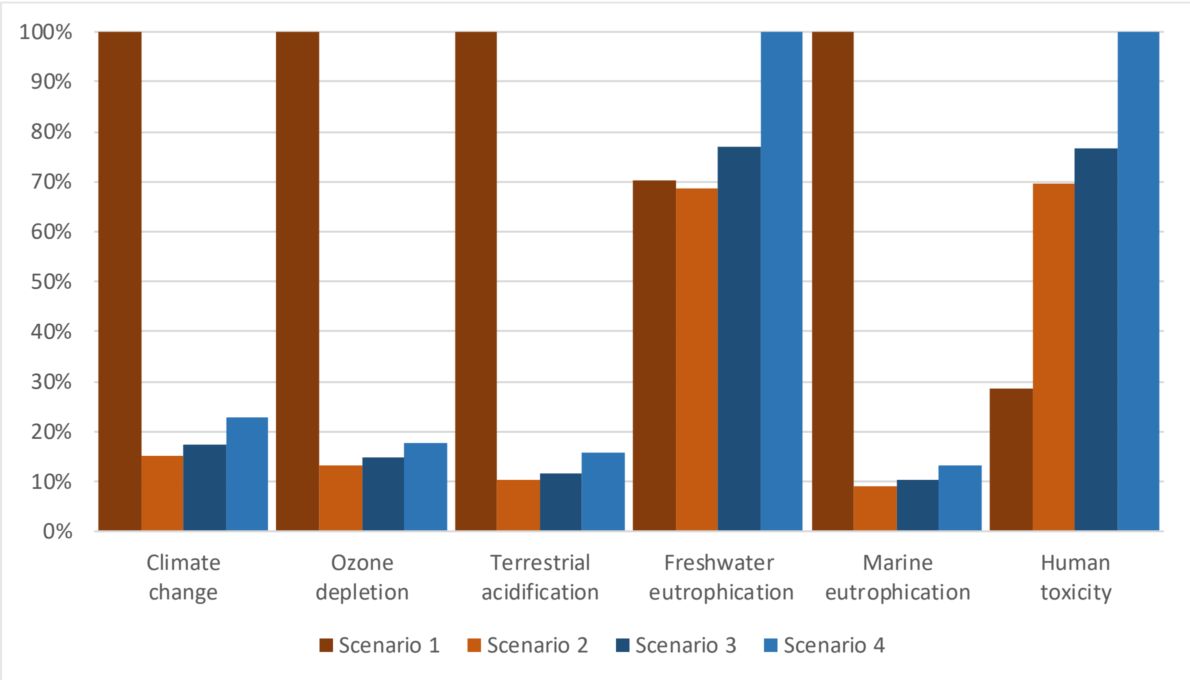

Figure 7-9: Comparison of results from the impact assessment in the following midpoint categories: climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication and human toxicity.

Figure 7-9 show that Scenario 1 has the largest impact on climate change, followed by Scenario 4, Scenario 3 and Scenario 2 with 23%, 17% and 15% contribution respectively. Scenario 1 has the largest impact on ozone depletion, terrestrial acidification and marine eutrophication as well. The emissions from this scenario are more than 77% larger than the other scenarios. The average contribution from the other scenarios in these categories are more or less equal. The impact on terrestrial acidification is 16% for Scenario 4, 12% for Scenario 3 and 10% for Scenario 2, compared to Scenario 1. The distribution between the scenarios is more even on the impact on freshwater eutrophication. Scenario 4 has the largest impact on this midpoint category, followed by Scenario 3 with 77%, Scenario 1 with 70% and Scenario 2 with 69%. In marine eutrophication, the emissions from Scenario 2, Scenario 3 and Scenario 4 are less than 87% compared to Scenario 1. Human toxicity is peaked by Scenario 4, while Scenario 1 has the lowest impact on this scenario.

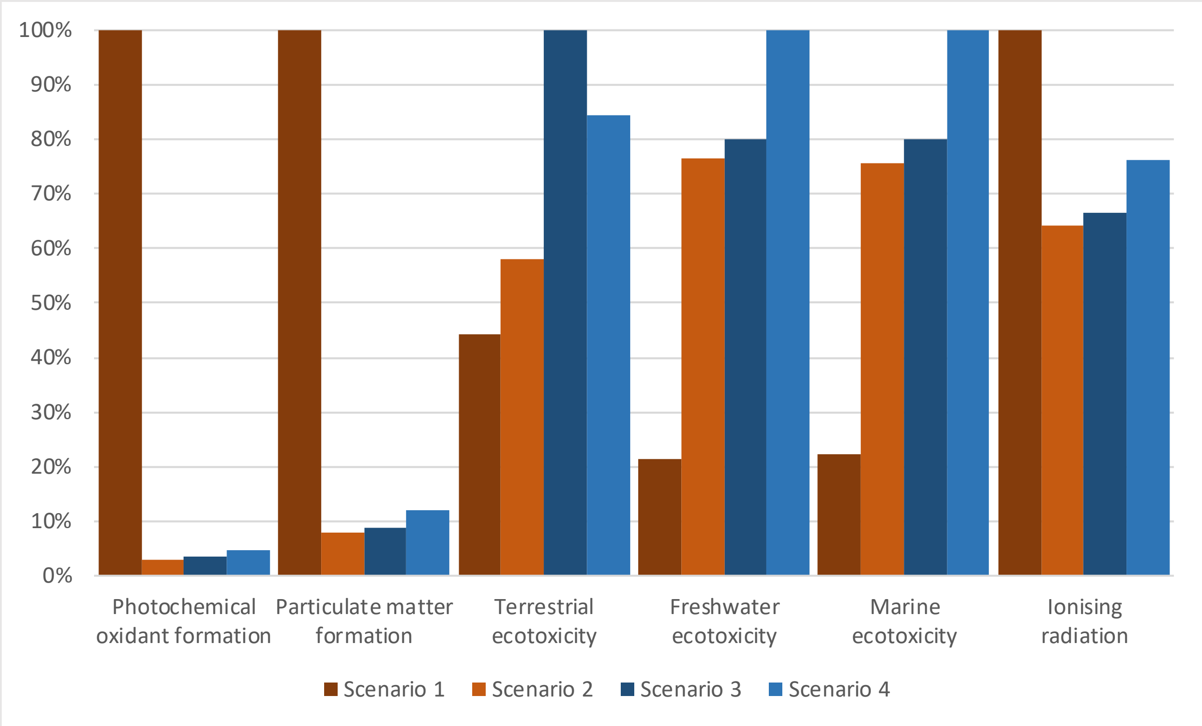

Figure 7-10: Comparison of results from the impactassessment in the following midpoint categories: Photochemical oxidation formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity and ionising radiation.

Figure 7-10 shows that Scenario 1 clearly has the biggest impact on photochemical oxidant formation, particulate matter formation and ionising radiation. The remaining scenarios have an approximately average distribution on the same categories. Terrestrial ecotoxicity is mostly affected by Scenario 3, due to the toxicity chemicals during the PV manufacturing. In freshwater ecotoxicity, the largest impact is from Scenario 4, followed by Scenario 3, 2 and 1 with 80%, 76% and 22% contribution respectively. Impacts from Scenario 4 peaks the marine ecotoxicity category. Scenario 2 and 3 have almost the same impact, followed by Scenario 1 with only 22% in comparison. Scenario 1 with the diesel combustion shows the best results in terrestrial ecotoxicity, freshwater ecotoxicity, and marine ecotoxicity.

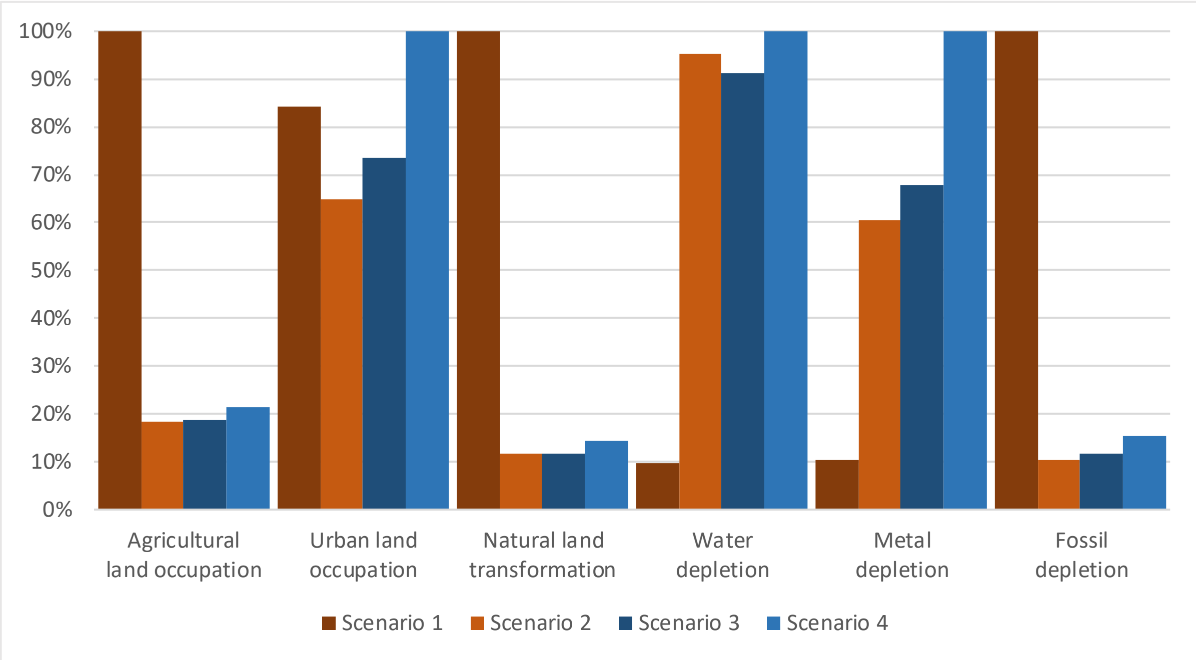

Figure 7-11: Comparison of results from the impactassessment in the following midpoint categories: Agricultural land occupation, urban land occupation, natural land occupation, water depletion, metal depletion and fossil depletion.

Figure 7-11 describes that Scenario 1 has the largest impact on agricultural land occupation, natural land occupation and fossil depletion. In these midpoint categories, Scenario 1 has more than 78% more emissions compared to the remaining scenarios. The other scenarios share on average the same impact on these three midpoint categories. In urban land occupation, water depletion and metal depletion, Scenario 4 has the largest impact. Scenario 1 has the lowest impact on these categories, except on urban land occupation, where Scenario 2 is lowest represented with 65% contribution compared to Scenario 4.

7.2 Impact from battery

As expressed in the previous results, the battery manufacturing is responsible for a significant impact share; especially in climate change, particulate matter formation and photochemical oxidant formation, the distribution is largest. The emissions to these three categories is shown in table *Table 7-1* with PKT as functional unit. The table shows that the scenarios that include most batteries (Scenario 3 and Scenario 4) have the largest emissions to all these groups. Therefore, a deeper consideration of the battery manufacturing process.

Table 7-1: Emissions to GWP, particulate matter formation (PMF) and photochemical oxidant formation (POF) in the three scenarios which are include batteries. The values are given as PKT as functional unit.

Description	***Scenario 2***	***Scenario 3***	***Scenario 4***
GWP [g CO_2-eq]	36,9	42,5	55,5
PMF [g PM_{10}-eq]	0,119	0,135	0,183
POF [mg NMVOC-eq]	0,128	0,147	0,194

Figure 7-12 shows the emissions on photochemical oxidant formation and particulate matter formation when one battery pack of 720 kWh is produced. The energy consumption during production has the biggest impact with approximately 115 kg PM10-equvialent on particulate formation, and 151 kg emission of photochemical oxidant formation. This can be explained by the large emissions from the coal generating electricity in the Chinese energy mix which is used as energy source. Emissions from the battery cell follows as the second largest contributor with 69,7 kg and 74,3 kg emissions to photochemical oxidant formation and particulate matter formation respectively. Production of the modules, sub-packs and strings follows then with the lowest emissions, which is mostly a construction of different metals to form the modules, sub-packs and strings.

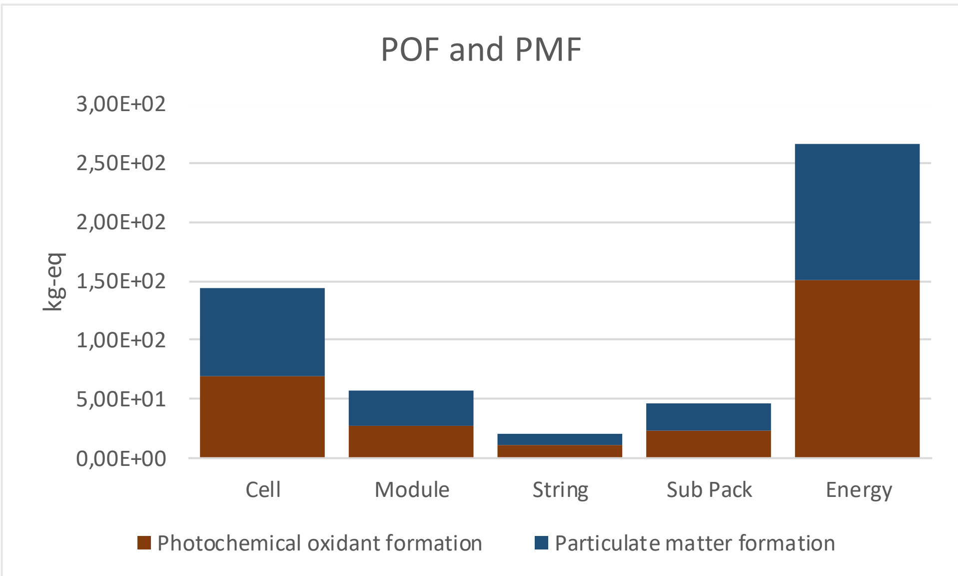

Figure 7-12: Results of photochemical oxidant formation and particulate matter formation during production of one battery pack in the UWS.

Figure 7-13 shows the impact on the global warming potential, i.e. the emission of CO_2-equivilent measured in kg. The figure shows that the same trend is observed for the GWP as for particulate matter formation. The energy used in the production has the largest impact followed by the cell production. The reason is expected to be the same as described in the previous paragraph. The emissions from the energy consumption is more than 3 times the emissions from battery cell production. The impact form the modules, strings and sub-packs is insignificant in comparison to the cell production and energy consumption. It is displayed in both figures that the battery string has the least impact on both midpoint categories.

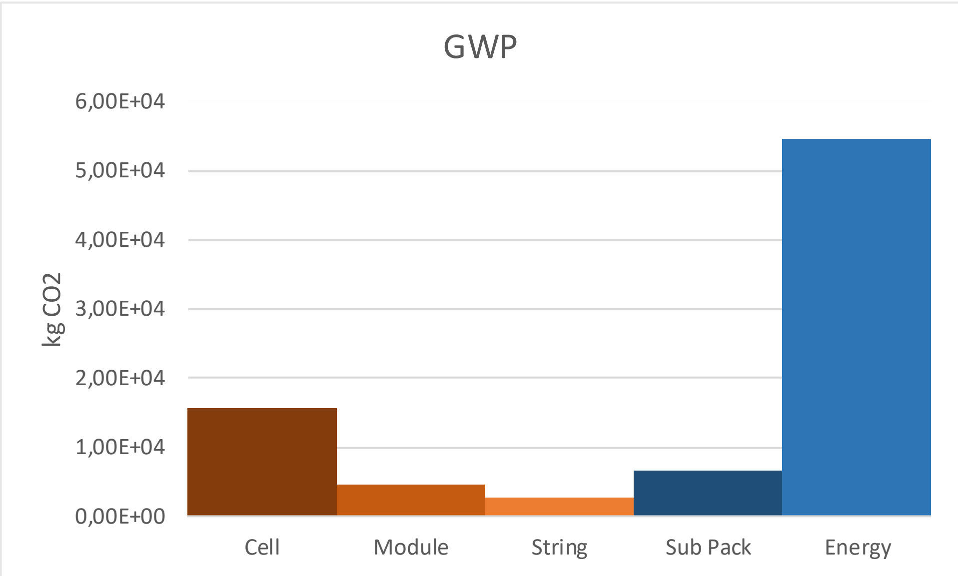

Figure 7-13: Results of GWP measured in CO_2-eq during production of one battery pack on the UWS.

7.3 Sensitivity analysis

Sensitivity analysis is performed in order to look at how much a small parameter change can affect the overall GWP. Different parameters were changed by one percent from its original value, and the change were logged in *Table 7-2*. Most of these parameters are selected based on the results from section 7.2, Scenario 2. This is parameters that have showed to be significance for the results in the study. In order to see the overall influence of these parameters is, and estimate how important they are for the overall results, it was performed a sensitivity analysis. The remaining parameters were selected based om uncertainty in the data collection, such as the amount of aluminium. The different parameters that are used in the sensitivity analysis is the amount of aluminium in both the hull and superstructure, lithium in the cell, lithiumhexafluorphosphate in the electrolyte, energy consumption in the battery manufacturing and the amount of copper in the transformer. In addition, the capacity utilization in the public transportation was selected as an interesting parameter to investigate.

Based on the assumption of the estimated energy consumption in Scenario 1, it was decided to perform a sensitivity analysis on the diesel combustion as well. This scenario has large emissions in most of the impact category, and it is therefore important to see how much this parameter can affect the GWP results.

Table 7-2: Result from the sensitivity analysis on the most important parameters on the GWP.

Parameters	***Parameter change***	***GWP change***
Aluminium	1%	0,027%
Capacity utilization	1%	0,990%
Whole Battery	1%	0,375%
Lithium (cathode)	1%	0,019%
Lithiumhexafluorphosphate (electrolyte)	1%	0,021%
Battery energy consumption	1%	0,240%
Copper use in transformer	1%	0,035%
Energy for operation	1%	0,395%
Diesel combustion in Scenario 1	1%	0,979%

Table 7-2 shows the results from the sensitivity analysis on GWP. The most sensitive factor is shown by the table to be the capacity utilization and the diesel combustion in Scenario 1, with a GWP change of almost 1%. The capacity utilization changes through the day according to the number of people travelling, an is not directly technology dependent. Most of the other parameters are in conjunction to the manufacturing process of batteries. Changing the whole battery capacity with one percent resulted in the biggest GWP change. The largest change within the battery manufacturing was experienced to originate from the energy usage with a GWP change of 0,240%. The amount of lithium has a minor overall impact on the overall results.

Another important parameter is the energy utilization for the operation phase. The sensitivity analysis shows that the impact on GWP is affected by 0,395% in the sensitivity analysis. This is the second largest impact of all parameters. The aluminium in comparison shows not to be very sensitive to the GWP, with only 0,027% impact change.

As stated, the sensitivity analysis shows that the energy had significant impact on the GWP. In order to investigate the importance of the energy mix for the battery manufacturing process, the Chinese and Norwegian energy mix were compared. The GWP results with the two energy mixes are shown in *Figure 7-14*.

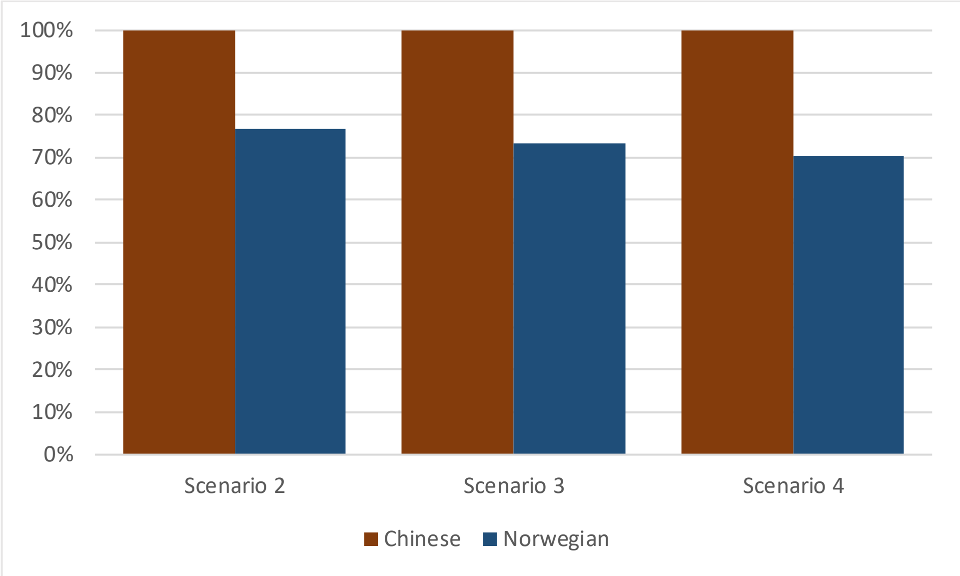

Figure 7-14: Results from the GWP for the battery production with Norwegian and Chinese energy mix.

The figure shows that CO_2-emission for producing the on-board battery pack for the UWS depends on the different scenarios, and hence the battery capacity. It was calculated that producing the battery with Chinese energy mix gives at least 23% more emissions than producing the batteries with a Norwegian energy mix. The difference is largest for Scenario 4, with 30% saved CO_2 emissions by producing the batteries in Norway.

8 Discussion

This chapter will discuss the results from the LCA in chapter 7. It will start with a comparison of the four scenarios and look at the reason for the emissions on the different impact categories. Further, the limitations in the study will be headlined, and assess how relevant the study is in a real life. At the end of the chapter, it will be given some suggestions on where it is needed for future work.

8.1 Comparison between the scenarios

The impact from the different life phases in each scenario has a significant variation in the four scenarios. The operation phase in Scenario 1 has the biggest impact on all midpoint categories. This is due to the combustion of diesel and its large emission related to this. The distribution between the life phases in the other scenarios is more equally shared. These scenarios are modelled with electrical energy as propulsion, which has less direct air emissions.

In comparison between all scenarios, the first scenario shows to have the largest normalized emissions in most of the midpoint categories. In total, it is the highest in ten of the 18 midpoint categories. These categories are mostly related to direct air emissions, such as climate change and particulate matters. In midpoint categories regarding toxicity and depletion, this scenario shows the lowest impact on six of the 18 midpoint categories. The reason could originate from the contribution from the battery manufacturing in all the other scenarios, as well as the additional contribution from the production of drivetrain. The battery manufacturing process has a potential of toxicity emissions in several categories. The batteries are also built-up of different metals, such as aluminium, lithium and copper, which may affect the metal depletion category. Scenario 3 is another scenario that has large emissions on toxicity and depletion groups. The reason for this may originate from the manufacturing process of both batteries and PV modules. The production of PVs involves some chemical actions, such as cadmium. Cadmium has a potential to be released to the environment during the manufacturing phase, which again can cause human toxicity and terrestrial ecotoxicity.

Another observation is that the impact in all midpoint categories from Scenario 4 is always larger than the impact from Scenario 2. It is important to keep in mind that these two scenarios only differ in battery capacity, due to the additional charging batteries in Scenario 4. Therefore, the impact from Scenario 4 is always larger than Scenario 2. However, looking at the different life-phases/groups in these two scenarios, it can be seen in which midpoint categories the battery production is most sensitive. The main difference between the two scenarios is that the battery production phase increases its contribution to most of the categories, while in the remaining groups, the contribution from the battery production decreases. For instance, the impact from the vessel's operation phase is reduced by 12 % emissions on climate change from Scenario 2 to Scenario 4. This is due to the extra emission from the additional battery capacity manufacturing in Scenario 4.

It is also worth mentioning that the impact difference between Scenario 4 and Scenario 2 on toxicity categories, land occupation, and metal depletion are significant. This shows that the manufacturing of batteries is sensitive to these impact categories and that the battery capacity is important to consider in the battery design process. One possible solution to avoid excess of battery capacity could be to expand the grid capacity, rather than using batteries as intermediate storage during the charging operation. This solution is not assessed in this study, but should be considered in similar studies in the future.

Compared to Scenario 1, the results show that the operation phase in scenarios 2, Scenario 3 and Scenario 4 has much less emissions in categories regarding direct air emissions, such as CO_2, NO_x, SO_2, ozone depletion and particulate matters. This is explained in *Table 8-1*, which shows the difference in CO_2 equivalent emissions between the scenarios, measured in grams per PKT. Scenario 2, Scenario 3 and Scenario 4 displays that the CO_2 savings are large when using electrical propulsion system, rather than conventional combustion propulsion. The biggest difference is between Scenario 1 and scenario2, where the CO_2 savings are 207,1 grams per PKT.

The table shows that the emissions from the boat production is the same in all scenarios, except in Scenario 1. This scenario only considers the production of the hull and superstructure, while the other scenarios considers the drivetrain and electrical components as well. The table also shows that the amount of batteries installed has a significant climate change impact. This is associated with the manufacturing process of the batteries. In the operation phase, the table shows that Scenario 3, which is implemented with PV modules, has the lowest CO_2 emissions with at least 0,6 g more saving per PKT compared to the other scenarios. The difference between the operation emissions between Scenario 2 and Scenario 4 has its origin from the extra losses in the conversion between the grid and the charging batteries. This is another advantage for charging the on board batteries directly from the grid.

Table 8-1: GWP potential for the four scenarios with PKT as functional unit.

	Scenario 1	***Scenario 2***	***Scenario 3***	***Scenario 4***
Total [g]	244	36,9	42,4	55,4
Battery [g]	-	14,3	18,8	32,2
Boat [g]	2,59	7,4	7,4	7,4
Operation [g]	241	14,2	13,6	14,8

A further analyse of the CO_2 emissions between the scenarios is shown in *Figure 8-1*.The figure represents the brake point for Scenario 2, Scenario 3 and Scenario 4 in comparison to Scenario 1. Scenario 2 has the earlies brake point after 5 months, followed by Scenario 3 with approximately 6 months and Scenario 4 after approximately 6,5 months. The meaning of the figure is that the line with the lowest value at any time has the lowest emissions. As shown, Scenario 1 has the lowest CO_2 emissions until the first brake point. i.e. the impact from the production of a diesel combustion vessel is lower than the impact from the production of battery propulsion vessels. After the brake point, the other scenarios have a total emission which is smaller than for Scenario 1 through its lifetime. Due to the low GWP in the Norwegian electricity, the graph for Scenario 2, Scenario 3 and Scenario 4 looks like a straight line, compared to Scenario 1. The results are sensitive to the amount of batteries in the scenario. The three break points for the scenarios are within a year, which is a very short time of period. Despite these results and that the ferry is intended to operate for 30 years, the GWP can be saved significantly by selecting battery as propulsion system.

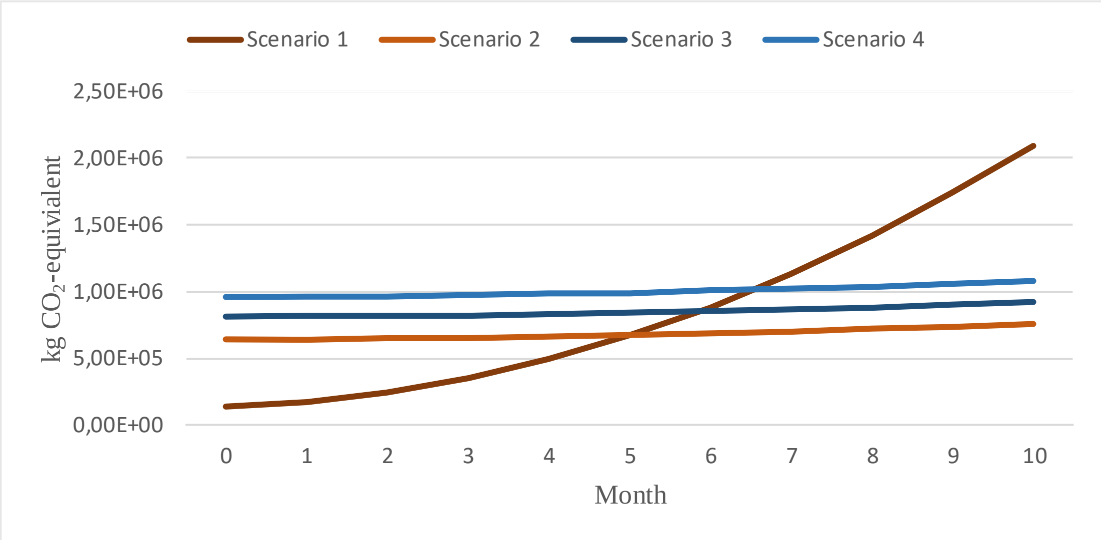

Figure 8-1: Break point of the four scenarios. Month is displayed on the x-axis while kg CO_2-equivialent is shown on the y-axis.

In the comparison between the scenarios in *Figure 7-9*, *Figure 7-10* and *Figure 7-11* it is observed that Scenario 3 has on the average more or less the same impact on the midpoint categories as Scenario 2 and Scenario 4. One exception is in the terrestrial ecotoxicity, where Scenario 3 has the highest impact. The overall results of this scenario make the PVs more interesting to consider in the future. The manufacturing process shows to have relatively low impact on CO_2 emissions. Additionally, when considering that PV generated energy has zero emissions (after production), the integration of PV modules on vessels can be a great option in areas where the energy generation is dominated by fossil fuels. This is shown in *Figure 8-2*, a CO_2 comparison between Scenario 2 and Scenario 3. Scenario 2 has the lowest emissions after the production of the two scenarios. When operating the vessels with Norwegian energy mix, a break point after 20 to 21 years will be experienced. After that, the future GWP from PVs will be lower than without PVs. The difference between the two scenarios is more or less insignificant with Norwegian energy mix. However, with a more fossil fuel dominated energy mix, the break point would be experienced much earlier. This could favour the option with PVs and hence reduce the GWP even more for Scenario 3. Another benefit for integrating PVs on the vessel is that they could reduce the charging load from the grid by producing a significant share of the energy consumption locally. This could again prevent that the grid needs to be expanded, or that additional charging batteries are needed in case of a weak grid. Which option is the best alternative being therefore dependent on where the vessel will operate, and the environment in this location.

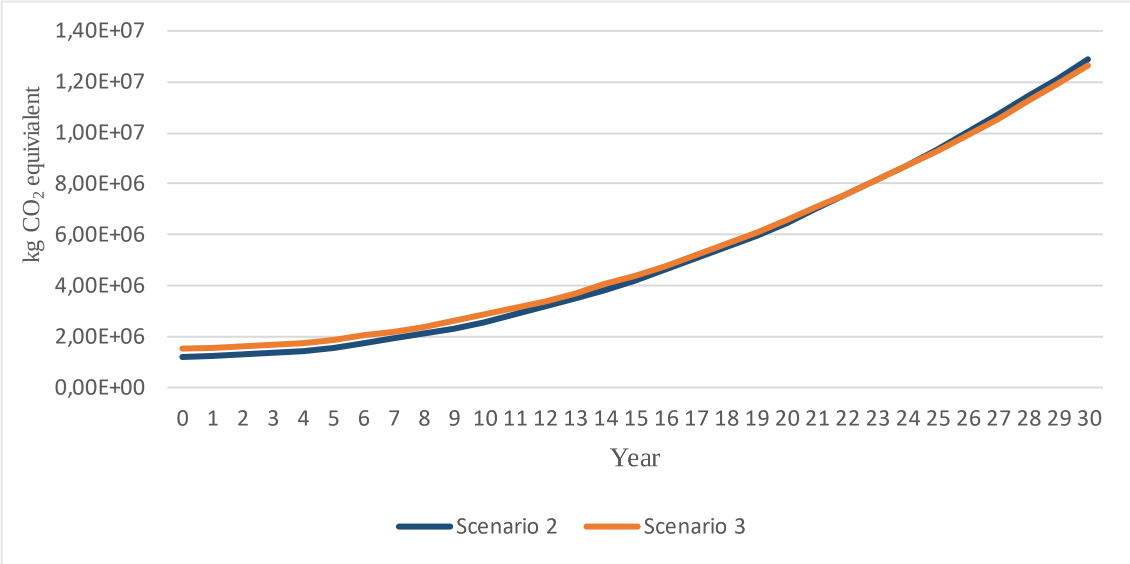

Figure 8-2: CO_2 emissions for Scenario 2 and Scenario 3 for a period of 30 years. The CO_2-equivialent is shown on the y-axis, while the years are shown on the x-axis.

8.2 Impact from batteries

The sensitivity analysis show that the battery is one of the most sensitive parameters on the GWP. This can be associated to the emissions from the energy consumption for production and the emissions from the cell manufacturing. These are the two factors within the battery that had the largest contribution to GWP as shown in *Figure 7-3*. Within the cell, both the lithium for the electrode and lithium for the electrolyte have the biggest emissions to GWP. However, the sensitivity analysis shows that the lithium did not constitute any significant on the GWP. The amount of lithium in the battery can therefore be considered as less significant with respect to the CO_2 emissions. However, this parameter may have bigger impacts on other midpoint categories which are more related to toxicity and metal depletion. This is shown in the previous results, where the battery shows to have a significant contribution in these categories.

The parameter which was most sensitive to GWP (within the battery) was the energy consumption during battery manufacturing. This parameter was very sensitive to the air related emissions, such as photochemical oxidant formation, particulate matter formation and global warming potential. In GWP, the energy consumption had 45% more emissions than the emission from battery cell (2. largest). The sensitivity analysis also showed that the GWP was influenced by 0,24 % with an energy change of 1 %.

The battery manufacturing location is another factor that plays an important role in these types of emissions. In this study, the batteries are assumed to be produced in China. By reconsidering the production location, and producing the batteries on a location with a cleaner energy mix, the results may change significantly. This was tested in a scenario analysis, displayed in *Figure 7-14*. The figure shows that the battery production location is a factor that has a significant impact on the results. In a battery pack, such as the UWS (Scenario 2), the GWP is saved by approximately 23% by producing the batteries in Norway, contra China. In the two other scenarios with battery propulsion, the GWP is saved with 26% and 30% for Scenario 3 and 4 respectively. The saving potential differs between the scenarios due to different battery capacity, and hence different energy consumption in the manufacturing phase. A potential battery manufacture in Norway can decrease the GWP significant, and hence making the advantage of battery propulsion significant compared to conventional propulsion systems today.

It should be mentioned that the amount of energy in the manufacturing process is an estimation which is based on Laselle et. al. report in [23]. The energy was normalized such that it could be used in the current study. This estimation is based on average energy consumption from different previous studies. The electricity usage will also change depending on the environment of the manufacturing location. This is because that the electricity consumption is mainly used in drying rooms for the coating operation of the cells. The authors indicate that less energy is needed in dry environment, while more energy is needed in wetter conditions [23]. The sensitivity analysis on the energy consumption is therefore an important parameter to examine.

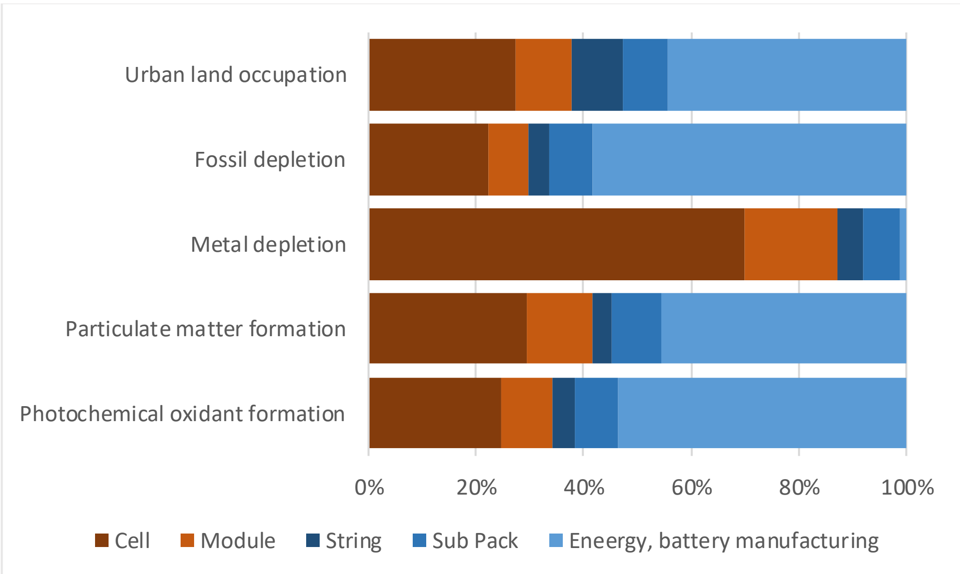

Figure 8-3: Analysis of the battery's most sensitive impact categories.

In addition to the large emission to GWP, the battery production also has significant impact on metal depletion, fossil depletion, urban land occupation, particulate matter formation, and photochemical oxidant formation. *Figure 8-3* was carried out to show the battery analysis to these categories, and which part of the battery that has the largest influence. As shown, the impact to metal depletion is mainly affected by the battery cell. This is due to the large extraction activity of metals to produce lithium and copper in the cell. The remaining categories has its main emissions from the energy consumption during production. Additionally, they have a significant impact from the battery cell as well. Again, this shows the importance of the energy during the manufacturing process. The analysis also show the importance to minimize the use of metals in batteries in the future. One option is to introduce more recycling of the battery, and hence limit the extraction of metals in the future.

8.3 Limitations and data quality

There are some limitations in this study that may affect the results with respect to a real life scenario. The results may change significantly if implementing economic limitations which could be experience with Scenario 3 with the installation of PV modules. The cost of PV panels has decreased the last years, but the price is still an important factor. According to a paper by WWF Norway and Accenture, the reason for the large PV prices in Norway is mainly due to the low energy prices, high technology prices, and low subsidies from the government. This will result in large payback time for an installation on board the UWS. However, due to the predicted expanding of the Norwegian grid in the future, the energy prices are expected to be significantly increase, which may make it more profitable to install PVs in the future [62]. Despite the minimum difference in the results with and without PVs, as discussed previous, the cheapest option would probably be without PVs when operating with a Norwegian energy mix.

Another uncertainty factor in the study is the exact amount of aluminium used for the hull. The numbers used in this study is an estimation performed by MCT. However, the results from the sensitivity analysis shows that the aluminium had minor impact on the GWP compared to other parameters. Therefore, the estimation on the amount of aluminium plays a relatively insignificant role in the overall results in this thesis. Hence, other parameters are more important to consider if the goal is to reduce the GWP.

As discussed earlier, the battery is a fundamental parameter in this thesis, and especially the energy consumption. It can be a limitation for the results in the study when considering the large impact this parameter can cause. The more energy used, the higher impact on GWP and other direct air emission categories. The energy consumption considered in this thesis may both increase or decrease from a real case scenario. Despite this, it is shown in the comparison between the four scenarios in *Figure 7-9* that Scenario 1 (diesel combustion) has an 85% higher contribution to climate change, compared to the UWS with battery electrical propulsion (Scenario 2). Despite the low payback time for this scenario (5 month in terms of GWP), the energy consumption for the battery production in Scenario 2 has to increase significant if the emissions shall be the same between the two scenarios. The results from the battery production and the battery operation could therefore be relevant to a real-life scenario.

One important simplification in this study is the estimated diesel consumption in Scenario 1, which may affect the results of this study. Therefore, the estimated fuels consumption in this thesis was compared to the calculated diesel combustion in a conventional diesel combustion ferry. The calculation is performed by Kullmann's comparative LCA of MS Ampere and a conventional diesel ferry. It should be noted that this ferry is built in steel, and only the hull is 1 000 tonnes heavy (compared to 69 tonnes for the UWS). This ferry has an average diesel consumption of 11,9 litres per km. The diesel consumption for the UWS is assumed to be 2,7 litres per km. Considering the weight difference of the ferries, the diesel estimation may seem as a manageable assumption. The inventory for this thesis is sharpened to suit the electrical option. This means that most of the component are the same for the scenarios with electrical propulsion and the scenario with diesel propulsion, except for the drivetrain and electrical motor. These parts are not considered for the diesel combustion scenario. The emissions for the diesel combustion ferry may therefore have a higher GWP during its production than presented here, if the inventory was more specified on this case scenario. Due to the uncertainty on this scenario, it was also performed a sensitivity analysis in the diesel combustion. The results showed that the diesel combustion was very sensitive to the GWP, which again imply the importance of this parameter.

The data from the LCI was collected with different quality. Much of the data are based on the Ecoinvent database, which is a database that represents the average impact on many different processes. This is a great tool to use if more accurate data are lacking. Nevertheless, the more data which are used from the Ecoinvent database, the more average or general results will be the outcome of the study. Therefore, it was tried to specify most of the inventory on the specific manufacturing processes of as many components as possible. This method gives a more specific and approximated result on the study.

The data on the batteries are collected from Grenland Energy and DNV GL. These data describe the process of all the sub components in great detail. This is one of the best data set in this study, and hence strengthens the results. However, the energy consumption is the part that is most uncertain in the battery manufacturing process. This is discussed earlier, and shows to be sensitive to the GWP, but not enough to change the conclusion.

The data regarding the electrical engine and mooring device is extracted from data sheets from manufactures, which means that they are expected to be a good source of data. The results from these components is show to have just a small impact on the impacts.

The converters and transformers is extracted from DNV GL together with the batteries. The copper in the transformer was the most sensitive parameter in emissions to GWP of all the electrical components. However, in the sensitivity analysis it was shown that this parameter had very small impact on the overall GWP. This means that these components have limited influence on the overall results.

8.4 Comparison to previous literature

The results from the previous studies presented in Chapter 2 varies, depending on the location of operation. The results of this study are based on the Norwegian energy mix, which showed that air emissions can be reduced by using the battery technology in the transportation. This result is both agreed and disagreed with much of the previous literature. Many authors, such as Ercan et. al. concluded that the battery technologies in buses showed good results in CO_2 and CO emissions, but due to worse results on the other impact categories, they concluded that the overall performance of the battery propulsion was on the average or lower. Hawkins et al. also found that powering EV with an average European energy mix gave good results in comparison to using coal produced energy. The battery had large emissions on human toxicity, eutrophication potential and freshwater ecotoxicity, which is in accordance with the current study.

More related studies on battery vessels are Kullmann, who did a comparison between MS Ampere and a conventional diesel ferry [8]. Laselle et. al. also reported a study on the energy payback time for batteries in a hybrid system in a supply ship, and batteries in an all-electric ferry [23]. They both assumed that the ferries were operating in Norway, and hence used Norwegian electricity mix. They both concluded that the battery technology can reduce the GWP.

One of the most interesting factors in this thesis is the passenger occupancy or capacity utilization. The results show that this factor is very sensitive to the GWP results. The PKT in this study is based on a Norwegian average passenger occupancy of 37%. This is a low utilization value, which may increase in a city such as Oslo. The occupancy in the Oslo area will vary through the day, as described in Chapter 2. The public transportation in rush-hours may experience occupancy near 100 % or more, while in-between these periods the occupancy may decrease to very small occupancy. Using per PKT as functional unit will therefore make the results to be very dependent on the occupancy, and hence vary through the day. This is shown in the sensitivity analysis, where it was found that the capacity utilization was the most sensitive of the tested parameters. These results are in accordance with the results that were found by Chester and Horvath [20]. This study did not include electrical propulsion systems, but the results regarding utilization capacity was the same as in the current study. With the help of these types of analysis it is possible to assess different transportation possibilities against each other. For instance, Chester and Horvath showed that driving a SUV with two persons had the same emissions per person km as a bus with eight passengers. These types of analysis can assess the importance of public transportation in the different areas, based on expected numbers of travellers. The more travellers, the better results in terms of per PKT. The results also change independently of the technology, only the occupancy.

The study by Chester and Horvath can be used as a rough reference comparison to the stody on UWS, in order to see if the results make sense. Chester and Horvath reported that a full loaded urban diesel bus has an emission of approximately 50 g CO_2- equivalent per PKT. The same bus has an emission of a more than 400 g CO_2- equivalent during off peak. UWS has 36,9 g CO_2- equivalent emissions with a passenger occupancy of 32,5%. This result show a significant difference in contrast to the diesel combustion bus. The different operation location is an important factor, which also makes them not direct comparable. The energy mix in Norway, plays a significant role of the emissions during operation. However, the comparison set the results of battery propulsion system in the UWS in perspective, and shows the large GWP saving battery propulsion can cause.

The operation of UWS is designed to operate between Sætre and Aker Brygge in the future. Therefore, a comparison between different transportation technologies in the same area were performed. The comparison includes travelling time, distance and CO_2 emissions. The CO_2 emissions from the UWS were compared to the emissions from a conventional diesel combustion bus and a passenger car. The bus was based on a report by the western Norway research institute, which concerns the energy consumption and emissions from different transportation options in Norway [63]. The bus was assumed to have 78 seats, and a passenger utilization of 32,5% (same as UWS) were used in the calculations. The emissions for a small person car were calculated based on EcoInvent's database, and 1,73 persons per car were used in the calculation [63]. The comparison is shown in *Figure 8-4*. According to Google maps, the travelling time with bus is 1 hour and 9 minutes, and approximately 44,6 km. The travelling time with car is 41 minutes and 48,6 km long, and for the UWS, the travelling time is 1 hour and 10 minutes. The travelling time with bus and UWS is direct comparable, while travelling with car is 30 minutes shorter in time. As shown in the figure, the UWS has the lowest GWP with 36,92 g CO_2-equivalent, while bus has an emission of 54,3 g CO_2-equivialent per PKT. The car is the option with the largest emissions, 126 g CO_2- equivalent per PKT, but it also has the shortest travelling time. Due to the same travelling time for bus and the UWS, it can be assumed that the travelling time is not a factor that will influence the selection between bus transportation and transportation with the UWS in the future. Therefore, it can be expected that the number of travellers with UWS in the future will remain the same (or increase) compared to the present travellers. Based on this information, the best alternative is to use the UWS for public transportation between Sætre and Aker Brygge, due to its low GWP.

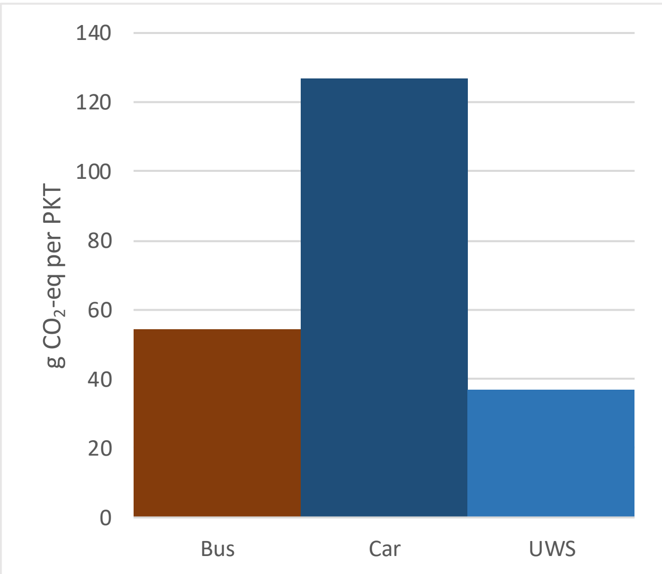

Figure 8-4: GWP comparison between bus, car and UWS given in per PKT.

Another factor that may favour transportation with the UWS, and hence increase the number of travellers is the situation in rush-hours. Travelling with the UWS avoid rush-hour travelling, which results in reduced travelling time, compared to travelling with bus and car. This is a factor that can contribute to increase the passenger occupancy for the UWS, and reducing the per PKT emissions even more.

For Scenario 3, it is difficult to compare with the previous literature. There are few studies that have implemented PV modules as energy source for propulsion. Nevertheless, Linjord reported in [33], an LCA on PV integrated roof tile that the energy payback time (in terms of GWP) for an installation in Norway is between 5 and 7 years, while in Spain the payback time was estimated to be 1,4 to 1,9 years with the same PVs. This shows how the difference in irradiance can influence the overall results on the GWP of PVs. The energy payback time for the PV modules were not estimated in this thesis. Nevertheless, it was shown in chapter 5 that the power production from a location like Oslo vary through the year. The average power production was found to be very small in comparison to the peak production in the summer months.

Operating the UWS with PV modules in for instance Spain, would therefore result in a significant increase in amount of irradiation and energy production, compared to the situation in Norway. The extra energy production from the PVs may reduce the energy need from the grid, and hence reducing the potential grid load, and produce more energy with low GWP. This is a case scenario that has not been tested in the LCA of the UWS. However, the combination of the results from Linjord's report and the results from the current LCA on the UWS indicate that this is a case that may reduce the GWP in the transportation sector in areas where the solar irradiation is high and the energy mix is dominated by fossil fuels.

8.5 Future work

In order to limit emissions related to the GWP, there are need for more low emission technologies in the transportation sector. The battery technology has in this study proved that battery propulsion is an option which can contribute to less emissions from the transportation sector. However, other concerns within the battery technology, such as the metal resources for the battery composition may not be large enough to replace all the present transportation with battery propulsion. For instance, lithium is a metal that many researches has indicated can be at risk of getting empty in the future. Therefore, more research is needed on other low emission technologies which can contribute to reducing the GWP. One opportunity is fuel cells running on hydrogen. MCT has announced that the world's first hydrogen ferry will be set in operation between Nesvik and Hjelmeland in Rogaland in 2021 [52].

The battery system in this study was conducted with the most detailed information, and is therefore one of the strengthens of this study. However, the battery technology is continuously changing, meaning that this is an industry that always needs research in the future. Another factor that is missing in the current study is the environmental burdens of expanding the grid capacity. Scenario 4 is a case which investigated the emission when additional charging batteries were implemented for maintaining a stable charging process. Whether this is a better solution than expanding the grid capacity is uncertain, and it should therefore be performed more research on this part.

Another option that can contribute to reduce the grid load is the battery exchange system, described previously in this report. This is an option that in addition can contribute to reduce the battery capacity on board the UWS, and hence reduce the weight and the energy consumption of the vessel. This system can contribute to reduce the overall travelling time, due to no charging time. Another important factor in the batteries is the use of batteries as a second lifetime. The batteries can for instance be used as energy storage in the grid when they are finished in the UWS. Recycling of the batteries is also a topic that is important to further research.

The cost of the transportation option is often deciding which transportation method that will be taken into operation. The cheapest alternative is often selected, without looking at the environmental impact of it. In order to change this way of thinking, it should be set different environmental requirements by the government when announcing new transportation contracts. This may result in a more environmental focus in the first place, where the alternatives with the lowest emissions are evaluated. The cheapest of these alternatives can then be selected as the best transportation option. The current study of the UWS can therefore be used in these types of decisions. Therefore, a further work for this study could be a detailed cost assessment of the UWS. This will give a complete assessment of the whole ferry, with both the environmental potential and its life cycle costs.

9 Conclusion

The transportation sector stands for a significant contribution to the impact of the global warming potential (GWP). In addition, the public transportation situation in the city of Oslo is in periods is near its capacity. This is especially experienced in rush hours when people are travelling to and from work. With that in mind, this study aims to use life cycle assessment (LCA) methodology to investigate the environmental potential of a battery electric passenger ferry operating in the Oslo-fjord, called urban water shuttle (UWS). The UWS can contribute to reduce the public transportation in urban areas, as well as decreasing the local and global air emissions in cities.

Four scenarios were analysed in the thesis; Scenario 1 uses a conventional diesel combustion propulsion system. This scenario is defined as the reference scenario in comparison to the other scenarios. Scenario 2 uses batteries which are charged from the grid as propulsion system. Scenario 3 uses batteries which are charged by photovoltaics and charged by the grid as propulsion system. Scenario 4 also use batteries that are charged from the grid as propulsion system. In addition, this scenario is implemented with additional batteries, located at each charging station, which are supporting the grid during charging.

The results from the study showed that Scenario 1 had the largest emissions to GWP and other air emission categories. However, the production of UWS with battery propulsion has larger GWP, compared to production of diesel combustion propulsion. Further, it was stated that powering the UWS with electricity showed to have a payback time of 5 months in terms of CO_2-equivialent. Scenario 3 and Scenario 4 have a payback time of 6 and 6,5 months respectively. It is therefore concluded that operating the UWS with battery propulsion system can reduce the GWP and other air related emissions, compared to the reference scenario.

The results showed that the energy consumption during battery manufacturing was sensitive to the GWP. This is an uncertain factor which may affect the results of this study. It is difficult to estimate the exact energy consumption for the manufacturing process because this factor may change with the different environment of the production location. However, this parameter is not large enough to change the conclusion that the battery option is the best alternative in this thesis.

It should be mentioned that the scenarios with battery system as propulsion showed to have higher emissions than the diesel combustion option in several impact categories regarding toxicity and depletion. In addition, the battery production had a significant influence to metal depletion, fossil depletion, photochemical oxidant formation, urban land occupation, particulate matter formation, and climate change. However, the impacts were not large enough to not favour battery propulsion rather than diesel combustion as propulsion system.

10 References

[1] D.-H. Lee, "Evaluation of the development of biobutanol with reference to continental level: The rebound effect and effectiveness of the Paris Agreement," *Int. J. Hydrogen Energy*, vol. 41, no. 46, pp. 21600–21616, Dec. 2016.

[2] D. F. Petersen, E. Enger, A. Dimmen, and T. M. Gustavsen, "Grunnlagsdokument Nasjonal transportplan 2018-2029," Oslo, 2016.

[3] "Miljøstatus.no -Miljøinformasjon fra offentlige myndigheter." [Online]. Available: http://www.miljostatus.no/.

[4] T. Homleid, J. M. Skjelvik, R. Reinvang, T. Heieraas, and E. H. Nordang, "Oslo-navet Behovsanalyse," Oslo, 2015.

[5] Avinor, Jernbaneverket, Kystverket, and S. Vegvesen, "Forslag til Nasjonal Transportplan 2014-2023," 2012.

[6] M. Zackrisson, L. Avellán, and J. Orlenius, "Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles – Critical issues," *J. Clean. Prod.*, vol. 18, no. 15, pp. 1519–1529, 2010.

[7] "Battery university." [Online]. Available: http://batteryuniversity.com/.

[8] A. B. Kullmann, "A Comparative Life Cycle Assessment of Conventional and All-Electric Car Ferries," no. June, 2016.

[9] Bellona and Siemens, "Syv av ti ferger er lønnsomme med Elektrisk drift -en mulighetsstudie," 2015.

[10] H. Baumann and A.-M. Tillman, *The Hitch Hiker ' s Guide to LCA- An orientation in life cycle assessment methodology and application*. Gøteborg: Studentlitteratur, 2003.

[11] N. Aadland, A. Knudsen, E. Tolo, and I. Østvik, "Prosjektrapport - Mulighetsstudie for elektrisk drift av passasjerfartøy i Indre Oslofjord," Bergen, 2016.

[12] E. Grapperud, "Høring -Konseptvalgutredning for økt transport inn mot og gjennom Oslo," 2016.

[13] S. Norway, "Statitics Norway." [Online]. Available: http://www.ssb.no/.

[14] Akershus fylkeskommune, "Datasett: Kollektivtransport sum Oslo og Akershus, nøkkeltall," 2016. [Online]. Available: http://statistikk.akershus-fk.no/webview/index/no/StatistikkServer/Statistikk-Akershus.c.StatistikkServer/Samferdsel-PROSAM.d.9/Kollektive-transporttjenester.d.29/Kollektivtransport-sum-Oslo-og-Akershus-noekkeltall/fCube/AFKkollektivtransportOA_C1. [Accessed: 04-May-2017].

[15] M. S. Eide, H. Gundersen, L. Laugen, M. Lande, E. Nyhus, and S. Mossevig, "Reduksjon av klimagassutslipp fra norsk innenriks skipsfart," 2016.

[16] C. Tagliaferri, S. Evangelisti, F. Acconcia, T. Domenech, P. Ekins, D. Barletta, and P. Lettieri, "Life cycle assessment of future electric and hybrid vehicles: a cradle-to-grave systems engineering approach," *Chem. Eng. Res. Des.*, vol. 112, pp. 298–309, 2016.

[17] H. Ma, F. Balthasar, N. Tait, X. Riera-Palou, and A. Harrison, "A new comparison between the life cycle greenhouse gas emissions of battery electric vehicles and internal

combustion vehicles," *Energy Policy*, vol. 44, pp. 160–173, 2012.

[18] A. Noshadravan, L. Cheah, R. Roth, F. Freire, L. Dias, and J. Gregory, "Stochastic comparative assessment of life-cycle greenhouse gas emissions from conventional and electric vehicles," *Int. J. Life Cycle Assess.*, vol. 20, no. 6, pp. 854–864, 2015.

[19] T. R. Hawkins, B. Singh, G. Majeau-Bettez, and A. H. Strømman, "Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles," *J. Ind. Ecol.*, vol. 17, no. 1, pp. 53–64, Feb. 2013.

[20] M. V. Chester and A. Horvath, "Environmental assessment of passanger transportation should include infrastructure and supply chains," *Environ. Res. Lett*, vol. 4, 2009.

[21] J. Antonio, G. Sánchez, J. María, L. Martínez, and J. Lumbreras, "Impact of Spanish electricity mix , over the period 2008 – 2030 , on the Life Cycle energy consumption and GHG emissions of Electric , Hybrid Diesel-Electric , Fuel Cell Hybrid and Diesel Bus of the Madrid Transportation System," vol. 74, pp. 332–343, 2013.

[22] T. Ercan and O. Tatari, "A hybrid life cycle assessment of public transportation buses with alternative fuel options," pp. 1213–1231, 2015.

[23] S. Laselle, L. O. Valøen, and B. Gundersen, "Life cycle analysis of batteries in maritime sector," 2016.

[24] M. A. Øverleir, "Hybridization of General Cargo Ships to meet the Required Energy Efficiency Design Index," no. June, 2015.

[25] H. E. Lindstad, G. S. Eskeland, and A. Rialland, "Batteries in offshore support vessels – Pollution, climate impact and economics," *Transp. Res. Part D Transp. Environ.*, vol. 50, pp. 409–417, Jan. 2017.

[26] D. Claus and J. O. Besenhard, *Handbook of Battery Materials*, 2nd. Editi. 2011.

[27] M. Winter and R. J. Brodd, "What Are Batteries, Fuel Cell and Supercapacitors?," pp. 4245–4269, 2004.

[28] J. B. Goodenough, H. D. Abruña, and M. V. Buchanan, "Basic Research Needs for Electrical Energy Storage," Whasington DC, 2007.

[29] D. Linden, *Handbook of Batteries*, 2nd. Editi. New York: McGraw-Hill, 1995.

[30] M. K. Gulbinska, "Lithium-ion Cell Materials in Practice."

[31] B. Scrosati and J. Garche, "Lithium batteries: Status, prospects and future," *J. Power Sources*, vol. 195, no. 9, pp. 2419–2430, 2010.

[32] S. R. Wenham, M. A. Green, M. E. Watt, R. Corkish, and A. Sproul, *Applied Photovoltaics*, Third. London, New York, 2011.

[33] T. Linjord, "Life cycle analysis og photovoltaic roof tile," University of Agder, 2016.

[34] I. Kobougias, E. Tatakis, and J. Prousalidis, "PV Systems Installed in Marine Vessels: Technologies and Specifications," *Adv. Power Electron.*, vol. 2013, pp. 1–8, 2013.

[35] International Organization for Standardization, "Environmental management - Life Cycle Assessment - Principles and Framework (ISO 14040:2006)," *Int. Organ. Stand.*, p. 26, 2006.

[36] I. O. for Standardization, “Environmental management Life cycle assessment Requirements and guidelines (ISO 14044:2006),” p. 60, 2006.

[37] B. A. Sandén and M. Karlström, “Positive and negative feedback in consequential life-cycle assessment,” *J. Clean. Prod.*, vol. 15, no. 15, pp. 1469–1481, 2007.

[38] “Ecoinvent.” [Online]. Available: http://www.ecoinvent.org/.

[39] V. Mihaylov, “Comparative life cycle impact assessment of a battery electric and a conventional powertrains for a passenger transport ferryboat A case study of the entire integrated system for,” 2014.

[40] M. Goedkoop, R. Heijungs, A. De Schryver, J. Struijs, and R. van Zelm, “ReCiPe 2008. A LCIA method which comprises harmonised category indicators at the midpoint and the endpoint level. Characterisation.,” p. 133, 2013.

[41] “PV GIS.” [Online]. Available: http://photovoltaic-software.com/pvgis.php.

[42] DNV GL, “Elektrifisering av bilferger i Norge – kartlegging av investeringsbehov i strømnettet,” 2015.

[43] P. Meshram, B. D. Pandey, and T. R. Mankhand, “Extraction of lithium from primary and secondary sources by pre-treatment , leaching and separation : A comprehensive review,” *Hydrometallurgy*, vol. 150, pp. 192–208, 2014.

[44] M. (Masaki) Yoshio, R. J. Brodd, and A. Kozawa, *Lithium-ion batteries : science and technologies*. Springer, 2009.

[45] B. Lawson, “Lithium Battery Manufacturing.” [Online]. Available: http://www.mpoweruk.com/battery_manufacturing.htm. [Accessed: 23-Mar-2017].

[46] “Hydro-Livssyklusen til aluminium.” [Online]. Available: http://www.hydro.com/no/hydro-i-norge/Om-aluminium/Aluminiumens-livssyklus/.

[47] R. B. H. Tan and H. H. Khoo, “An LCA study of a primary aluminum supply chain,” *J. Clean. Prod.*, vol. 13, no. 6, pp. 607–618, May 2005.

[48] E. David and J. Kopac, “Aluminum recovery as a product with high added value using aluminum hazardous waste,” *J. Hazard. Mater.*, vol. 261, pp. 316–324, Oct. 2013.

[49] “Elkem.” [Online]. Available: https://www.elkem.com/technology-and-innovation/our_technology_and_processes/.

[50] J. O. Odden, G. Halvorsen, H. Rong, and R. Gløckner, “Silicon for the Chemical and Solar Industry IX Comparison of the energy consumption in different production processes for solar grade silicon.”

[51] “Energy Mix: Definition and Facts | Planète Énergies,” 2015. [Online]. Available: http://www.planete-energies.com/en/medias/close/about-energy-mix. [Accessed: 01-May-2017].

[52] “NCE Maritime CleanTech.” [Online]. Available: https://maritimecleantech.no/.

[53] “SimaPro.” [Online]. Available: https://simapro.com/about/.

[54] L. A.-W. Ellingsen, G. Majeau-Bettez, B. Singh, A. K. Srivastava, L. O. Valøen, and A. H. Strømman, “Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack,” *J. Ind. Ecol.*, vol. 18, no. 1, pp. 113–124, Feb. 2014.

[55] G. Skomedal, "Årlig strømproduksjon fra et solcellepanel," 2015. [Online]. Available: https://solcellekysten.no/2015/06/24/arlig-stromproduksjon-fra-et-solcellepanel/.

[56] ABB, "EPD- AC machine 250 kW power."

[57] K. Longva, "Fordelingstransformatorer og levetid," 1999.

[58] M. T. AS, "Møre Trafo AS." [Online]. Available: http://moretrafo.no/produkter/.

[59] P. of M. Covatec, "Covatec." [Online]. Available: http://www.cavotec.com/en/ports-maritime/automated-mooring-systems_36/moormaster™-200c-arm-design_37/.

[60] Covatech, "Data sheet MoorMaster 400."

[61] Epd-norge, "Data sheet for 'Fora Form seats.'"

[62] N. Jensen and P. Ødegaard, "Mot lysere tider Solkraft i Norge – Fremtidige muligheter for verdiskaping," 2015.

[63] M. Simonsen, "Transport, energi og miljø -Sluttrapport," 2010.

11 Appendices

Appendix A- Energy calcualtion for the mooring operation.

Power (peak):	17	kW	60	min/hour
Mooring time (min during charging):	Energy consumption			
5	1,42	kWh		
18	5,10	kWh		
10	2,83	kWh		
10	2,83	kWh		
6	1,70	kWh		
20	5,67	kWh		
10	2,83	kWh		
21,4	6,06	kWh		
Total per day	**28,45**	kWh		
Per lifetime	**311491,00**	kWh		

Appendix B- PV calculations

Energy consumption for two roundtrips with UWS.

	Time (min)	Velocity	Time (min)	Power (kW)	Energy (kWh)
Sætre-Fagerstrand					
	0				
	2	maneuvering	2	150	5
	12,16	20	10,16	600	101,6
	17,56	6	5,4	130	11,7
	18,56	maneuvering	1	150	2,5
Total					**120,8**
Fagerstrand-Aker brygge					
	0				
	2	maneuvering	2	150	5
	35,92	20	33,92	600	339,2
	44,02	6	8,1	130	17,55
	45,02	maneuvering	1	150	2,5
Total					**364,25**

Energy consumption Sætre-Aker Brygge	485,05 kWh
Energy consumption two roundtrips UWS:	1940,2 kWh

Basis in the PV calculations:		
$E_{sun} = A * \eta$*H*PR		
PR=	0,8	
η=	0,14	
A_vessel=	240	m^2
Desired production from PVs (10 %)	194,02	kWh

Energy produced from the UWS:

Elektrisitet fra UWS	Month	H_d (kWh/m^2)	E_vessel (kWh)
	jan	0,36	9,68
	feb	0,9	24,19
	mars	2,45	65,86
	apr	3,77	101,34
	mai	5,16	138,70
	jun	5,63	151,33
	jul	5	134,40
	aug	3,99	107,25
	sep	2,6	69,89
	okt	1,22	32,79
	nov	0,46	12,36
	des	0,22	5,91
	AVG	**2,66**	**71,50**

Energy produced from land-based PVs:

Tilt angle= 44		
Month	**H_d (kWh/m^2)**	**E_land (kWh)**
jan	0,99	36,32
feb	1,71	62,73
mars	3,95	144,90
apr	4,71	172,77
mai	5,52	202,49
jun	5,61	205,79
jul	5,11	187,45
aug	4,65	170,57
sep	3,73	136,83
okt	2,19	80,33
nov	1,15	42,18
des	0,71	26,04
AVG	**3,34**	**122,52**

Needed PV-area to meet the energyproduction, A=	327,5213858	m^2
$A = \frac{E}{\eta \times H \times PR}$		

Additional grid produced electricity:	1746,18	kWh

E_tot=E_vessel+E_land

Appendix C- Vessel inventory

1 Transformer

Materials/fuels	***Amount***	***Unit***
Powder coat, steel {GLO}| market for | Alloc Def, U	34	m2
Copper {GLO}| market for | Alloc Def, U	3060	kg
Metal working, average for copper product manufacturing {GLO}| market for | Alloc Def, U	3060	kg
Cast iron {GLO}| market for | Alloc Def, U	2040	kg
Epoxy resin insulator, Al2O3 {GLO}| market for | Alloc Def, U	2040	kg
Electricity/heat		
Electricity, medium voltage {NO}| market for | Alloc Def, U	4987	kWh
Heat, district or industrial, other than natural gas {NO}| heat and power co-generation, hard coal | Alloc Def, U	2727	kWh

1 Converter

Materials/fuels		
Metal working, average for steel product manufacturing {GLO}| market for | Alloc Def, U	745,8	kg
Cast iron {GLO}| market for | Alloc Def, U	233,2	kg
Copper {GLO}| market for | Alloc Def, U	266,2	kg
Aluminium, cast alloy {GLO}| market for | Alloc Def, U	133,3	kg
Aluminium, wrought alloy {GLO}| market for | Alloc Def, U	133,3	kg
Metal working, average for copper product manufacturing {GLO}| market for | Alloc Def, U	266,2	kg
Polyethylene, low density, granulate {GLO}| market for | Alloc Def, U	27,5	kg
Steel, low-alloyed {GLO}| market for | Alloc Def, U	745,8	kg
Electricity/heat		
Electricity, high voltage {FI}| heat and power co-generation, hard coal | Alloc Def, U	1243	kWh
Electricity, medium voltage {FI}| electricity voltage transformation from high to medium voltage | Alloc Def, U	683	kWh

Cables

Materials/fuels		
Aluminium, wrought alloy {GLO}| market for | Alloc Def, U	262,5	kg
Metal working, average for aluminium product manufacturing {GLO}| market for | Alloc Def, U	262,5	kg

Aluminium (Norwegian production)

Resources		
Water, river, NO	0,0403416	m3
Transformation, from unknown	7,5368E-06	m2
Occupation, inland waterbody, unspecified	0,00075368	m2a
Transformation, to inland waterbody, unspecified	7,5368E-06	m2
Materials/fuels		
Ethylene glycol {GLO}| market for | Alloc Def, U	0,00049943	kg
Lubricating oil {GLO}| market for | Alloc Def, U	0,00357021	kg
Tap water {Europe without Switzerland}| market for | Alloc Def, U	4,50374093	kg
Aluminium casting facility {GLO}| market for | Alloc Def, U	3,5124E-13	p
Silver {GLO}| market for | Alloc Def, U	2,1807E-06	kg
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Alloc Def, U	0,00053188	kg
Magnesium {GLO}| market for | Alloc Def, U	1,5908E-05	kg
Copper {GLO}| market for | Alloc Def, U	0,00524876	kg
Aluminium, primary, ingot {RoW}| market for | Alloc Def, U	0,02677959	kg
Water, deionised, from tap water, at user {RoW}| market for water, deionised, from tap water, at user | Alloc Def, U	0,00077595	kg
Soap {GLO}| market for | Alloc Def, U	0,00188888	kg
Steel, unalloyed {GLO}| market for | Alloc Def, U	0,20075598	kg
Potassium hydroxide {GLO}| market for | Alloc Def, U	1,1363E-05	kg
Sawnwood, softwood, raw, dried (u=20%) {RoW}| market for | Alloc Def, U	2,8371E-05	m3
Steel, low-alloyed {GLO}| market for | Alloc Def, U	3,7726E-06	kg
Rolling mill {GLO}| market for | Alloc Def, U	4,9715E-09	p
Sodium sulfate, anhydrite {RoW}| market for | Alloc Def, U	0,00010235	kg
Chemical, inorganic {GLO}| market for chemicals, inorganic | Alloc Def, U	2,7789E-05	kg
Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Def, U	0,00055519	kg
Ammonia, liquid {RoW}| market for | Alloc Def, U	0,00018986	kg
Steel, low-alloyed, hot rolled {GLO}| market for | Alloc Def, U	0,02073589	kg
Titanium dioxide {RoW}| market for | Alloc Def, U	0,00036475	kg
Silica sand {GLO}| market for | Alloc Def, U	0,01383773	kg
Aluminium oxide {GLO}| market for | Alloc Def, U	0,01377466	kg
Silicon carbide {GLO}| market for | Alloc Def, U	0,0002884	kg
Nitric acid, without water, in 50% solution state {GLO}| market for | Alloc Def, U	0,00045231	kg
Isopropanol {GLO}| market for | Alloc Def, U	0,00280273	kg
Zircon, 50% zirconium {GLO}| market for | Alloc Def, U	0,00245889	kg
Methyl ethyl ketone {GLO}| market for | Alloc Def, U	7,5816E-06	kg
Carbon black {GLO}| market for | Alloc Def, U	7,1681E-05	kg
Nitrogen, liquid {RoW}| market for | Alloc Def, U	0,02913424	kg
Tetraethyl orthosilicate {GLO}| market for | Alloc Def, U	0,0072859	kg
Wax, lost-wax casting {GLO}| market for | Alloc Def, U	0,00395848	kg
Sodium nitrite {GLO}| market for | Alloc Def, U	3,289E-06	kg
Clay {RoW}| market for clay | Alloc Def, U	0,00037508	kg
Propylene glycol, liquid {GLO}| market for | Alloc Def, U	8,2224E-05	kg
Kaolin {GLO}| market for | Alloc Def, U	0,00880199	kg
Sulfuric acid {GLO}| market for | Alloc Def, U	0,00011009	kg
Ethoxylated alcohol (AE7) {GLO}| market for | Alloc Def, U	0,0001109	kg

Steel, chromium steel 18/8, hot rolled {GLO}| market for | Alloc Def, U	0,02164826	kg
Polystyrene, high impact {GLO}| market for | Alloc Def, U	6,4712E-05	kg
Printed wiring board, for through-hole mounting, Pb containing surface {GLO}| market for | Alloc Def, U	3,8453E-05	m2
Resistor, auxilliaries and energy use {GLO}| market for | Alloc Def, U	6,1102E-05	kg
Selective coat, aluminium sheet, nickel pigmented aluminium oxide {GLO}| market for | Alloc Def, U	5,2602E-07	m2
Silicone product {GLO}| market for | Alloc Def, U	0,00116786	kg
Printed wiring board, surface mounted, unspecified, Pb free {GLO}| market for | Alloc Def, U	0,00031765	kg
Capacitor, film type, for through-hole mounting {GLO}| market for | Alloc Def, U	0,0002654	kg
Wire drawing, copper {GLO}| market for | Alloc Def, U	0,00251125	kg
Printed wiring board, for through-hole mounting, Pb free surface {GLO}| market for | Alloc Def, U	4,5936E-05	m2
Ferrite {GLO}| market for | Alloc Def, U	0,00030487	kg
Zinc coat, coils {GLO}| market for | Alloc Def, U	2,9764E-06	m2
Sheet rolling, aluminium {GLO}| market for | Alloc Def, U	0,00383377	kg
Sheet rolling, steel {GLO}| market for | Alloc Def, U	0,02234745	kg
Polyester resin, unsaturated {GLO}| market for | Alloc Def, U	8,9635E-05	kg
Aluminium, wrought alloy {GLO}| market for | Alloc Def, U	0,00682586	kg
Brass {CH}| market for brass | Alloc Def, U	8,199E-07	kg
Brass {RoW}| market for brass | Alloc Def, U	0,00016316	kg
Plug, inlet and outlet, for network cable {GLO}| market for | Alloc Def, U	0,0022026	p
Transformer, high voltage use {GLO}| market for | Alloc Def, U	0,00024473	kg
Transformer, low voltage use {GLO}| market for | Alloc Def, U	2,634E-05	kg
Transistor, surface-mounted {GLO}| market for | Alloc Def, U	7,2792E-06	kg
Transistor, auxilliaries and energy use {GLO}| market for | Alloc Def, U	7,8041E-05	kg
Aluminium, cast alloy {GLO}| market for | Alloc Def, U	0,01849631	kg
Fan, for power supply unit, desktop computer {GLO}| market for | Alloc Def, U	3,9157E-05	kg
Plug, inlet and outlet, for computer cable {GLO}| market for | Alloc Def, U	0,0014684	p
Transistor, wired, small size, through-hole mounting {GLO}| market for | Alloc Def, U	1,3538E-06	kg
Metal working, average for aluminium product manufacturing {GLO}| market for | Alloc Def, U	0,00083918	kg
Inductor, auxilliaries and energy use {GLO}| market for | Alloc Def, U	0,00016239	kg
Mounting, through-hole technology, Pb-free solder {GLO}| market for | Alloc Def, U	2,5686E-05	m2
Cable, printer cable, without plugs {GLO}| market for | Alloc Def, U	9,7893E-05	m
Diode, glass-, for through-hole mounting {GLO}| market for | Alloc Def, U	2,4217E-06	kg
Inductor, miniature radio frequency chip {GLO}| market for | Alloc Def, U	8,223E-09	kg
Switch, toggle type {GLO}| market for | Alloc Def, U	7,7336E-06	kg
Potentiometer, unspecified {GLO}| market for | Alloc Def, U	5,9715E-06	kg
Capacitor, electrolyte type, < 2cm height {GLO}| market for | Alloc Def, U	5,0513E-06	kg
Liquid crystal display, unmounted {GLO}| market for | Alloc Def, U	4,8947E-06	kg
Printed wiring board, through-hole mounted, unspecified, Pb free {GLO}| market for | Alloc Def, U	1,8203E-05	kg
Diode, auxilliaries and energy use {GLO}| market for | Alloc Def, U	2,6439E-06	kg
Resistor, surface-mounted {GLO}| market for | Alloc Def, U	3,4194E-05	kg
Inductor, ring core choke type {GLO}| market for | Alloc Def, U	0,00016239	kg
Capacitor, auxilliaries and energy use {GLO}| market for | Alloc Def, U	0,00046263	kg
Light emitting diode {GLO}| market for | Alloc Def, U	3,0079E-06	kg

Cable, connector for computer, without plugs {GLO}| market for | Alloc Def, U	0,00203129	m
Capacitor, electrolyte type, > 2cm height {GLO}| market for | Alloc Def, U	0,00039329	kg
Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U	0,01030165	kg
Capacitor, for surface-mounting {GLO}| market for | Alloc Def, U	2,2153E-06	kg
Transistor, wired, big size, through-hole mounting {GLO}| market for | Alloc Def, U	6,2064E-06	kg
Resistor, metal film type, through-hole mounting {GLO}| market for | Alloc Def, U	8,9279E-06	kg
Integrated circuit, logic type {GLO}| market for | Alloc Def, U	3,6854E-06	kg
Cable, ribbon cable, 20-pin, with plugs {GLO}| market for | Alloc Def, U	6,9935E-05	kg
Synthetic rubber {GLO}| market for | Alloc Def, U	0,00225042	kg
Insulated gate bipolar transistor, electric vehicle application {GLO}| market for | Alloc Def, U	0,00086021	kg
Resistor, wirewound, through-hole mounting {GLO}| market for | Alloc Def, U	3,4968E-06	kg
Polyphenylene sulfide {GLO}| market for | Alloc Def, U	0,00201071	kg
Permanent magnet, for electric motor {GLO}| market for permanent magnet, electric passenger car motor | Alloc Def, U	0,00012358	kg
Nylon 6 {GLO}| market for | Alloc Def, U	7,5012E-05	kg
Injection moulding {GLO}| market for | Alloc Def, U	0,00558613	kg
Road vehicle factory {GLO}| market for | Alloc Def, U	1,6457E-11	p
Zinc {GLO}| market for | Alloc Def, U	0,00015146	kg
Section bar rolling, steel {GLO}| market for | Alloc Def, U	0,02034785	kg
Tap water {GLO}| market group for | Alloc Def, U	0,1820938	kg
Chromium {GLO}| market for | Alloc Def, U	4,8747E-05	kg
Polypropylene, granulate {GLO}| market for | Alloc Def, U	0,00342615	kg
Nickel, 99.5% {GLO}| market for | Alloc Def, U	2,8437E-05	kg
Ethylene, average {GLO}| market for | Alloc Def, U	0,00037577	kg
Polyvinylchloride, suspension polymerised {GLO}| market for | Alloc Def, U	0,0003132	kg
Reinforcing steel {GLO}| market for | Alloc Def, U	0,03158425	kg
Alkyd paint, white, without solvent, in 60% solution state {GLO}| market for | Alloc Def, U	0,00012628	kg
Coating powder {GLO}| market for | Alloc Def, U	0,00027426	kg
Flat glass, uncoated {GLO}| market for | Alloc Def, U	0,00074819	kg
Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Alloc Def, U	0,00010443	kg
Viscose fibre {GLO}| market for | Alloc Def, U	0,00041149	kg
Polyurethane, flexible foam {GLO}| market for | Alloc Def, U	0,00065338	kg
Tempering, flat glass {GLO}| market for | Alloc Def, U	0,00074819	kg
Lead {GLO}| market for | Alloc Def, U	0,00149746	kg
Glass fibre reinforced plastic, polyester resin, hand lay-up {GLO}| market for | Alloc Def, U	9,9689E-06	kg
Polyethylene, low density, granulate {GLO}| market for | Alloc Def, U	0,00035098	kg
Epoxy resin, liquid {GLO}| market for | Alloc Def, U	0,00027426	kg
Printed wiring board, mounted mainboard, desktop computer, Pb free {GLO}| market for | Alloc Def, U	4,7393E-05	kg
Silicon, electronics grade {GLO}| market for | Alloc Def, U	0,0011973	kg
Epoxy resin insulator, Al2O3 {GLO}| market for | Alloc Def, U	0,00449219	kg
Tin {GLO}| market for | Alloc Def, U	0,00013419	kg
Palladium {GLO}| market for | Alloc Def, U	2,1404E-08	kg
Platinum {GLO}| market for | Alloc Def, U	1,1416E-07	kg
Hot rolling, steel {GLO}| market for | Alloc Def, U	0,00121943	kg

Oxygen, liquid {RoW}| market for | Alloc Def, U	0,0022488	kg
Section bar extrusion, aluminium {GLO}| market for | Alloc Def, U	2,296E-05	kg
Zinc concentrate {GLO}| market for | Alloc Def, U	0,37712684	kg
Precious metal refinery {GLO}| market for | Alloc Def, U	1,4356E-11	p
Perlite {GLO}| market for | Alloc Def, U	1,7027E-05	kg
Retention aid, for paper production {GLO}| market for | Alloc Def, U	0,00012935	kg
Urea, as N {GLO}| market for | Alloc Def, U	3,6875E-06	kg
Transport, passenger car, large size, petrol, EURO 3 {GLO}| market for | Alloc Def, U	0,00017986	km
Ammonium chloride {GLO}| market for | Alloc Def, U	0,00011893	kg
Soda ash, dense {GLO}| market for | Alloc Def, U	0,00741204	kg
Quicklime, milled, loose {RoW}| market for quicklime, milled, loose | Alloc Def, U	0,0088986	kg
Sodium silicate, without water, in 37% solution state {GLO}| market for | Alloc Def, U	4,7664E-06	kg
Cement, Portland {RoW}| market for | Alloc Def, U	0,01386329	kg
Strontium carbonate {GLO}| market for | Alloc Def, U	0,00021731	kg
Copper sulfate {GLO}| market for | Alloc Def, U	3,8337E-05	kg
Foaming agent {GLO}| market for | Alloc Def, U	5,5292E-06	kg
Manganese dioxide {GLO}| market for | Alloc Def, U	0,00048947	kg
Sodium sulfide {GLO}| market for | Alloc Def, U	6,7822E-05	kg
Potassium permanganate {GLO}| market for | Alloc Def, U	8,5411E-06	kg
Hydrogen, liquid {RoW}| market for | Alloc Def, U	0,00086792	kg
Sodium dithionite, anhydrous {GLO}| market for | Alloc Def, U	0,00019443	kg
Hydrogen peroxide, without water, in 50% solution state {GLO}| market for | Alloc Def, U	1,0383E-06	kg
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Alloc Def, U	0,00010733	kg
Pyridine {GLO}| market for | Alloc Def, U	4,9174E-05	kg
Sheet rolling, chromium steel {GLO}| market for | Alloc Def, U	0,0209547	kg
Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for | Alloc Def, U	0,01557864	kg
Polyvinylchloride, bulk polymerised {GLO}| market for | Alloc Def, U	0,00025129	kg
Cast iron {GLO}| market for | Alloc Def, U	0,01018073	kg
Electricity/heat		
Diesel-electric generating set production 10MW {GLO}| market for diesel-electric generating set production 10MW | Alloc Def, U	0,00197242	MJ
Heat, district or industrial, natural gas {Europe without Switzerland}| market for heat, district or industrial, natural gas | Alloc Def, U	0,29046401	MJ
Electricity, medium voltage {NO}| market for | Alloc Def, U	0,7557499	kWh
Propane, burned in building machine {GLO}| market for | Alloc Def, U	0,00392859	MJ
Heat, district or industrial, natural gas {RoW}| heat production, natural gas, at boiler modulating >100kW | Alloc Def, U	1,00564603	MJ
Heat, central or small-scale, other than natural gas {GLO}| market group for | Alloc Def, U	0,12044162	MJ
Electricity, low voltage {GLO}| market group for | Alloc Def, U	4,4615E-05	kWh
Electricity, medium voltage {GLO}| market group for | Alloc Def, U	0,11455728	kWh
Heat, district or industrial, natural gas {GLO}| market group for | Alloc Def, U	0,1218037	MJ
Heat, district or industrial, other than natural gas {GLO}| market group for | Alloc Def, U	0,00344236	MJ

Heat, district or industrial, other than natural gas {NO}| heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas | Alloc Def, S	0,00150854	MJ
Heat, central or small-scale, other than natural gas {RoW}| heat production, light fuel oil, at boiler 100kW condensing, non-modulating | Alloc Def, U	0,00099015	MJ
Electricity, high voltage {NO}| market for | Alloc Def, U	0,88343003	kWh
Diesel, burned in building machine {GLO}| market for | Alloc Def, U	0,00856754	MJ
Heat, district or industrial, other than natural gas {NO}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Conseq, U	0,04317755	MJ
Emissions to air		
Nitrogen, atmospheric	0,02913424	kg
1-Propanol	0,00176905	kg
Water/m3	0,00046131	m3
Water/m3	0,0005921	m3
NMVOC, non-methane volatile organic compounds, unspecified origin	0,00027146	kg
Arsenic	1,7156E-08	kg
Lead	1,3211E-07	kg
Carbon dioxide, fossil	0,00287101	kg
Sulfuric acid	3,9188E-05	kg
Particulates, > 10 um	5,882E-06	kg
Zinc	1,5764E-05	kg
Carbon monoxide, fossil	1,1117E-05	kg
Sulfur dioxide	0,00383179	kg
Mercury	1,6668E-08	kg
Nitrogen oxides	3,0166E-05	kg
Particulates, > 2.5 um, and < 10um	6,1524E-06	kg
Copper	1,4571E-07	kg
Cadmium	1,4571E-07	kg
Particulates, < 2.5 um	4,0228E-05	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	1,2203E-15	kg
Emissions to water		
TOC, Total Organic Carbon	3,5944E-05	kg
Water, NO	0,00015478	m3
COD, Chemical Oxygen Demand	9,2131E-05	kg
DOC, Dissolved Organic Carbon	3,5944E-05	kg
BOD5, Biological Oxygen Demand	5,9335E-05	kg
Phosphate	2,0312E-08	kg
TOC, Total Organic Carbon	2,5908E-06	kg
COD, Chemical Oxygen Demand	6,9951E-06	kg
Phosphate	3,6241E-08	kg
BOD5, Biological Oxygen Demand	9,4225E-07	kg
DOC, Dissolved Organic Carbon	2,5908E-06	kg
Selenium	2,7575E-07	kg
Fluoride	5,6361E-06	kg
Zinc	1,8455E-06	kg
Cadmium	2,6157E-08	kg
Arsenic	5,9368E-09	kg
Mercury	1,2155E-09	kg
Water, NO	0,03977682	m3

Copper	1,3186E-07	kg
Lead	1,078E-07	kg
Waste to treatment		
Waste mineral oil {RoW}| market for waste mineral oil | Alloc Def, U	0,00756425	kg
Inert waste {RoW}| market for inert waste | Alloc Def, U	0,00346849	kg
Hazardous waste, for underground deposit {GLO}| market for | Alloc Def, U	0,00153545	kg
Wastewater, average {RoW}| market for wastewater, average | Alloc Def, U	0,00403838	m3
Aluminium scrap, new {RoW}| market for | Alloc Def, U	0,00909798	kg
Fly ash and scrubber sludge {RoW}| market for fly ash and scrubber sludge | Alloc Def, U	0,0009274	kg
Hazardous waste, for incineration {RoW}| market for hazardous waste, for incineration | Alloc Def, U	0,0040633	kg
Scrap aluminium {RoW}| market for scrap aluminium | Alloc Def, U	6,4513E-05	kg
Waste emulsion paint, separated {GLO}| market for | Alloc Def, U	4,5949E-06	kg
Spent solvent mixture {RoW}| market for spent solvent mixture | Alloc Def, U	0,00661501	kg

Mooring

Materials/fuels		
Cast iron {GLO}| market for | Alloc Def, U	4250	kg
Aluminium, wrought alloy {GLO}| market for | Alloc Def, U	131,25	kg
Metal working, average for aluminium product manufacturing {GLO}| market for | Alloc Def, U	131,25	kg
Metal working, average for steel product manufacturing {GLO}| market for | Alloc Def, U	4250	kg

125 Seats

Materials/fuels		
Aluminium, primary, liquid {GLO}| market for | Alloc Def, U	1590,116	kg
Steel, low-alloyed {GLO}| market for | Alloc Def, U	919	kg
Synthetic rubber {GLO}| market for | Alloc Def, U	1,2496	kg
Polyurethane, rigid foam {GLO}| market for | Alloc Def, U	112,464	kg

Appendix D- PV inventory

Silica sand [1 kg]

Materials/fuels		
Sand {GLO}| market for | Alloc Def, U	1,04	kg
Electricity/heat		
Heat, district or industrial, other than natural gas {Europe without Switzerland}| market for heat, district or industrial, other than natural gas | Alloc Def, U	0,2	MJ

Solar grade silicon [1kg]

Materials/fuels		
Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U	0,136	tkm
Silica Sand	4,02	kg
Transport, freight, lorry, unspecified {GLO}| market for | Alloc Def, U	0,836	tkm
Wood chips, wet, measured as dry mass {SE}| softwood forestry, pine, sustainable forest management | Alloc Def, U	1,50532276	kg
Petroleum coke {GLO}| market for | Alloc Def, U	0,35039638	kg
Hard coal {RoW}| market for | Alloc Def, U	2,57463194	kg
Propane {GLO}| market for | Alloc Def, U	0,01098528	kg
Silicone factory {GLO}| market for | Alloc Def, U	1E-11	p
Electricity/heat		
Electricity, medium voltage {NO}| market for | Alloc Def, U	47,595017	kWh
Emissions to air		
Arsenic	0,00000048	kg
Lead	2,94E-07	kg
VOC, volatile organic compounds	0,0002718	kg
Cadmium	4,53E-09	kg
Carbon dioxide, biogenic	2,7180068	kg
Carbon dioxide, fossil	9,06002265	kg
Carbon monoxide	0,00951302	kg
Copper	0,0003171	kg
Chromium	0,00000906	kg
Mercury	0,0000861	kg
Dinitrogen monoxide	0,0000974	kg
Methane	0,0003624	kg
Molybdenum	1,02E-07	kg
Nickel	2,88E-07	kg
Nitrogen oxides	0,03488109	kg
PAH, polycyclic aromatic hydrocarbons	0,00385051	kg
Zinc	0,00000109	kg
Sulfur dioxide	0,02423556	kg
Particulates, unspecified	0,0012684	kg

Emissions to water		
Aluminium	0,0000179	kg
Arsenic	7,25E-07	kg
Iron	0,000079	kg
Copper	0,00000442	kg
Chromium	3,62E-07	kg
Nickel	0,00000652	kg
Zinc	9,06E-07	kg
Waste water/m3	0,20794564	m3
Final waste flows		
Hazardous waste, unspecified treatment	0,00051642	kg
Glass waste	0,00017441	kg
Waste, organic	0,02906682	kg
Waste, inorganic	0,93674745	kg
Metal waste	0,01937939	kg
Packaging waste, paper and board	0,00438279	kg
Electronic waste	0,00270442	kg

Silicon ingot [1 kg]

Resources		
Water, river, RER	2,0508	m3
Water, cooling, unspecified natural origin, RER	2,333	m3
Materials/fuels		
Solar Grade Silicon (Elkem Solar)	1,07	kg
Hydrogen fluoride {GLO}| market for | Alloc Def, U	0,050664	kg
Acetone, liquid {GLO}| market for | Alloc Def, U	0,049003	kg
Argon, liquid {GLO}| market for | Alloc Def, U	5,7944	kg
Lime, hydrated, packed {GLO}| market for | Alloc Def, U	0,19103	kg
Ceramic tile {GLO}| market for | Alloc Def, U	0,33645	kg
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Alloc Def, U	0,041528	kg
Nitric acid, without water, in 50% solution state {GLO}| market for | Alloc Def, U	0,094684	kg
Acetic acid, without water, in 98% solution state {GLO}| market for | Alloc Def, U	0,10797	kg
Silicone factory {GLO}| market for | Alloc Def, U	1E-11	p
Tap water {Europe without Switzerland}| market for | Alloc Def, U	94,073	kg
Electricity/heat		
Electricity, medium voltage {DE}| market for | Alloc Def, U	85,6	kWh
Heat, district or industrial, natural gas {Europe without Switzerland}| market for heat, district or industrial, natural gas | Alloc Def, U	68,2	MJ
Emissions to air		
Water/m3	1,22576845	m3
Emissions to water		

DOC, Dissolved Organic Carbon	0,040475	kg
Nitrogen	0,0091039	kg
COD, Chemical Oxygen Demand	0,13034	kg
Water, DE	3,25210455	m3
TOC, Total Organic Carbon	0,040475	kg
Acetic acid	0,053987	kg
BOD5, Biological Oxygen Demand	0,13034	kg
Fluoride	0,0023713	kg
Hydroxide	0,0074169	kg
Hydrocarbons, unspecified	0,022841	kg
Waste to treatment		
Waste, from silicon wafer production, inorganic {GLO}| market for | Alloc Def, U	3,6364	kg

Silicon wafer [1m^2]

Materials/fuels		
Silicon Ingot	0,885	kg
Steel, low-alloyed, hot rolled {GLO}| market for | Alloc Def, U	1,4826	kg
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Alloc Def, U	0,015	kg
Paper, woodfree, coated {RER}| market for | Alloc Def, U	0,19	kg
Silicon carbide {GLO}| market for | Alloc Def, U	2,63	kg
Water, completely softened, from decarbonised water, at user {GLO}| market for | Alloc Def, U	65	kg
Wire drawing, steel {GLO}| market for | Alloc Def, U	1,49	kg
Wafer factory {GLO}| market for | Alloc Def, U	0,000004	p
Glass wool mat {GLO}| market for | Alloc Def, U	0,01	kg
Acetic acid, without water, in 98% solution state {GLO}| market for | Alloc Def, U	0,039	kg
Triethylene glycol {GLO}| market for | Alloc Def, U	2,71	kg
Hydrochloric acid, without water, in 30% solution state {GLO}| tetrafluoroethane production | Alloc Def, U	0,0027	kg
Polystyrene, high impact {GLO}| market for | Alloc Def, U	0,2	kg
Packaging film, low density polyethylene {GLO}| market for | Alloc Def, U	0,1	kg
Alkylbenzene sulfonate, linear, petrochemical {GLO}| market for | Alloc Def, U	0,24	kg
Brass {RoW}| market for brass | Alloc Def, U	0,00745	kg
Acrylic binder, without water, in 34% solution state {GLO}| market for | Alloc Def, U	0,002	kg
Dipropylene glycol monomethyl ether {GLO}| market for | Alloc Def, U	0,3	kg
Tap water {Europe without Switzerland}| market for | Alloc Def, U	0,00598748	kg
Tap water {CH}| market for | Alloc Def, U	0,0000125	kg
Electricity/heat		
Heat, district or industrial, natural gas {Europe without Switzerland}| market for heat, district or industrial, natural gas | Alloc Def, U	4	MJ
Electricity, medium voltage {DE}| market for | Alloc Def, U	8	kWh
Emissions to air		

Water/m3	0,0097509	m3
Emissions to water		
Lead	0,0000303	kg
DOC, Dissolved Organic Carbon	0,011083	kg
Cadmium	0,00000605	kg
AOX, Adsorbable Organic Halogen as Cl	0,00050129	kg
BOD5, Biological Oxygen Demand	0,029555	kg
Mercury	0,00000605	kg
TOC, Total Organic Carbon	0,011083	kg
COD, Chemical Oxygen Demand	0,02955	kg
Chromium	0,0000303	kg
Nickel	0,0000605	kg
Phosphate	0,00050129	kg
Nitrogen	0,0099449	kg
Water, RER	0,0552551	m3
Copper	0,0000605	kg
Waste to treatment		
Waste, from silicon wafer production {GLO}| market for | Alloc Def, U	0,11	kg

PV cell 1 [m^2]

Resources		
Water, cooling, unspecified natural origin, GLO	0,99847386	m3
Materials/fuels		
Silicon Wafer	1,06	m2
Phosphoric acid, fertiliser grade, without water, in 70% solution state {GLO}| market for | Alloc Def, U	0,00767405	kg
Solvent, organic {GLO}| market for | Alloc Def, U	0,00143403	kg
Hydrochloric acid, without water, in 30% solution state {RER}| market for | Alloc Def, U	0,04560889	kg
Metallization paste, back side, aluminium {GLO}| market for | Alloc Def, U	0,07190668	kg
Isopropanol {GLO}| market for | Alloc Def, U	0,07889135	kg
Sodium silicate, spray powder, 80% {GLO}| market for | Alloc Def, U	0,07478254	kg
Hydrogen fluoride {GLO}| market for | Alloc Def, U	0,03772026	kg
Silicone product {GLO}| market for | Alloc Def, U	0,00121214	kg
Argon, liquid {GLO}| market for | Alloc Def, U	0,02568081	kg
Acetic acid, without water, in 98% solution state {GLO}| market for | Alloc Def, U	0,00282697	kg
Nitrogen, liquid {RER}| market for | Alloc Def, U	1,85311437	kg
Nitric acid, without water, in 50% solution state {GLO}| market for | Alloc Def, U	0,02666677	kg
Ethanol, without water, in 99.7% solution state, from ethylene {GLO}| market for | Alloc Def, U	0,000641	kg
Metallization paste, front side {GLO}| market for | Alloc Def, U	0,00739606	kg
Oxygen, liquid {RER}| market for | Alloc Def, U	0,10190529	kg
Phosphoryl chloride {GLO}| market for | Alloc Def, U	0,00159493	kg
Ammonia, liquid {RER}| market for | Alloc Def, U	0,00673869	kg
Metallization paste, front side {GLO}| market for | Alloc Def, U	0,00493077	kg

Calcium chloride {GLO}| market for | Alloc Def, U	0,021572	kg
Titanium dioxide {RER}| market for | Alloc Def, U	0,00000142	kg
Polystyrene, expandable {GLO}| market for | Alloc Def, U	0,0004072	kg
Tetrafluoroethylene {GLO}| market for | Alloc Def, U	0,00315565	kg
Photovoltaic cell factory {GLO}| market for | Alloc Def, U	0,0000004	p
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Alloc Def, U	0,15696275	kg
Water, completely softened, from decarbonised water, at user {GLO}| market for | Alloc Def, U	137,243658	kg
Electricity/heat		
Heat, district or industrial, natural gas {Europe without Switzerland}| market for heat, district or industrial, natural gas | Alloc Def, U	4,77	MJ
Electricity, medium voltage {DE}| market for | Alloc Def, U	30,2	kWh
Heat, district or industrial, other than natural gas {Europe without Switzerland}| market for heat, district or industrial, other than natural gas | Alloc Def, U	1,16	MJ
Emissions to air		
Hydrogen chloride	0,00026626	kg
Silver	0,00077248	kg
Ethane, hexafluoro-, HFC-116	0,0001186	kg
Aluminium	0,00077248	kg
Silicon	0,0000727	kg
Particulates, < 2.5 um	0,00266258	kg
Tin	0,00077248	kg
Hydrogen fluoride	0,00000485	kg
Methane, tetrafluoro-, CFC-14	0,00024762	kg
Nitrogen oxides	0,00005	kg
Sodium	0,0000485	kg
Lead	0,00077248	kg
Water/m3	0,40749517	m3
NMVOC, non-methane volatile organic compounds, unspecified origin	0,19353106	kg
Emissions to water		
Water, RER	0,51089239	m3
Waste to treatment		
Wastewater from PV cell production {GLO}| market for | Alloc Def, U	0,21732996	m3
Waste, from silicon wafer production {GLO}| market for | Alloc Def, U	0,27570726	kg

Appendix E- Battery inventory

One cell

Materials/fuels		
Battery separator {CN}| production | Alloc Def, U	0,0014	kg
Aluminium, wrought alloy {GLO}| aluminium ingot, primary, to market | Alloc Def, U	0,0031	kg
Sheet rolling, aluminium {RoW}| processing | Alloc Def, U	0,0031	kg
Cathode, LiMn2O4, for lithium-ion battery {CN}| production | Alloc Def, U	0,0113	kg
Copper {GLO}| market for | Alloc Def, U	0,0075	kg
Graphite, battery grade {CN}| production | Alloc Def, U	0,0062	kg
Lithium hexafluorophosphate {CN}| production | Alloc Def, U	0,0044	kg
Steel, chromium steel 18/8, hot rolled {RoW}| production | Alloc Def, U	0,0092	kg
Metal working, average for chromium steel product manufacturing {RER}| processing | Alloc Def, U	0,0092	kg
Transport, freight, sea, transoceanic tanker {GLO}| market for | Alloc Def, U	0,74844	tkm
Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Conseq, U	0,04158	tkm

One Module

Materials/fuels		
Aluminium, cast alloy {GLO}| aluminium ingot, primary, to market | Alloc Def, U	0,0232	kg
Aluminium, wrought alloy {GLO}| aluminium ingot, primary, to market | Alloc Def, U	0,0232	kg
Copper {GLO}| market for | Alloc Def, U	0,5283	kg
Metal working, average for copper product manufacturing {RoW}| processing | Alloc Def, S	0,5283	kg
Acrylonitrile-butadiene-styrene copolymer {RER}| production | Alloc Def, U	0,439	kg
Metal working, average for chromium steel product manufacturing {RER}| processing | Conseq, U	0,0279	kg
Steel, low-alloyed {RoW}| steel production, electric, low-alloyed | Alloc Def, U	0,0279	kg
Synthetic rubber {RoW}| production | Alloc Def, U	0,0075	kg
Integrated circuit, memory type {GLO}| production | Alloc Def, U	0,0089	kg
Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U	16,76376	tkm
Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Alloc Def, U	0,93132	tkm

Sub pack

Materials/fuels		
Aluminium, wrought alloy {GLO}| aluminium ingot, primary, to market | Alloc Def, U	5	kg
Metal working, average for aluminium product manufacturing {RoW}| processing | Alloc Def, U	5	kg
Copper, blister-copper {RoW}| production | Alloc Def, U	0,9	kg
Metal working, average for copper product manufacturing {RoW}| processing | Alloc Def, U	0,9	kg
Metal working, average for steel product manufacturing {RoW}| processing | Alloc Def, U	6	kg

Metal working, average for chromium steel product manufacturing {RoW}| processing | Alloc Def, S	6	kg
Powder coat, steel {RoW}| powder coating, steel | Alloc Def, U	1,11315	m2
Acrylonitrile-butadiene-styrene copolymer {RoW}| production | Alloc Def, U	1,2	kg
Transport, freight, sea, transoceanic ship {GLO}| processing | Alloc Def, U	212,22	tkm
Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	11,79	tkm

String

Materials/fuels		
Steel, low-alloyed, hot rolled {RoW}| production | Alloc Def, U	65	kg
Metal working, average for chromium steel product manufacturing {RoW}| processing | Alloc Def, S	65	kg
Transport, freight, sea, transoceanic ship {GLO}| processing | Alloc Def, U	1053	tkm
Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	1053	tkm

Energy consumption for battery manufacturing

Electricity/heat		
Electricity, medium voltage {CN}| market group for | Conseq, U	200	kWh
Electricity, medium voltage {CN}| market group for | Conseq, U	0,00388889	kWh
Electricity, medium voltage {NO}| market for | Alloc Def, U	0	kWh
Electricity, medium voltage {NO}| market for | Alloc Def, U	0	kWh

Appendix F- Results

Scenario 1

Impact category	Total	Others	Production, boat	Operation
Climate change [kg CO2 eq]	1,29E+07	3,06E+04	1,37E+05	1,28E+07
Ozone depletion [kg CFC-11 eq]	2,30E+00	3,04E-03	7,22E-03	2,29E+00
Terrestrial acidification [kg SO2 eq]	1,40E+05	1,44E+02	8,04E+02	1,39E+05
Freshwater eutrophication [kg P eq]	2,32E+03	1,66E+01	8,04E+01	2,22E+03
Marine eutrophication [kg N eq]	8,41E+03	7,50E+00	3,46E+01	8,36E+03
Human toxicity [kg 1,4-DB eq]	1,84E+06	2,89E+04	1,16E+05	1,70E+06
Photochemical oxidant formation [kg NMVOC]	2,25E+05	9,77E+01	5,17E+02	2,24E+05
Particulate matter formation[kg PM10 eq]	8,07E+04	9,16E+01	3,83E+02	8,02E+04
Terrestrial ecotoxicity [kg 1,4-DB eq]	3,62E+02	4,96E+00	3,60E+01	3,21E+02
Freshwater ecotoxicity [kg 1,4-DB eq]	3,81E+04	1,40E+03	2,83E+03	3,39E+04
Marine ecotoxicity [kg 1,4-DB eq]	3,87E+04	1,29E+03	2,75E+03	3,46E+04
Ionising radiation [kBq U235 eq]	5,59E+05	5,26E+03	4,50E+03	5,49E+05
Agricultural land occupation [m2]	1,72E+06	4,51E+03	5,91E+03	1,71E+06
Urban land occupation [m2]	3,32E+04	4,13E+02	1,32E+03	3,15E+04
Natural land transformation [m2]	4,72E+03	8,93E+00	1,53E+01	4,70E+03
Water depletion [m3]	7,14E+04	9,90E+03	2,26E+03	5,92E+04
Metal depletion [kg Fe eq]	1,90E+05	9,80E+03	4,20E+04	1,39E+05
Fossil depletion [kg oil eq]	4,53E+06	7,30E+03	3,05E+04	4,49E+06

Scenario 2

Impact category	Total	Others	Production, battery	Operation	Production, boat
Climate change [kg CO2 eq]	1,95E+06	5,15E+04	7,57E+05	7,54E+05	3,89E+05
Ozone depletion [kg CFC-11 eq]	3,06E-01	1,15E-02	5,36E-02	1,09E-01	1,32E-01
Terrestrial acidification [kg SO2 eq]	1,45E+04	5,18E+02	5,09E+03	2,45E+03	6,46E+03
Freshwater eutrophication [kg P eq]	2,27E+03	1,02E+02	5,79E+02	2,53E+02	1,33E+03
Marine eutrophication [kg N eq]	7,48E+02	2,99E+01	2,19E+02	1,24E+02	3,75E+02
Human toxicity [kg 1,4-DB eq]	4,47E+06	2,15E+05	1,05E+06	3,49E+05	2,85E+06
Photochemical oxidant formation [kg NMVOC]	6,74E+03	2,32E+02	2,54E+03	1,74E+03	2,24E+03
Particulate matter formation[kg PM10 eq]	6,31E+03	2,44E+02	2,28E+03	1,42E+03	2,37E+03
Terrestrial ecotoxicity [kg 1,4-DB eq]	4,73E+02	2,01E+01	1,14E+02	8,50E+01	2,54E+02
Freshwater ecotoxicity [kg 1,4-DB eq]	1,35E+05	4,53E+03	2,18E+04	6,22E+04	4,69E+04
Marine ecotoxicity [kg 1,4-DB eq]	1,31E+05	4,57E+03	2,23E+04	5,44E+04	4,94E+04
Ionising radiation [kBq U235 eq]	3,59E+05	9,81E+03	3,27E+04	2,72E+05	4,47E+04
Agricultural land occupation [m2]	3,17E+05	8,34E+03	2,68E+04	2,44E+05	3,74E+04
Urban land occupation [m2]	2,55E+04	9,45E+02	9,29E+03	7,10E+03	8,21E+03
Natural land transformation [m2]	5,45E+02	1,30E+01	6,84E+01	3,94E+02	6,93E+01
Water depletion [m3]	7,08E+05	1,02E+04	3,92E+03	6,87E+05	6,55E+03
Metal depletion [kg Fe eq]	1,10E+06	5,46E+04	3,82E+05	1,02E+05	5,66E+05
Fossil depletion [kg oil eq]	4,64E+05	1,26E+04	1,67E+05	1,86E+05	9,89E+04

Scenario 3

Impact category	Total	Others	Production, boat	Production, battery	Operation	PVs
Climate change [kg CO2 eq]	2,25E+06	5,15E+04	3,89E+05	9,98E+05	7,17E+05	9,03E+04
Ozone depletion [kg CFC-11 eq]	3,43E-01	1,15E-02	1,32E-01	7,23E-02	1,03E-01	2,35E-02
Terrestrial acidification [kg SO2 eq]	1,63E+04	5,18E+02	6,46E+03	6,76E+03	2,33E+03	2,84E+02
Freshwater eutrophication [kg P eq]	2,54E+03	1,02E+02	1,33E+03	7,78E+02	2,40E+02	8,73E+01
Marine eutrophication [kg N eq]	8,68E+02	2,99E+01	3,75E+02	2,93E+02	1,18E+02	5,19E+01
Human toxicity [kg 1,4-DB eq]	4,93E+06	2,15E+05	2,85E+06	1,42E+06	3,32E+05	1,18E+05
Photochemical oxidant formation [kg NMVOC]	7,78E+03	2,32E+02	2,24E+03	3,36E+03	1,65E+03	3,07E+02
Particulate matter formation[kg PM10 eq]	7,12E+03	2,44E+02	2,37E+03	3,02E+03	1,35E+03	1,41E+02
Terrestrial ecotoxicity [kg 1,4-DB eq]	8,15E+02	2,01E+01	2,54E+02	1,54E+02	8,08E+01	3,06E+02
Freshwater ecotoxicity [kg 1,4-DB eq]	1,42E+05	4,53E+03	4,69E+04	2,93E+04	5,92E+04	1,98E+03
Marine ecotoxicity [kg 1,4-DB eq]	1,39E+05	4,57E+03	4,94E+04	3,00E+04	5,18E+04	2,74E+03
Ionising radiation [kBq U235 eq]	3,71E+05	9,81E+03	4,47E+04	4,37E+04	2,59E+05	1,41E+04
Agricultural land occupation [m2]	3,24E+05	8,34E+03	3,74E+04	3,57E+04	2,32E+05	1,07E+04
Urban land occupation [m2]	2,90E+04	9,45E+02	8,21E+03	1,23E+04	6,76E+03	7,41E+02
Natural land transformation [m2]	5,59E+02	1,30E+01	6,93E+01	9,13E+01	3,75E+02	9,89E+00
Water depletion [m3]	6,78E+05	1,02E+04	6,55E+03	5,25E+03	6,54E+05	2,44E+03
Metal depletion [kg Fe eq]	1,24E+06	5,46E+04	5,66E+05	5,16E+05	9,68E+04	1,20E+04
Fossil depletion [kg oil eq]	5,32E+05	1,26E+04	9,89E+04	2,20E+05	1,77E+05	2,34E+04

Scenario 4

Impact category	Total	Others	Production, boat	Production, battery	Operation
Climate change [kg CO2 eq]	2,93E+06	5,15E+04	3,89E+05	1,71E+06	7,86E+05
Ozone depletion [kg CFC-11 eq]	4,10E-01	1,15E-02	1,32E-01	1,53E-01	1,13E-01
Terrestrial acidification [kg SO2 eq]	2,20E+04	5,18E+02	6,46E+03	1,25E+04	2,55E+03
Freshwater eutrophication [kg P eq]	3,31E+03	1,02E+02	1,33E+03	1,61E+03	2,63E+02
Marine eutrophication [kg N eq]	1,11E+03	2,99E+01	3,75E+02	5,73E+02	1,29E+02
Human toxicity [kg 1,4-DB eq]	6,42E+06	2,15E+05	2,85E+06	3,00E+06	3,64E+05
Photochemical oxidant formation [kg NMVOC]	1,03E+04	2,32E+02	2,24E+03	6,00E+03	1,81E+03
Particulate matter formation[kg PM10 eq]	9,66E+03	2,44E+02	2,37E+03	5,57E+03	1,48E+03
Terrestrial ecotoxicity [kg 1,4-DB eq]	6,88E+02	2,01E+01	2,54E+02	3,26E+02	8,85E+01
Freshwater ecotoxicity [kg 1,4-DB eq]	1,77E+05	4,53E+03	4,69E+04	6,08E+04	6,49E+04
Marine ecotoxicity [kg 1,4-DB eq]	1,73E+05	4,57E+03	4,94E+04	6,24E+04	5,67E+04
Ionising radiation [kBq U235 eq]	4,25E+05	9,81E+03	4,47E+04	8,72E+04	2,83E+05
Agricultural land occupation [m2]	3,68E+05	8,34E+03	3,74E+04	6,80E+04	2,54E+05
Urban land occupation [m2]	3,94E+04	9,45E+02	8,21E+03	2,28E+04	7,40E+03
Natural land transformation [m2]	6,71E+02	1,30E+01	6,93E+01	1,78E+02	4,11E+02
Water depletion [m3]	7,43E+05	1,02E+04	6,55E+03	1,05E+04	7,16E+05
Metal depletion [kg Fe eq]	1,83E+06	5,46E+04	5,66E+05	1,10E+06	1,06E+05
Fossil depletion [kg oil eq]	6,92E+05	1,26E+04	9,89E+04	3,87E+05	1,93E+05

GWP analysis of battery

Groups	*Amount [kg CO_2]*
Total	230006,962
Cell	44158,71904
Module	12718,83329
String	7712,374828
Sub pack	18788,18796
Energy, battery manufacture	146628,8468

GWP analysis of one battery cell

Groups	*Amount [kg CO_2]*
Total	0,44229486
Separator	0,006399789
Aluminium	0,054690395
Sheet rolling, aluminium	0,002125138
Cathode, $LiMn_2O_4$	0,115643653
Copper	0,052897336
Graphite	0,012126946
Lithium hexafluorphosphate	0,125392514
Steel	0,041701756
Metal working	0,023076953
Transport, sea	0,004394634
Transport, lorry	0,003845745

GWP analysis of the drivetrain

Groups	*Amount [kg CO_2]*
Total	234336,651
Converter	102070,062
Transformer	126408,43
Cables	5858,15844

GWP analysis of one transformer

Groups	*Amount [kg CO_2]*
Total	42136,1433
Powder coat, steel	112,1748348
Copper	21582,1129
Metal working, copper	9426,161789
Cast iron	3401,67965
Epoxy resin insulator, Al2O3	6777,55797
Electricity, medium voltage {NO}	153,6517665
Heat	682,804395

Battery production with Norwegian and Chinese energy mix

		Numbers	
Scenario 2			
	Norwegian	1,40E+06	kg
	Chinese	1,83E+06	kg
Scenario 3			
	Norwegian	1,54E+06	kg
	Chinese	2,10E+06	kg
Scenario 4			
	Norwegian	1,92E+06	kg
	Chinese	2,73E+06	kg