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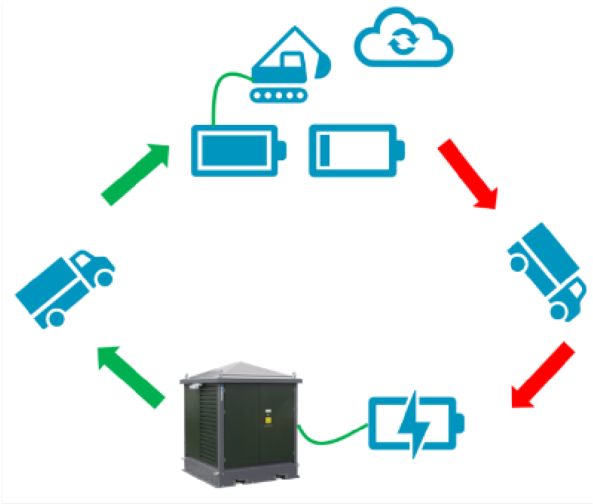
Energy and Environmental Technology

Life Cycle Assessment of Mobile Batteries for Emission-Free Construction Sites



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Summary:

Nowadays, due to increasing demand for energy and limited availability, there has been an increased focus on developing emission-free construction sites. To address this issue, life cycle assessment (LCA) is used as a useful tool in different fields to assess energy requirements and emissions throughout the life cycle of products.

The objective of this study is to present LCA for Skagerak battery, with a focus on the Global Warming Potential (GWP) as an impact category. In order to supply energy to construction equipment, the project involves transporting fully charged batteries from a charging station to the construction site. When the batteries are depleted, fully charged batteries are transported by a truck to replace them. For this pilot project, Skagerak Energi is providing two charging platforms, one bidirectional platform, and four mobile battery containers totaling 576 kWh, all using CCS type 2 charging cables.

In the production phase, the study estimates the GWP and energy consumption related to battery production based on information from different research papers, and then the GWP of transportation to the Skagerak company by using Skagerak's data is presented. NMC 111 is used as the mobile battery in this project, so the relevant literature is reviewed to provide an overview of the production step for this battery.

This study's next step is estimating the energy loss due to energy conversion and transportation required for charging the battery. The GWP for these steps is presented. Skagerak uses biogas for transportation in order to charge the battery; the GWP of different biogases is presented, and then the differences between diesel and biogas are covered. The specification of the Samsung SDI battery has been used to estimate energy loss for the battery used on the construction site.

Preface

The Master Thesis titled “Life cycle assessment of mobile batteries for emission-free construction sites” was done by the master’s student from Energy and Environmental Technology as a part of FMH606 Master's Thesis, 2023 at the University of South-Eastern Norway (USN), Porsgrunn.

The main objective of this study is to present a life cycle assessment (LCA) for the mobile batteries used in Skagerak’s pilot project “Mobile energy to emission-free construction sites.”

The project focused on both the production and use phases. Production phase included analyzing energy use for different stages of battery production, as well as transportation to Skagerak company. Regarding production, the data and tables of related research papers have been used, and for transportation information was provided by Skagerak. Use phase included studying energy loss due to energy conversion, and data was extracted from related research papers. Global Warming Potential as an impact factor was estimated for both the production and use phases.

I would like to express my sincere gratitude to my supervisor, Elin Fjeld , for her supervision, expert guidance, helpful insights, and her support during the work on this thesis. Her expertise, patience, and encouragement have been instrumental in shaping my research. I would like to thank my co-supervisor Marianne S. Eikeland for her collaboration in my thesis. I would also like to thank Skagerak Energi, the external partner, for providing me with information and guidance.

Porsgrunn, 15.05.2023

Safa Khodabakhsh

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Nomenclature

LCA— Life Cycle Assessment

CO_2— Carbon dioxide

N_2O—Nitrous oxide

CH_4—Methane

SSB—Statistics Norway

NMC— Nickel-Manganese-Cobalt

GWP— Global Warming Potential

SOC— State of Charge

DOD— Depth of Discharge

SOH— State of Health

$LiCoO_2$— Lithium Cobalt Oxide

$LiMn_2O_4$— Lithium Manganese Oxide

LFP— Lithium Iron Phosphate

NCA— Lithium Nickel Cobalt Aluminum Oxide

CTG—cradle-to-grave

CTC—cradle-to-cradle

LCT—life cycle Thinking

ILCD—Life Cycle Data System

LCI—life cycle inventory

LCIA— life cycle impact assessment

ADP—Abiotic Depletion Potential

POP—Photochemical Ozone Creation Potential

AP—Acidification Potential

GHG—Greenhouse Gas

BOL—Beginning of Life

PGMs—Platinum Group Metals

ROW—Rest of the World

RER—Rest of Europe Region

GLO—Global

GTP—Global Temperature Potential

TFEC—Total Final Energy Consumption

TTW—Tank-to-wheel
DF—Dual-Fuel
SI—Spark-Ignited
CBG— Compressed Biogas
CNG— Compressed Natural Gas
LBG— Liquefied Biogas
LNG— Liquefied Natural Gas
AD—Anaerobic Digestion
TG—Thermal Gasification

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1 Introduction

The construction industry in Norway is a major source of CO_2 emissions. Electrification is a possible option, but limited access to power grids on construction sites can slow development and limit progress. Skagerak Energi has begun a pilot project using mobile battery containers to provide power construction equipment to overcome this issue. Nevertheless, Batteries have effects on the environment which should be evaluated. The objective of this study is to conduct a life cycle assessment (LCA) of mobile batteries used on construction sites to identify and highlight factors with the highest environmental impact and propose solutions to reduce them.

1.1 Background

Construction activities in Norway accounted for direct emissions of approximately 2 million tons of CO_2 in 2019 (SSB). Electrification of the sector is desirable to reduce these emissions. To realize a fossil-free construction site, access to sufficient electrical energy and power is required. On many of the construction sites, access to electric power from the power grid is limited. Expanding the power grid on these sites in connection with the construction process is often not very appropriate, as there is often no need for this upgrade after the construction process has been completed.

To meet the electrical energy needs during construction without upgrading the local power grid, mobile battery technology might be a solution. The batteries are charged at a location where the grid has good capacity and driven to the relevant construction site to supply battery-powered construction machines. Skagerak Energi has started a pilot project where mobile battery containers are used in the electrification of a construction site in Skien, University of South-Eastern Norway is a research partner in the project.

The use of batteries should reduce the CO_2 emissions from the construction site. However, the production and use of batteries also represent environmental impacts. To assess the gain and possibly improve the environmental footprint further, a life cycle assessment of mobile batteries.

1.2 Previous Work

In 2020, a cradle-to-grave Life Cycle Inventory (LCA) of NMC battery production showed that the production phase has the highest environmental impact. As a result, focusing on battery technology for construction sites has become more important, especially since reducing emissions from construction projects is the center of attention. Municipal programs in Oslo are already concentrating on changing to electric (zero emission) construction technology, but there are some limitations on the use of electrification on construction sites.[1], [2]

In June 2020, Skagerak submitted a funding request for a pilot project aimed at providing energy for free-emission construction sites. In 2022, Skagerak received the equipment and started internal system testing. Later that year, Skagerak Energi began their first trial project for mobile batteries.[3]

In 2021, one research paper[1] presented the Life Cycle Assessment for a Nickel-Manganese-Cobalt (NMC) Lithium-ion battery used for Electric Light-Duty Commercial Vehicles. The results indicated that the production of NMC111battery has the highest impacts factor.

Many projects and theses focusing on mobile batteries have been completed in collaboration with USN university and Skagerak.

One of the results is that using battery technology and renewable energy sources in construction projects could significantly reduce environmental impact. This project showed that that using renewable energy can decrease greenhouse emissions effectively by about 40%.[4]

1.3 Objectives

The main objective of this study is to perform a simplified LCA for the mobile batteries used in Skagerak’s pilot project. It was planned to present a detailed LCA of the Skagerak’s battery, but as real data were not accessible, the plan changed to present simplified LCA both for production and use phases.

First LCA of the production phase is presented, including energy use for cathode production, battery assembly, and then transportation to Skagerak company. NMC 111 is used as the mobile battery in this project, so the relevant literature is reviewed to provide an overview of the production step.

Also, the use phase is assessed including analyzing energy loss due to energy conversion and transportation required for charging the battery. Global Warming Potential (GWP) as an impact factor is calculated for both production stage and use phase. According to Skagerak, this company uses biogas for transportation to charge the battery; the GWP of biogases is estimated, and then the differences between diesel and biogas is covered. To estimate energy loss for the battery used on the construction site, the specification of the Samsung SDI battery has been used. Finally, the factors that give the highest contribution to mobile batteries environmental impact is identified.

1.4 Methods

As the battery is NMC 111, the relevant literature is reviewed to provide an overview of the production step for the mobile battery which is used to supply power for a construction site. Firstly, the energy consumption for the production stage of the battery is estimated using research papers, followed by an evaluation of global warming potential associated with the production phase. Battery containers and charging containers will not be considered. Then the energy consumption during transportation based on the information provided by Skagerak is reviewed. Next, inputs for the use phase of the battery is estimated by reviewing literature. Then, a comparison of different transportation alternatives is presented, which involves analyzing the energy consumption of diesel and biogas vehicles, as well as comparing different types of biogas vehicles.

1.5 Scope

The scope of this project includes the lifecycle assessment of the NMC-111 battery. The studied steps are as follows:

Production steps includes several steps, like the production of battery and battery assembly,relevant research papers are used to estimate the energy consumption during priduction and then transportation from production site to Skagerak company by using Skagerak’s data is presented.

The use phase depends on the energy used for producing electricity, so energy mix can be different geographically. Since there is no specific data on using the Skagerak battery for a construction site, the specification of the Samsung SDI battery has been used to estimate energy loss for the battery used on the construction site, also some assumptions are considering which are expressed in chapter six.

1.6 Limitation

Access to real data to define the exact life cycle assessment regarding Skagerak’s battery was not possible, also defining different steps like products and processes were impossible, therefore, openLCA was not used. The information for the production stage has been extracted from research papers.

Since the energy used to produce electricity, known as the energy mix, can be impacted by location, GWP calculations for the use phase cannot be precise and accurate. Therefore, in many projects, LCA is defined to only examine the production step. To estimate energy loss for the battery used in the construction site, specification of Samsung SDI battery has been used and some assumption has been considered, these assumptions will be presented in the chapter six.

2 Battery Technology

In the past few decades, battery technology has developed, resulting in the development of high-performance batteries that power a variety of devices. As NMC is categorized as a Li-ion battery, first this kind of battery is introduced, then different types of Li-ions are reviewed, and finally NMC specifications are presented.

Before introducing Lithium-ion batteries, it is necessary to present guidance to understand battery specifications.

2.1 Basic Knowledge of Battery

2.1.1 Battery pack and Battery cell

Battery pack refers to the whole energy storage and its smallest part is called battery cell, which can hold energy itself. One battery pack consists of desired number of cells. A negative electrode, a positive electrode, an electrolyte, and a separator are common components of Lithium battery cell.[5], [6]

2.1.2 Anode, Cathode and electrolyte

In a battery, the cathode is the positive electrode which absorbs the electron and anode is known as negative electrode which is released electrons during discharge.[7]

According to [8] the positive electrode for NMC battery is Li(Ni0.33Co0.33Co0.33)O2 and Negative electrode is graphite.

The electrolyte in NMC can be found liquid, polymer or solid and it facilitates ions transport between anode and cathode.[9]

2.2 Battery Condition

Some of the important parameters are explained which are used later in chapter 6.

2.2.1 State of Charge (SOC) (%)

State of charge indicates the remaining charge of the battery, this parameter can be from 0% to 100%.When SOC is 100% , it means that the cell is fully charged , while a SOC of 0% shows the cell is fully discharged.[10]

2.2.2 Depth of Discharge (DOD) (%)

The percentage of battery capacity that has been discharged. This term is defined as a percentage of maximum capacity. DOD shows the percentage of the battery that is discharged related to overall battery capacity.[11], [12]

2.2.3 State of Health (SOH) (%)

A battery with an 80% SOH has lost 20% of its original capacity or ability to hold a charge.[11], [12]

2.3 Battery Technical Specifications

This section describes two technical specifications for batteries, which are used later in Chapter 6.

• Cycle Life (number for a specific DOD)

Cycle life refers to the number of discharge-charge cycles that a battery can experience before considering that its useful life is ended. Cycle life is calculated for specific charge and discharge conditions. The rate and depth of cycles can impact the actual life of the battery and other conditions such as temperature and humidity can influence the battery's actual life.[13]

- C-rates

C-rates is a measure to show the charge and discharge rate of one battery in relation to its capacity. This rate can be calculated by dividing charge or discharge current of battery(Ampere) by its capacity which is measured in ampere-hours.[13]

2.4 Lithium-ion Battery

A Li-ion battery is categorized as a secondary or rechargeable battery. They consist of cells in which lithium ions transfer from the anode to the cathode through an electrolyte during discharge and they move back during charging.

The cathode is composed of a composite material (an intercalated lithium compound) and the name of the Li-ion battery is based on that. Typically, the anode is made of porous lithiated graphite. The electrolyte can be found in liquid, polymer, or solid. The separator's porous design limits thermal runaway.

2.4.1 Types of Lithium-ion Batteries

Various lithium-ion battery types are classified according to cathode materials. The cathode is composed of a composite material (a lithium compound with intercalation). There are two types of electrodes: intercalation electrodes and conversion electrodes. Intercalation electrodes are materials that can conduct lithium ions into their host structure reversibly. Metal oxides are the most common intercalation electrodes materials like $LiCoO_2$, $LiMn_2O_4$, and $LiFePO_4$. Conversion electrodes interact chemically with lithium ions to generate a new compound during the charging and discharging cycle. Metal fluorides such as FeF_3, CuF_2, and CoF_2 are the most common conversion electrode materials.

$LiCoO_2$ is the most used cathode material as they are stable, but its capacity is lower than other nickel-cobalt-aluminum (NCA) oxides. The high price of cobalt compared to other transition metals, such as manganese and iron is a disadvantage for using it. [14], [15]

2.4.1.1 Lithium Manganese Oxide ($LiMn_2O_4$)

$LiMn_2O_4$ is a cathode material with a cubic spinel structure. These combinations are cheaper than other materials so there is a lot of research on manganese oxide-based cathodes.

2.4.1.2 Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) – NMC

NMC is a combination of nickel, manganese, and cobalt. As these combinations for Li-ion systems can be customized to use as power or energy cells, it is one of the most successful cathodes. As Skagerak's battery is NMC, specific information is provided in 2.5

2.4.1.3 Lithium Iron Phosphate ($LiFePO_4$) – LFP

One of the newest and latest cathode materials is $LiFePO_4$. Low price, low energy density, high safety and high life cycles make these batteries like a competitor and alternative to Nickel Manganese Cobalt batteries (NMC). LFP batteries are being used in a variety of applications, including automotive use, utility-scale stationary applications, and backup power are the applications that can use this type of battery.

2.4.1.4 Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$) – NCA

Lithium nickel cobalt aluminum oxide battery or NCAA is like the NMC. In comparison to other materials such as $LiCoO_2$, $LiFePO_4$, and NMC 333, NCA has a higher capacity. But there are some disadvantages like high prices and the shortage of cobalt and nickel.[16]

2.5 Li NMC Battery

Every year, lithium battery technology progresses. The safety of using such products can be considerably improved by introducing new substances to stabilize the chemical process. Also, modern technologies in the field of production of rechargeable power supplies help to enhance the power of one element, which reduces the size and mass of assemblies from these kinds of batteries. This battery has a unique ratio per kilo, which means that this battery can store a high amount of energy in comparison to other types of batteries.

NMC battery is categorized as a rechargeable battery. This battery contains a complex alloy of nickel, manganese, and cobalt. The combination of these metals is used to create the battery cathode, which significantly enhances the power of the power source. A very impressive advantage of this battery is its high cell voltage and high energy density.[16], [17]

2.5.1 Common Types of NMC

Batteries with NMC chemistry are the most used in the automotive sector. Due to the high energy density of these kinds of batteries, they can store a large amount of energy with a low weight and volume.

There are various types of NMC chemistry:

- NMC 111 (Nickel 33.3% – Manganese 33.3% – Cobalt 33.3%)
- NMC 622 (Nickel 60% – Manganese 20% – Cobalt 20%)
- NMC 811 (Nickel 80% – Manganese 10% – Cobalt 10%)

Picture Figure 2.1 shows different types of NMC chemistry.

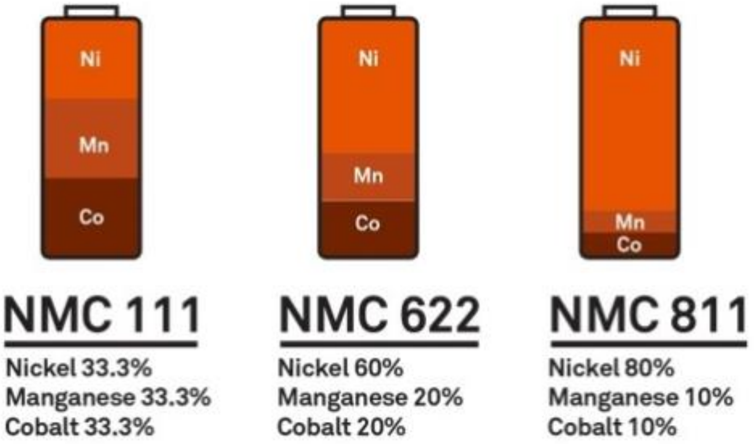


Figure 2.1: Different Chemistries of NMC[18]

As can be seen in the picture above, there are three types of NMC showing different percentages of the materials used for the cathode.

The oldest combination is NMC 111 and the most common is NMC 622, but NMC 811 is known as the newest. Due to high nickel concentration and a very low manganese and cobalt content, NMC 811 is an alternative with higher energy density but cheaper than other types of NMC.[18]

There are many attempts to reduce the percentage of Cobalt in NMC batteries, economic and safety and societal issues are the most important reasons for this effort, but this is still in a laborious process as cobalt can make the battery more stable and it can help to increase the life cycle. Up to 20% of the weight of the cathode in lithium ion EV batteries can be made of Cobalt.[19]

Some companies like Svolt are working and experimenting with new technologies to reduce the amount of Cobalt. This Chinese company recently presented the first NMX cell, completely free of cobalt. They announced two sizes of NMX (115 Ah and 226 Ah) they made of 75 percent nickel and 25 percent manganese. As they are totally free of Cobalt, and the amount of the nickel is low, they are about five percent cheaper than common NMC battery cells , but they are not much more sustainable.[20]

2.5.2 Specification of commercial NMC batteries

Table 2.1 shows characteristics of commercial NMC battery. As can be seen in table below , positive electrode is $Li(Ni0.33Co0.33Co0.33)O_2$ and negative electrode is graphite.

Table 2.1: Characteristics of Commercial NMC Battery [8]

Battery Name	Lithium nickel manganese cobalt oxide(NMC)
Positive electrode	$Li(Ni0.33Co0.33Co0.33)O_2$
Negative electrode	Graphite
Charge(C)	0.7~1
Discharge (C)	1

3 Skagerak's Project

3.1 Background

Nowadays, many efforts have been made to develop free-emission construction sites. To achieve this goal, lots of research focused on finding ways to provide required power without relying on fossil fuels.

Accessing enough renewable energy sources to power construction sites and discovering sustainable solutions are the most important challenges. Energy storage, distribution, and management should be considered to accept and perform new development.

To make sure that the project is free of emission, Skagerak offers a wide range of services related to construction projects.

The budget for Skagerak's pilot project is around NOK 33 million, with NOK 13 million in support from Enova and NOK 20 million is provide by the company. Some changes happened because of the ban on oil burners in construction sites, therefore today the importance of greenhouse gas emissions in construction processes is rather than building operation. Direct emissions from construction activities in Norway is around 2 million tons of CO2 in 2019, according to SSB.

The Norwegian government has a goal to obtain fossil-free transportation industry by 2025. Electrification will play a vital role in the construction industry in the future. Since the power grid has limited capacity, battery technology will become important.

There are several challenges to replace battery technology instead of old technologies. Providing enough energy for machinery and equipment is the first challenge. Then, many builders and contractors are not interested in replacing electrification. The implementation of new energy solutions on construction sites is one of the most important challenges.

Skagerak Energi has been working on this concept since winter of 2019.However, in June 2020, Skagerak applied for support for their pilot project titled "Mobil Energy for Fossil-Free Construction Sites". At first the scope was larger. Enova asked Skagerak to reduce the pilot project's scope. After reducing the scope according to Enova's request, Enova granted Skagerak a grant of up to NOK 13,000,000 from the Climate and Energy Fund in December 2020. The support is for a pilot project lasting 3 years (2021-2024) and for construction projects only in Grenland. It includes 4 mobile battery containers, 2 mobile charging skids, and 2 charging stations.[3]

3.2 Pilot Project

The concept is to transport fully charged batteries from a charging station to a construction site, where they can provide required power for construction equipment. When the construction machines are fully charged and the mobile battery is depleted, a fully charged truck arrives at the site. The depleted used battery is transported to the nearest charging station, while the new fully charged battery is moved to the construction site.

The charging of these batteries takes place in areas where the distribution network has sufficient capacity, such as Vallermyrene, Rødmyr, Menstad, and Nenset in Grenland, which have a capacity of 1250 kVA. [3]

3.2.1 Skagerak's Mobile Battery Project

The idea is transporting a container packed with batteries to a specific location, where they are continuously charged to power devices. For providing the power, the container is connected to the equipment.

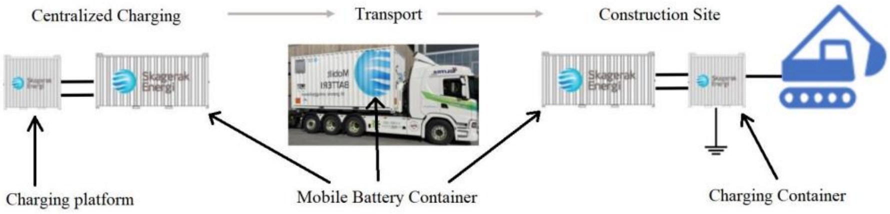


Figure 3.1: Different Steps of Charging the Mobile Battery[21]

For this pilot project, Skagerak Energi is providing two charging platforms, one bidirectional platform, and four mobile battery containers totaling 576 kWh. The whole system uses combined charging system (CCS) type 2 charging cables for each connecting component to guarantee compliance. The industry standard for charging electric vehicles in Europe is the CCS type 2 charging cable, which has a 360-kW capacity. Figure 3.2 shows the system's design and layout.[17], [21]

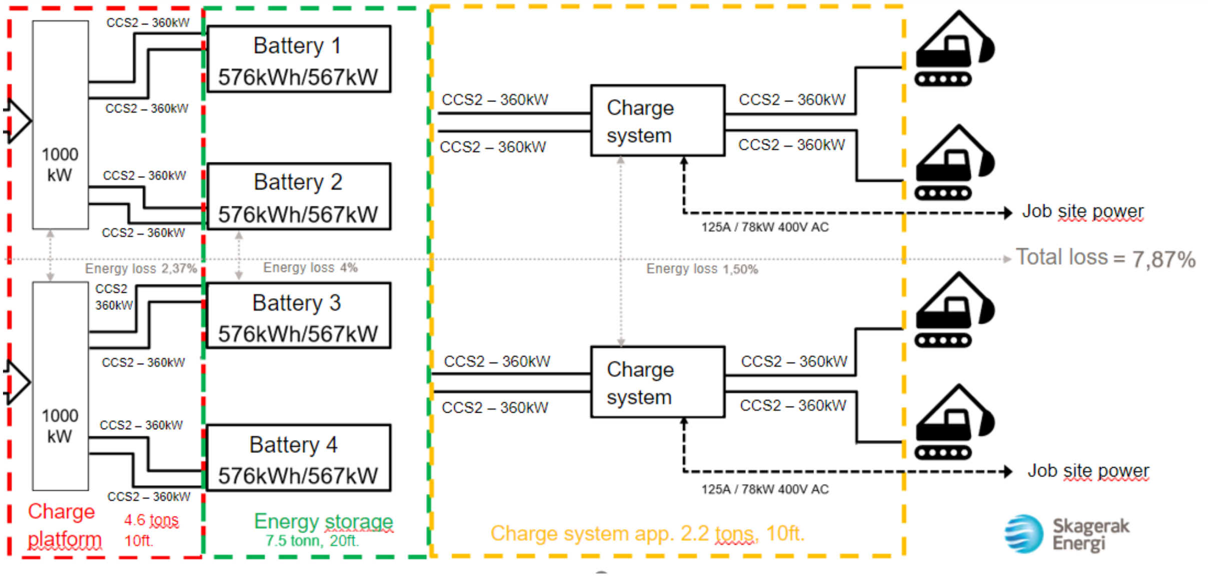


Figure 3.2: Overview of The System [22]

3.2.2 Battery Container

The battery container is made up of two battery racks. Each of them includes battery cells arranged to provide a system voltage of 600V DC with a total capacity of 576 kWh, where each rack has the capacity of 288 kWh. The battery container is charged by two CCS type 2 cables where each cable is connected to one of the battery racks.[21]

3.2.3 Charging Container

The charging container is installed with an intractable screen showing what's connected to the battery, charging time and the time left before the machine is fully charged. The charging container has 4 CCS type 2 charging cables. Two for connecting to the battery and two for charging construction machines.[17], [21]

3.2.4 Estimating CO_2 emissions for the operation machinery of typical construction site

The use of construction machinery can be different for different construction projects. Therefore, energy use and emissions from construction machinery can be significantly affected by the complexity of the project. Table 3.2 shows the diesel consumption of construction machinery, which is related to a typical construction site, the specification of the construction site can be seen in Table 3.1.[23]

As shown in Table 3.2,the excavator has the highest energy demand electricity with 150 MWh, resulting in 130 tons CO_2 emissions. The total amount of electrical energy required for all equipment, including excavator, mobile crane and diverse small machines is 280MWh.[23]

Table 3.1:Specification of typical construction site [23]

Parameters	
Type of Building	School
Area	7415 m^2, scaled up to 10,000 m^2
Engine Type	Steg IIIA
Energy carrier	Mineral diesel
Efficiency	30%

Table 3.2:Required energy and Emission caused by construction machinery.[23]

Type	Number	Duration	Consumption Diesel	Energy Demand Electricity	CO_2e	NOx
Excavator(30tons)	3	11 months	51700 liter	150 MWh	130 tons	2010 kg
Mobile Crane (60 tons)	1	1600 hours	32800 liter	100MWh	30tons	440kg
Diverse Small Machines	-	-	9700 liter	30MWh	90tons	270kg
Total			91500 liter	280 MWh	240 tons	3730

The daily energy demand (Electricity) for an excavator (30tons) is 250 kWh, and if we calculate the energy demand of this equipment for one year, excluding vacations (200 days),it would be 50MWh.[23]

4 Overview of Life Cycle Assessment

The increasing demand for energy, coupled with limited availability, makes energy conservation a crucial issue. Researchers have extensively studied this matter, and life cycle assessment (LCA) has emerged as a useful tool in various fields for evaluating energy requirements and emissions throughout the life cycle of products. This chapter provides an overview of general information of LCA and the definition of different impact factors. Global warming potential as an impact factor is chosen to be assessed, so this chapter includes general information regarding this impact factor. Lastly, life cycle assessment of a Samsung battery is presented as an example.

4.1 Importance and Definition of LCA

Life cycle assessment (LCA) has become massively important, not only among academics but also among industry stakeholders. This method considers every stage of production, from the collection of raw materials to manufacturing processes, energy and water consumption, waste, and emissions related to transportation. The possibility of recycling all or a part of the product is one of the disposal options that is finally considered. These last considerations represent the cradle-to-grave (CTG) and cradle-to-cradle (CTC) approaches to product impact.

Cradle-to-grave (CTG) method includes assessing a product's whole life cycle up to disposal. It causes increasing producers' awareness of their resource consumption and encourages the implementation of life cycle thinking (LCT) to reduce waste. The cradle-to-cradle (CTC) proposes that products at the end of their life cycle should be converted into raw materials in order to produce products of higher quality. This method of using LCT promotes recycling techniques that have recently been developed and improved in a wide range of industries.

The International Organization for Standardization (ISO) has established protocols for conducting comprehensive and credible LCA research. ISO 14040 and ISO 14044 serve as the foundation for the International Reference Life Cycle Data System (ILCD). It offers technical guidance for conducting accurate LCAs that take into account specific product criteria.
ISO 14040 and ISO 14044 provide instructions for carrying out thorough and reliable LCA research, which have four interdependent phases. These stages should not be considered complete until the entire study is finished. The four phases are as follows:

- goal and scope;
- life cycle inventory (LCI);
- life cycle impact assessment (LCIA);
- interpretation.

In the goal and scope stage, which is the first step, the intended application and audience should be defined. Also, it’s important if the purpose of the study and its results will be used for a comparative study that will be published to the public. By concentrating on the investigation's basis, this step is essential to save time in the following steps.

To provide a real inventory of all the flows involved in a product or process' life cycle, including raw materials, energy and water requirements, atmospheric emissions, and resource consumption, data is collected during the LCI phase through input and output analysis. Sankey diagrams are frequently used to demonstrate this process.

After collecting data through input and output analysis, the life cycle inventory (LCI) is created by considering all the raw materials, energy and water requirements, atmospheric emissions, and resource usage involved in a product or process' life cycle. The LCI is important for impact assessment, which involves first classifying the type of impact related to the used material, such as climate change or ozone depletion. Then, each inventory item is characterized and classified under a common unit of comparison, such as the equivalent CO_2 weight for global warming potential (GWP). Databases are often used to facilitate this process.

The final stage of the LCA process is the interpretation of the collected data. This involves reviewing and analyzing the LCI and LCIA, recognizing problems that result from these two stages and choosing a systematic approach to solve them. This stage results in a set of restrictions and suggestions.[24]

4.2 Definition of Impact Categories

During the Life Cycle Impact Assessment (LCIA) of an LCA, different emissions are combined into actionable numbers. It means different emissions that cause the same impact- are converted into one unit that translates into one impact category.

For example, the impact category 'climate change' is presented in kg CO_2 equivalents (kg CO_2-eq). However, other greenhouse gas emissions than carbon emissions (CO_2) cause climate change as well. Such as methane (CH_4) or laughing gas (N_2O). By expressing these other GHG emissions with different measuring units in kg CO_2 equivalents it is possible to come to a single metric for climate change.

Impact categories collect complex data into accessible numbers, these numbers give a clear picture of what the impact is.[25]

4.2.1 Impact Categories (overview)

Table 4.1 shows an overview of the 15 environmental impact categories, along with their units, and description. Additional parameters and indicators, waste types, and output flows of materials & energy can be seen in Tables 4.2-4.4.

These 15 categories, along with the criteria and indicators, are all derived from the EN15804 (A1+A2) standard for LCAs in the construction industry, other impact assessment methods (such as the PEF 3.0), utilize completely different categories. EN15804 +A2 offers a great overview.[25]

Table 4.1: Environmental Impacts [25]

Impact Category/Indicator	Unit	Description
Climate change – total, fossil, biogenic and land use	kg CO2-eq	Indicator of potential global warming due to emissions of greenhouse gases to air. Divided into 3 subcategories based on the emission source: (1) fossil resources, (2) bio-based resources, (3) land use change.
Ozone depletion	kg CFC-11-eq	Indicator of emissions to air that cause the destruction of the stratospheric ozone layer
Acidification	kg mol H+	Indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and Sulphur oxides
Eutrophication – freshwater	kg PO4-eq	indicator of the enrichment of the freshwater ecosystem with nutritional elements, due to the emission of nitrogen or phosphor containing compounds
Eutrophication – marine	Kg N-eq	Indicator of the enrichment of the marine ecosystem with nutritional elements, due to the emission of nitrogen containing compounds.

Eutrophication – terrestrial	mol N-eq	Indicator of the enrichment of the terrestrial ecosystem with nutritional elements, due to the emission of nitrogen containing compounds.
Photochemical ozone formation	kg NMVOC-eq	Indicator of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalyzed by sunlight.
Depletion of abiotic resources – minerals and metals	kg Sb-eq	Indicator of the depletion of natural non-fossil resources.
Depletion of abiotic resources – fossil fuels	MJ, net calorific value	Indicator of the depletion of natural fossil fuel resources.
Human toxicity – cancer, non-cancer	CTUh	Impact on humans of toxic substances emitted to the environment. Divided into non-cancer and cancer-related toxic substances.
Eco-toxicity (freshwater)	CTUe	Impact on freshwater organisms of toxic substances emitted to the environment.
Water use	m3 world eq. deprived	Indicator of the relative amount of water used, based on regionalized water scarcity factors.
Land use	Dimensionless	Measure of the changes in soil quality (Biotic production, Erosion

		resistance, Mechanical filtration).
Ionizing radiation, human health	kBq U-235	Damage to human health and ecosystems linked to the emissions of radionuclides
Particulate matter emissions	Disease incidence	Indicator of the potential incidence of disease due to particulate matter emissions

Table 4.2 provides ae description of parameters used to explain impact factors, along with their units

Table 4.2: Parameters and their Description of Resources Used[25]

Parameter	Unit	Description
Primary renewable energy (materials)	MJ	Use of renewable primary energy resources as raw materials
Primary renewable energy (energy)	MJ	Use of renewable primary energy, excluding renewable primary energy resources used as raw materials
Primary renewable energy (total)	MJ	Sum of the two values above
Primary non-renewable energy (materials)	MJ	Use of non-renewable primary energy resources as raw materials
Primary non-renewable energy (energy)	MJ	Use of non-renewable primary energy, excluding renewable primary energy resources used as raw materials
Primary non-renewable energy (total)	MJ	Sum of the two values above

Use of secondary material	kg	Material recovered from previous use or from waste which substitutes primary materials
Use of fresh water	m3	Freshwater use in absolute values
Use of renewable secondary fuels	MJ	Renewable fuel recovered from previous use or from waste which substitutes primary fuels
Use of non-renewable secondary fuels	MJ	Non-renewable fuel recovered from previous use or from waste which substitutes primary fuels

Table 4.3 and Table 4.4 show other environmental information , Table 4.3 shows waste type information , their units and description , while Table 4.4 indicates outflows which includes component for re-use , materials for recycling and energy recovery and energy production , the description for each item and their unit can be seen in this table.

Table 4.3: Other Environmental Information: waste Type[25]

Indicator	Unit	Description
Hazardous waste disposed	kg	Hazardous waste has a certain degree of toxicity that necessitates special treatment
Non-hazardous waste disposed	kg	Non-hazardous waste is non-toxic and similar to household waste. It consists of inert waste and ordinary household waste
Radioactive waste disposed	kg	Radioactive waste mainly originates from nuclear energy reactors

Table 4.4: Other environmental information: Output flows[25]

Indicator	Unit	Description
Components for re-use	kg	Material or components leaving the modelled system boundary which is destined for reuse
Materials for recycling	kg	Material leaving the modelled system boundary which is destined for recycling
Materials for energy recovery	kg	Material leaving the modelled system boundary which is destined for use in power stations using secondary fuels (minimum energy efficiency 60% or 65% for installations opened after 2008)
Energy production	MJ	Energy exported from waste incineration and landfill

4.3 Most Common Impact Factors for NMC

In one study [1] four impact categories have been selected for different NMC chemistries.

- GWP(Global Warming Potential),
- ADP(Abiotic Depletion Potential),
- POP(Photochemical Ozone Creation Potential) ,
- AP(Acidification Potential).

These categories were chosen because of several reasons. Firstly, GWP is the most commonly used impact category, while ADP represents resource exploitation and is related to potential problems with the demand for battery materials in the future. POP and AP are reviewed when different chemistries of the battery are used.

There is no noticeable difference in GWP between the NMC chemistries. NMC111 has the highest GHG emissions, while nickel-rich batteries have slightly lower GHG emissions and

greater recycling advantages. However, due to the higher impact from nickel production, NMC811 has a somewhat higher GHG intensity than NMC622.
Since GWP shows no significant difference between the NMC chemistries and it is the most commonly used impact category, this study will focus on reviewing GWP.

Greenhouse gases (GHGs) work as a blanket insulting the Earth. They warm the Earth by absorbing energy and reducing the rate of energy escaping. The impact of GHGs can be different on the Earth's warming. Two factors consider, their ability to absorb energy which is called “radiative efficiency”, and the amount of time that they stay in the atmosphere which is known as "lifetime".[1]

4.3.1 Global Warming Potential (GWP)

The Global Warming Potential (GWP) provides comparisons of the global warming impacts of various gases on the environment. GWP is a metric to measure the amount of energy that the emissions of 1 ton of a gas will absorb during a specific period, relative to the emissions of 1 ton of carbon dioxide (CO_2). The period of GWPs is usually considered 100 years. GWPs provide a standard unit of measure, so it’s possible to sum together emissions estimates from different gases and it allows to compare reduction potential in emission across industries and gases. Carbon dioxide, Methane and Nitrous Oxide are usually considered for GWP calculation.

- Carbon dioxide CO_2 is being used as reference and the GWP of this gas is considered 1, regardless of the time period. The effects of CO_2 on the climate system remain for a very long time.
- GWP of Methane (CH_4) is estimated to be 27-30 over a period of 100 years. The average lifespan of CH_4 is around ten years but this gas has higher energy absorption than CO_2. The CH_4 also has some indirect effects, for example, CH_4 is a precursor to ozone, which is considered as greenhouse gas.
- GWP of N_2O is 273 over a period of 100 years. The average lifespan of N_2O is more than 100 years.

In many cases, the 100-year GWP is used to measure the relative impact of various GHGs. However, there are different metrics that are used for comparing greenhouse gases to each other. These metrics can be different based on time period, calculation method and the climate endpoint measured. For example, sometimes 20-year GWP is used instead of 100-year GWP, when 20-year GWP is used, gases with shorter lifetimes are prioritized. Since GWP is calculated based on CO_2, GWP will be higher for the gases that their lifetime is shorter than CO_2 and vice versa. For CH_4, which has shorter lifetime than CO_2, GWP100 is 27-30, while GWP_{20} is 81-83.

Global Temperature Potential (GTP) is another alternative. GWP is used to measure the amount of heat absorbed over a specific time period as a result of gas emission, while the GTP refers to temperature change at the end of that time period (in relation to CO2). The calculation of the GTP is more complex than calculation for the GWP. For calculating GTP, it is important to model the climate sensitivity, it means it should be determined how much the climate system responds to rising concentrations of greenhouse gases, another factor is the pace pf this response.[26]

CO_2-equivalents have become like a tool for reporting greenhouse gas emissions, and it is used to define mitigation strategies, therefore, the importance of a reliable link between reported emissions and their warming impacts is undeniable.

In this study GWP_{100} has been calculated but it should be noted that this calculation is not precise. The atmospheric lifetime and radiative impacts of different climate pollutants can both vary significantly. As GWP_{100} compares emissions using a single scaling variable, therefore it cannot always be accurate. For more precise calculation GWP* is an alternative. For representing the warming impact of different gases, GWP_{100} utilizes a single value over a 100-year time period, while GWP* uses a time-dependent variable that indicates the warming impact of various gases over time.[27]

4.4 OpenLCA

OpenLCA is an open source and free software for Sustainability and Life Cycle Assessment, with the following features:

- Fast and reliable calculation of your Sustainability Assessment and/or Life Cycle Assessment.
- Very detailed insights into calculation and analysis results; identify main drivers throughout the life cycle, by process, flow, or impact category, visualize results, and locate them on a map.
- Best in class import and export capabilities; easy to share your models.
- Life Cycle Costing and social assessment smoothly integrated in the life cycle model.
- User-friendly; user interface in a variety of languages; advanced and efficient. repository and collaboration feature (currently developed).
- Continuous improvement and implementation of new features. It plays in the same league as commercial LCA software, such as SimaPro, GaBi or Umberto, but offers distinct differences.

openLCA is versatile and able to meet the needs of different user groups.

4.4.1 Data for OpenLCA

OpenLCA provides a collection of data sets and databases worldwide for LCA software.

4.4.1.1 OpenLCA Nexus

Already in summer 2012 OpenLCA created a website called openLCA Nexus, where databases for use in openLCA are provided. The data designed are aligned as much as possible with the openLCA software. It’s possible to use the Nexus page to search for individual data sets, focusing on different criteria such as product, sector, age, time, or price of the data set or database.

4.4.1.1.1 LCIA Methods & Databases

When performing an LCA, it is important to ask if the database and Life Cycle Impact Assessment (LCIA) method are compatible with each other.OpenLCA has an LCIA method package, now in version 2.1.1, with over 40 methods, these methods are downloadable in Nexus.

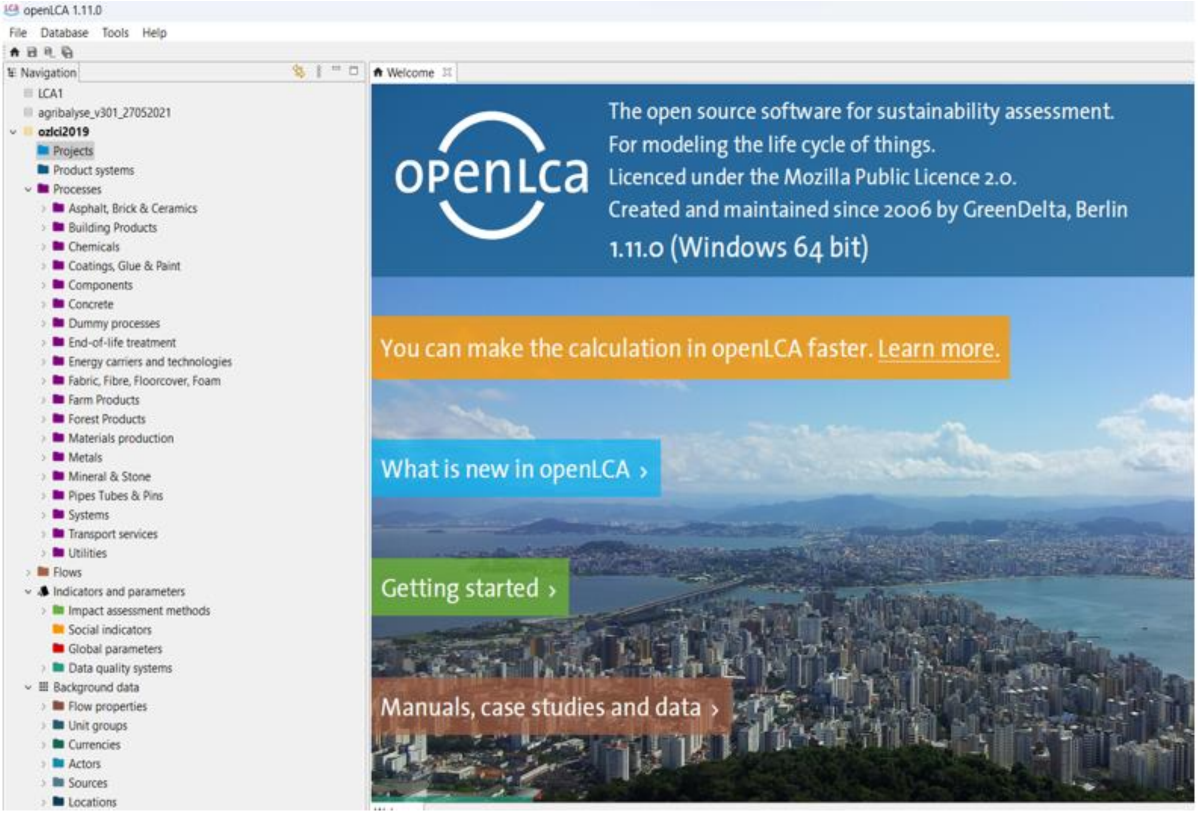
There are a lot of LCIA methods that can be employed in LCA. The method usually depends on the factors below:

- the impact categories that should be defined for the project (from the creator of the study, or the client,
- the audience and stakeholders of the study, as well as where they are most interested,
- It is crucial to ensure that the method and database are compatible in terms of flows. If the method and database use different flows, the resulting impacts will be zero.

Typically, the documentation of a database includes suggestions on which LCIA methods are most appropriate for it. These documentations can be found under documents on the database download page in Nexus (e.g., documents for EuGeos’ 15804-IA).[28]

There is a possibility to import the databases which were downloaded from OpenLCA Nexus to OpebLCA.

4.4.1.1.2 Database Elements



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For modeling the life cycle of things.
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Created and maintained since 2006 by GreenDelta, Berlin
1.11.0 (Windows 64 bit)

You can make the calculation in openLCA faster. Learn more.

Figure 4.1:OpenLCA database[28]

All data bases have the same structure, and they include the elements as follows:

- Projects: comparison and assessment of the product systems
- Product system: network of processes
- Processes: a collection of interdependent actions that convert inputs into outputs.
- Flows: Product, material, or energy flow between processes of the product system.
- Indicators and parameters:
  - Impact assessment methods: methods for environmental Life Cycle Impact Assessment (LCIA)
  - Social indicators: indicators for social LCA
  - Global parameters: Parameters accessible across the entire database
  - Data quality systems: Indicators and scores used to assess and determine the quality of data
  - Background data: Flow properties, unit groups, currencies, actors, sources and locations.[28]

4.4.1.1.3 Ecoinvent 3.9.1

The latest version of the Ecoinvent database, version 3.9.1, released on 15th December 2022, includes major updates and 1000 new processes (datasets), 1800 updated datasets and 270 new products.[29]

4.4.2 Possibility of Using OpenLCA

OpenLCA software is used for LCA calculation, especially for complex studies involving different products, processes, and impact categories. The objective of this study is to present LCA for Skagerak battery, with focus on Global Warming Potential (GWP) impact category. Access to real data for defining different steps in OpenLCA (products, processes, flows) was impossible. Therefore, information on the production stage has been extracted from literature review. The GWP for Skagerak Energi has been estimated based on the GWP extracted from literature, therefore there is no need to use OpenLCA software for GWP calculation in this study.

4.4.3 GHG Emissions for Samsung Batteries

Life Cycle Assessments (LCAs) were designed to identify GHG emissions and other environmental loads. In order to analyze the substantial environmental impact, the whole product life cycle from the extraction of raw materials to product use and disposal is assessed. The objective of performing LCAs is to improve environmental impact and following up the principles in ISO14040/44 and PEFCRs (Product Environmental Footprint Category Rules. Conventional Cradle-to-Gate LCA centered on the partial life cycle of products from manufacturing to the factory gate before they are handed over to customers. A Cradle-to-Grave approach evaluates the environmental impact of products from manufacturing to disposal. This

extended technique is planned for more analyses of product environmental effect. These assessments include reuse, recycling, and other impacts related to resource circulation.[30]
According to Samsung report[30], environmental impacts for their battery which are analyzed by LCAs Global warming are as follows:

- Global warming
- Abiotic resource depletion
- Acidification
- Eutrophication
- Ozone layer depletion
- Photochemical oxidation
- Human toxicity
- Freshwater aquatic Eco toxicity
- Marine water aquatic Eco toxicity
- Terrestrial Eco toxicity

According to the latest Samsung report the largest amount of GHG emissions are related to the first step, which is before manufacturing,53% of the GHG emission is produced in this step and while the cell component stage is the source of 68% of emissions. Samsung divided whole phases into five steps, before manufacturing, manufacturing, distribution, use and disposal. As the use phase in this report is particular for electrical vehicles, this number is not relevant for our study.[31]

Figure 4.2: GHG emissions for each phase for Samsung batteries[31]

5 Emission Caused by Production Phase

The main objective of this study is to analyze LCA for the mobile batteries used in Skagerak's pilot project. In production phase, energy use for cathode production, battery assembly, and then transportation to Skagerak company is assessed. NMC 111 is used as the mobile battery in this project, as access to real data was impossible, so the relevant research papers are reviewed to provide an overview of the production step for this battery.
First, the energy consumption for the production stage of the battery is presented then global warming potential related to the production phase based on Skagerak's battery capacity is estimated, this estimation is based on some research papers. Battery containers and charging containers are not considered. Also the energy consumption during transportation based on the information provided by Skagerak is reviewed. As it was explained in chapter 4, LCA includes four steps, goal and scope, life cycle inventory (LCI) life cycle, impact assessment (LCIA) and interpretation. In this chapter these four stages will be assessed.

5.1 goal and scope

The main objective is to determine the possible environmental effects throughout the production stages of the NMC battery pack's life cycle.

As can be seen in Figure 5.1,LCA of the battery includes three stages, battery production, use stage and end-of-life. As this chapter is defined to study production part, the goal and scope is explained for this part.

In the battery production stage, there are two steps, the first step is production of cell components, which include anode, electrolytes, binder, passive components, and cathode production. The second step includes production of non-cell components, final battery assembly and finally transportation of the battery to customer.

The supply of raw materials, component manufacturing, cell and pack battery assembly, transportation, and infrastructure are all included in the NMC production stage. The Ecoinvent 3.6 database was used by research paper to determine required energy for each LCA step of NMC 111 battery.[1]

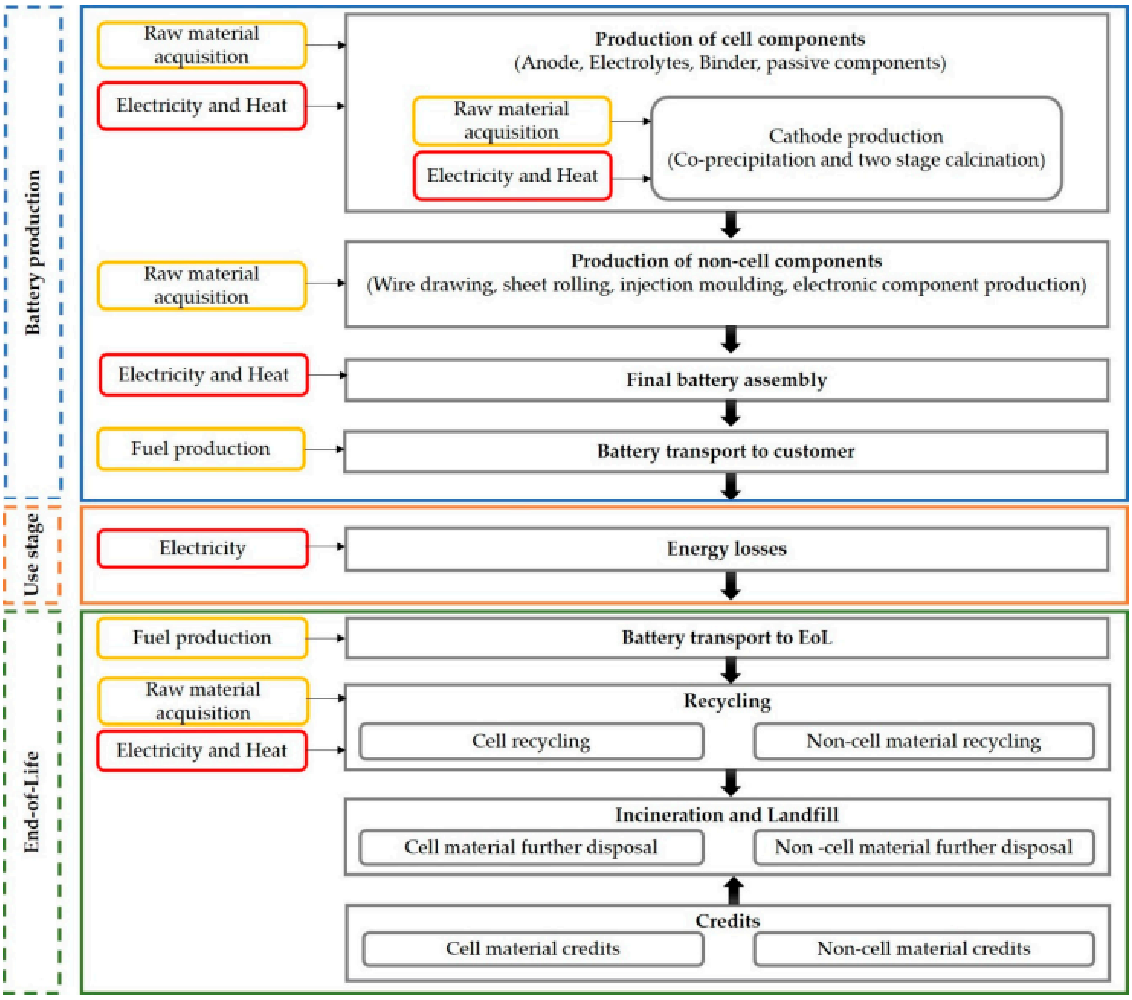

Figure 5.1: System boundaries of the LCA of the battery (adapted from PEFCR)[1]

To compare the used battery in the study with the battery that Skagerak used for their project, it should be mentioned that the electric vehicle analyzed on research [1] contains a 192-cell NMC111 battery as part of its equipment. Each battery cell consists of a graphite anode and a cathode made of LiNi0.33Co0.33Mn0.33O2, which has the same molar ratios of Nickel, Manganese, and Cobalt. A single battery pack has a weight and energy capacity of 226 kg and 35 kWh, respectively.

The battery container for Skagerak’s project is made up of two battery racks. The total capacity of the battery is 576 kWh, where each rack has a capacity of 288 kWh. The battery container is charged by two CCS type 2 cables.[21]

Table 5.1 shows battery capacity for [1] and Skagerak’s battery.

Table 5.1: Comparison of Specification of Different Batteries [1], [21]

Reference	Battery capacity
[1]	32 kWh (for battery cell)
Skagerak’s project[21]	288 KW(for battery rack)

5.1.1 Functional unit

The quantification of a product's function is defined by the functional unit. The main goal of a functional unit is to provide a reference to which the inputs and outputs are related, the purpose is to make sure of comparability of the LCA results. 1 kWh of the battery pack's nominal energy capacity is the functional unit of the battery. For comparison with other studies, the impacts are also listed in the supporting material section per kilogram of the battery pack.[32]

5.2 Life Cycle Inventory

A product system is made up of the various processes needed to produce, use, dispose of, recycle, or reuse the product, and each process should also have an inventory of the input and output flows. Quantification of the life-cycle inventory (LCI) is the second phase of an LCA analysis.[33]

The NMC battery materials were divided into two groups as can be seen in Table 5.2, the first group shows the materials of the cells, and all the materials that complete the battery pack are included in the second group. As the energy demand for the production phase is important, the inputs for the cathode and cells were taken from [34].

Table 5.2 shows the LCI for precursors production of NMC 111, input materials, water and energy consumption for these stages are presented.

Table 5.2: LCI for different type of NMC precursors production[34]

NMC111	
Material input (ton/ton product)	
$NiSO_4$	0.564
$CoSO_4$	0.564
$MnSO_4$	0.550
NaOH	0.890
NH_4OH	0.124
Water consumption (gal/ton product)	
water	168.62
Energy consumption (mmBtu/ton product)	
Natural gas	38.618

The supply of raw materials, component manufacturing, cell and pack battery assembly, transportation, and infrastructure are all included in the NMC production stage. According to references and laboratory tests, the bills for the materials and energy needed for each LCA stage of an NMC111 battery were collected. All the specific emissions were taken from the Ecoinvent 3.6 database by the research papers. The Ecoinvent 3.6 database was used to determine the amount of energy needed for each LCA step of an NMC 111 battery based on the emissions of each element.

The Argonne National Laboratory served as the source for the NMC111 battery's bill of materials (BOM). The BOMs for NMC111 are reported in Table 5.3,which includes cell materials and non-cell materials per kg of battery pack.[35]

Table 5.3: Bills of materials (BOMs) of NMC 111 per kg of battery pack[35]

Cell materials	**NMC111(kg)**
Active Cathode Material	0.287
Graphite	0.160
Carbon black	0.020
Binder (PVDF)	0.025
Copper	0.134
Aluminum	0.069
Electrolyte: LiPF6	0.018
Electrolyte: Ethylene Carbonate	0.050
Electrolyte: Dimethyl Carbonate	0.050
Plastic: Polypropylene	0.012
Plastic: Polyethylene	0.003
Non-Cell materials	
Copper	0.003
Aluminum	0.184
Steel	0.007
PET	0.005
Electronics	0.037

5.3 Battery Production phase:

To ensure that only primary material was used as input to the production process, proxies have been used in the modeling of the principal cell materials (Copper, Cobalt, Nickel, and Manganese). Ecoinvent models in the global average were utilized for other materials, which often do not take secondary materials into account as input. Secondary materials are the materials that are not the main products during manufacturing and other industrial fields. According to a model, the global average for mining, smelting, and refining nickel is 68% sulfidic ore and 32% platinum group metals (PGMs) from South Africa and Russia (86% and 14%, respectively). Cobalt proxy is based on “Cobalt global production”. It applies to 1 kg of

Cobalt from reduction of gray and black cobalt oxide [Ecoinvent] and secondary cobalt has been determined to be to zero. 25% of manganese production comes from the rest of Europe, while 75% comes from the rest of the world (these modules do not consider secondary sources of manganese [Ecoinvent]).[1], [28], [29], [36]

The information on the "market for" modules for each material is represented in the data for transportation of raw materials and/or components to the battery production site. The production of 1 kilogram of manganese throughout the rest of the world is represented by the manganese "ROW" production model in Ecoinvent. The "manganese RER production" model in Ecoinvent describes the manufacture of 1 kg of manganese only from primary resources within the Rest of Europe region.[1], [28], [29], [36]

Some abbreviations have been used in the tables which show the list of inventories for each step of production, these abbreviations have been clarified through the Table 5.4.

Table 5.4: Explanation of Abbreviation [36], [37]

Abbreviation	Item
GLO	Global
Market for	All transactions involving the same reference product in a particular geographic area.
ROW	Rest of word
RER	Rest of Europe region
Cut-Off system	The first production of materials is always granted to the primary user of a material. The primary producer of a material does not earn any credit for the supply of any recyclable resources if the material is recycled. Because of this reason, recyclable materials are available burden-free to recycling processes, and secondary (recycled) materials only be impacted by the effects of recycling procedures.

Battery production phase according to [1] include cathode production, cell production, non-cell production materials and battery assembly, which are expressed in sections5.3.15.3.4. Each section shows products, the amount of product and processes used for production. The details are shown in Table 5.5-Table 5.8.

5.3.1 Cathod Production

The first step in production is cathode production according to [1].China dominates the global market for NMC cathodes[38]. A two-stage procedure to produce the typical materials are used for cathodes in NMC cells. The first step is related to NMC precursor and in the second stage, a lithium compound is applied to the precursor during calcination.

The complete LCI of cathode production is shown in Table 5.5.Table 5.5 table has been extracted from [36] and it was used in [1] to calculate GWP , which is used to estimate GWP for Skagerak's battery in this study ,some data has been deleted from original table, which was not applicable for this study.

Table 5.5:Life Cycle Inventory of Cathode Production per kg Cathode [1], [36]

Refrence product	Amonut	Processes used
Cobalt Sulfate	0.536 kg	Cobalt virgin {GLO} proxy 2
Nickel Sulfate	0.535 kg	Nickel virgin, 99.5% {GLO} proxy^2
Lithium Carbonate	0.383 kg	Lithium carbonate {GLO}| market for | Cut-off, U
Manganese Sulfate	0.522 kg	Manganese virgin {GLO} proxy^2
Sodium Hydroxide	0.844 kg	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U
Ammonium Hydroxide	0.117 kg	Ammonia, liquid {RoW}| market for | Cut-off, U
Natural gas	42.6 MJ	Heat, district, or industrial, natural gas {GLO}| market group for | Cut-off, U
Electricity	25.2 MJ	Electricity, medium voltage {CN}| market group for | Cut-off, U
Water	7.6 kg	Water deionized {RoW}| market for water. deionized | Cut-off, U

1.Infrastructure amount taken from “Battery cell, Li-ion {CN}| production | Cut-off, U” infrastructure as proxy.

2.Data gaps for Cobalt Sulfate, Nickel Sulfate and Manganese Sulfate have been managed according to PEFCR [Recharge 2018].

5.3.2 Battery Cell Production

The Argonne National Laboratory uses a prismatic pouch cell structure based on Everbatt. EverBatt is a battery recycling process and supply chain model built on Excel. It can be used to evaluate processes, detect tolerance for various factors, and compare the effects of virgin batteries to those with recycled material.[38]

A tri-layer polymer/Aluminum material is used to create the pouch. Foils made of aluminum are used as collector at the cathode and Copper's foils is used as current collectors at the anode.[39]

Graphite and a PVDF (polyvinylidene fluoride) binder are the two main components of the anode. The graphite is heated up at 1100°C in an inert or reducing environment to verify that there are no oxygen impurities present.[40]

A porous membrane separates the two electrodes from the active material particles while the polymeric binder material holds them together.[39]

This separator's pores as well as the pores of the active components are both filled with an electrolyte referred to as LiPF6 (lithium hexafluorophosphate). The NMC solvent N-methyl-2-pyrrolidone (NMP) was added to the mixture and then evaporated then the paste had been added to the substrate.[40]

The inventory list of this process is shown in Table 5.6. This table has been extracted from [36] and it was used in [1] for GWP calculation, and GWP for Skagerak’s battery in this study has been estimated based on that, some data has been deleted from original table, which was not relavant for this study.

Table 5.6:Life Cycle Inventory of Cell Production per kg Cell[36], [39], [40]

Reference product	Amount	Processes used
Inputs from Technosphere (material /fuels)		
Aluminum	0.095 kg	Aluminum, primary, ingot {CN}| production | Cut-off, U
Graphite	0.221 kg	Graphite {GLO}| market for | Cut-off, U
PVC	0.034 kg	Polyvinylchloride, suspension polymerized

		{GLO}| market for | Cut-off, U[2]
Heat	23.6 MJ	Heat, district, or industrial, natural gas {GLO}| market group for | Cut-off, U
Electricity	1.40 kWh	Electricity, medium voltage {CN}| market group for | Cut-off, U
EC	0.069 kg	Ethylene carbonate {GLO}| market for | Cut-off, U
PP	0.016 kg	Polypropylene, granulate {GLO}| market for | Cut-off, U
LiPF6	0.025 kg	Lithium hexafluorophosphate {GLO}| market for | Cut-off, U
PE	0.004 kg	olyethylene, low density, granulate {GLO}| market for | Cut-off, U
PET	0.003 kg	Polyethylene terephthalate, granulate, amorphous from virgin {GLO}| market for | Cut-off, U
Copper	0.184 kg	Copper {RER}| production, primary | Cut-off, U[3]
DC	0.069 kg	Dimethyl carbonate {GLO}| market for dimethyl carbonate | Cut-off, U

Carbon Black	0.027 kg	Carbon black {GLO}| market for | Cut-off, U
NMP	0.003 kg	N-methyl-2-pyrrolidone {GLO}| market for | Cut-off, U
Cathode	0.396 kg	Cathode production
Emissions to air NMP	0.003kg	

1.Infrastructure amount taken from "Battery cell, Li-ion {CN}| production | Cut-off, U" infrastructure as proxy.

2.PVC replaces PVDF.

3.Copper {RER}| production, primary | Cut-off, U" has been used as proxy of the copper production to consider only primary material obtained from mining.[1], [36], [39], [40]

5.3.3 Production of the Non-Cell Materials

The inventory to produce the cell containers, separator, BMS, cooling system, and final packing is displayed in Table 5.7. The separator's primary function is to keep the two electrodes from coming into contact while allowing the electrons in the electrolyte to flow with the least amount of resistance feasible.[40]

The production of non-cell material contributes less than 36% of the (GWP) of battery production stage. Table 5.7 has been extracted from [36], which was used in [1] for GWP calculation , and GWP estimation for Skagerak battery is based on that. Some data from original table has been removed, which was not relevant for this study.

Table 5.7: Life Cycle Inventory of Non-cell Materials per 1 kg Battery Pack[1], [36], [40]

Reference product	Amount	Processes used
Inputs from Technosphere (material /fuels)		
Copper	0.003 kg	Copper {GLO}| market for | Cut-off, U Wire drawing, copper {GLO}| market for | Cut-off, U
Aluminium	0.184 kg	Aluminum, wrought alloy {GLO}| market for | Cut-off, U Sheet rolling, aluminum {GLO}| market for | Cut-off, U

Steel	0.007 kg	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U Sheet rolling, steel {GLO}| market for | Cut-off, U
PET	0.005 kg	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Cut-off, U Injection molding {GLO}| market for | Cut-off, U
Electronics	0.004 p	Power supply unit, for desktop computer {CN}| production | Cut-off, U

5.3.4 Battery Assembly

According to[1], the last step of production is battery assembly. Table 5.8 indicates the required energy for battery assembly per kg battery pack. Electricity, heat, and natural gas have been calculated.

Table 5.8: Life Cycle Inventory of the Amount of Energy Required for the Final Assembly of 1 kg Battery Pack.[36]

Reference product	Amount	Processes used
Inputs from Technosphere (material /fuels)		
Electricity	6.5 kWh	Electricity, medium voltage {CN}| market group for | Cut-off, U
Heat, natural gas	7.8 MJ	Heat, district, or industrial, natural gas {GLO}| market group for | Cut-off, U

5.4 GWP of Battery Production Stage

First, battery production has been presented which is based on [1].According to [1] GWP of battery Production stage per kg of battery pack is 20.95 and GWP of battery production per kWh is 136. 63.Cathode production, energy demand, cell and non-cell materials and transport from manufacturing plant to customer have been considered. The details of GWP in battery production is shown in Table 5.9.

As discussed, the production step includes cathode production, cell production, non-cell production materials and battery assembly, so GWP for each step should be calculated, GWP for each step of production with details can be seen in sections 5.4.15.4.5.All data has been extracted from [1] and then based on calculated GWP , GWP for Skagerak battery is estimated.

Table 5.9: Impact Assessment of Battery Production Stage per kg of Battery Pack and Impact Assessment of Battery Production per kWh[36]

GWP (Kg CO2 eq)	Unit	Cathode Production	Energy demand	Cell production (Cathode excluded)	Non-cell materials	Transport *
	kg	4.66E+00	1.1E+01	2.53E+00	2.7E+00	6.67E-02
	kWh	3.01E+01	7.21E+01	1.64E+01	1.76E+01	4.31E-01

*Transport: To model transport of batteries from manufacturing plant to customer, transport data of “Battery, Li-ion, rechargeable, prismatic {GLO}| market for | Cut-off, U” has been used as proxy.

5.4.1 GWP for Cathode Production

As the first step for production was cathode production, so GWP of all used materials and energy in cathode production can be seen in Table 5.10. Cathode production per kg battery pack is 7.20 and GWP of cathode production per kWh is 33.24.The details can be seen in Table 5.10.

Table 5.10: Impact Assessment of Cathode Production per kg Battery Pack and Impact Assessment of Cathode Production per kWh[36]

GWP	Unit	Infrastr.	Co	Mn	Ni	Elec.	heat	Li$_2$CO3	NaOH	NH$_3$	water
(Kg CO2 eq)	kg	1,67E-02	1,50E+00	4,88E-01	2,03E+00	2,04E+00	5,00E-01	2,41E-01	3,16E-01	6,93E-02	1,01E-03
	kWh	1,08E-01	9,64E+00	3,14E+00	1,31E+01	1,31E+01	3,22E+00	1,55E+00	2,03E+00	4,46E-01	6,48E-03

5.4.2 GWP of Cell Production

The second step in production of battery was cell production, so GWP for this part the next step. GWP of cell production per kg battery pack 3.5399 kg and 73.099 kWh. Table 5.11 indicates the details about used materials.

Table 5.11: GWP (Kg CO_2 eq) of Cell Production per kg Battery Pack and per kWh[36]

criteria	Al	Graph	PVC	Infrast.	Heat	Elec.	EC	PP	LiPF6	PE	PET	Cu	DMC	CB	NMP	cathode
kg	1,6E+00	1,1E-02 0	6,0E-02	4,2E-02	7,0E-010	1,0E+00	7,7E-02	2,6E-02	3,3E-01	7,1E-03	6,8E-03	2,2E-01	1,1E-01	3,6E-02	1,4E-02	7,2E+00
kWh	1,0E+01	7,2E-02	3,9E-01	2,7E-01	4,5E+00	6,6E+00	5,0E-01	1,7E-01	2,1E+00	4,6E-02	4,3E-02	1,4E+00	6,9E-01	2,3E-01	8,8E-02	4,6E+01

5.4.3 GWP of Non-Cell Materials Production

After cathode and cell production, GWP of non-cell materials should be calculated. Table 5.12 is shown GWP of non-cell materials production per kg battery pack is 2.5828 kg.

Table 5.12: Impact Assessment of Non-cell Materials Production per kg Battery Pack [36]

GWP (Kg CO2 eq)	Unit	Infrastr.	Cu	Wire drwaing copper	Al	Sheet rolling aluminum	steel	Sheet rolling steel	PET	Injection moulding	PSU
	kg	5,7E-02	1,5E-02	2,0E-03	2,3E+00	1,2E-01	1,3E-02	2,6E-03	1,5E-02	6,2E-03	1,6E-01

5.4.4 GWP for Final Assembly

GWP for final assembly is 6.898 kg. As can be seen in Table 5.13 electricity and heat have been considered for this calculation.

Table 5.13:Impact Assessment of Final Assembly's Energy per kg of Battery Pack[36]

GWP (kg CO2 eq)	Electricity	Heat
	6,58E+00	3,18E-01

5.4.5 A Summary of GWP of production phase

For the battery used in literature[1], GWP for different production stages can be seen in Table 5.14.As can be seen, the largest amount of GWP in this table is related to cell production, which is 73.099 kWh.

According to the Samsung battery, as they have a high focus on the sustainable extraction of cobalt and other materials, they announced that emission for battery cell of NMC111 is 39 kg/kWh.it is not clear what stages are considered to achieve this number, but it seems that some stages has not been considered for GWP calculation or an efficient method was used by Samsung for produce the battery. As it can be seen in Table 5.14,for calculation GWP, some stages like cell production ,non-cell material production ,cathode production and final assembly have been calculated. These results are according to the battery used in electrical car based on research paper.[1], [31], [36], [41]

Table 5.14 GWP per kWh in Different Stages of Production for the Battery Used in Literature[1], [36]

GWP	Parameter and unit	Amount	Table No.
	Battery production stage per kg	20.95	Table 5.9
	Battery production per kWh	136.63	Table 5.9
	Cathode production per kg battery pack	7.20	Table 5.10
	Cathode production per kWh	33.24	Table 5.10
	Cell production per kg battery pack	3.539	Table 5.11
	Cell production per kWh	73.09	Table 5.11
	Non-cell materials production per kg battery pack	2.58	Table 5.12
	Final assembly per kg of the battery pack	6.89	Table 5.13

5.5 Comparison of GWP on NMC for Different Batteries

To have an overview of different NMC batteries based on their location, weight and capacity, information has been collected in Table 5.15.In addition, GWP of manufacturing per kg and per kWh is shown, as can be seen GWP for different batteries, even from different locations is in the range of 17-22 (kgCO2eq/kg) and 104-196(kgCO2eq/kWh) and most of batteries have been produced in China.[1]

Table 5.15:GWP per kg and per kWh for Different NMC Batteries[1]

Refrence	Prpduction location	Battery mass(kg)	Battery capacity (kWh)	GWP of Manufacturing (kgCO2eq/kWh)	GWP of Manufacturing (kgCO2eq/kg)
[40]	EU	-	-	196	22
[42]	KR/NO	253	26.6	172	18
[43]	CN	170	28	104	17.2
[44]	US	-	40	121	-
[45]	CN	188.7	27	117	17

[1]	CN	226	35	135	21.2
[1]	CN	226	35	100	15.4

5.6 Transportation After production

For calculating emission for transportation, the battery after production, the GHG emission calculating is used. The data was provided by Skagerak. The transportation was done for these items: three Samsung SDI batteries, Siemens Electronics & Components, two Rittal Cabinets, container and KE system to Skagerak Energi. The transport mode was road, rail, water and rail. Also fuel used for some transportation is presented. The objective was to calculate GHG emissions based on CO_2, CH4 and N_2O.

5.6.1 Introduction for GHG Emission Calculation Tool:

The US Environmental Protection Agency (EPA), the Intergovernmental Panel on Climate Change (IPCC), and the UK Department for Environment, Food and Rural Affairs (DEFRA) provided the emission variables used in this tool. Together with World Resources Institute (WRI), Clear Standards Inc. created the instrument.[46], [47]

The tool using the format below:

World Resources Institute (2015). GHG Protocol tool for mobile combustion. Version 2.6.

This tool can calculate emission caused by CO_2, CH_4 and N_2O for vehicles, public transport by road, rail, air and water and also for mobile machinery. The tool is currently set for the UK and US, so for other countries, ‘other’ category is used and as the emission can be changed based on the location, therefore calculation cannot be accurate.

There are three steps to see the result, enter activity data is the first step, then setting up GWP and custom emission factor is the second step, then final step is viewing the summary.

The most accurate data for calculating CO_2 emissions depends on fuel use, while the most accurate information for calculating CH_4 and N_2O emissions comes from distance traveled.

For sources of non-public transportation, it is necessary to include information on fuel usage and distance traveled. Where one type of data is not accessible, the tool uses fuel economy information (where available) to convert between these data types. Records of fuel consumption are especially important because CO_2 accounts for more than 95% of GHG emissions. Data on vehicle distance or weight-distance can be utilized for calculating the emission from on-road freight transportation. Table 5.16 indicates details about transportation of the battery from production site to skagrak’s company. The distance, total weight of freight and fuel used are shown in this table.[46], [47]

Table 5.17 shows the emission according to CO_2, CH_4 and N_2O.

Table 5.16: Transportation Detail for the Battery from Production Step to Skagerak Company[47]

Source Description	Mode of Transport	Type of Activity	Vehicle Type	Distance Travelled	Total Weight	Fuel Used

					of Freight	
Samsung SDI Battery 1	Water		Watercraft - Shipping - Small Container Vessel (2500 tones deadweight)	1235	3.6	
Samsung SDI Battery 2	Rail		Rail	10267	3.6	100% Biodiesel
Samasung SDI Battery 3	Road		Road Vehicle - HGV - Articulated - Engine Size Unknown	1200	3.6	E85 Ethanol/ Gasoline
Siemens Electronics and Component	Road		Road Vehicle - Light Goods Vehicle - Fuel Unknown	1375	0.1	100% Biodiesel
Rittal cabinets 1	Raod		Road Vehicle - Light Goods Vehicle - Fuel Unknown	329	0.45	
Rittal Cabinet 2	Water		Watercraft - Shipping - Small Container Vessel (2500 tones deadweight)	600	0.45	
Container	water		Watercraft - Shipping - Small Container Vessel (2500 tones deadweight)	1430	2.3	

KE System to Skagerak Energi	Road		Road Vehicle - HGV - Articulated - Engine Size 3.5 - 33 tones	411	6.45	

Table 5.17: GHG emission for Battery Cell and Component During Transportation Step from Production Site to Skagerak[47]

Source Description	Fossil Fuel CO2 (metric tons)	CH4 (kilograms)	N2O (kilograms)	Total GHG Emissions, exclude Biofuel CO2 (metric tons CO2e)
Samsung SDI Battery 1	0.133	0.011	0.004	0.134
Samsung SDI Battery 2	0.579	0.046	0.014	0.584
Samsung SDI Battery 3	0.797	0.009	0.007	0.799
Siemens Electronics & Components	0.025	2.990E-04	2.307E-04	0.025
Rittal Cabinets 1	0.027	3.220E-04	2.484E-04	0.027
Rittal Cabinets 2	0.008	6.879E-04	2.349E-04	0.008
Container	0.098	0.008	0.003	0.099
KE system to Skagerak Energi	0.489	0.006	0.004	0.491
Total GHG Emissions, exclude Biofuel CO2				2.167

Emission regarding fuel use and distance is shown in Table 5.18, This data are according to Scope 3.According to Greenhouse Gas Protocol which is presented on World Resources Institute, The GHG Protocol Corporate Value Chain (Scope 3) sets the procedures and recommendations that companies and other organizations must follow in order to create and publicly share a GHG emissions inventory that includes indirect emissions from value chain activities. Figure 5.2 indicates three scopes of GHG protocol, as can be seen scope three accounts to indirect emission and it’s known as upstream activities together with scope 2.[46]

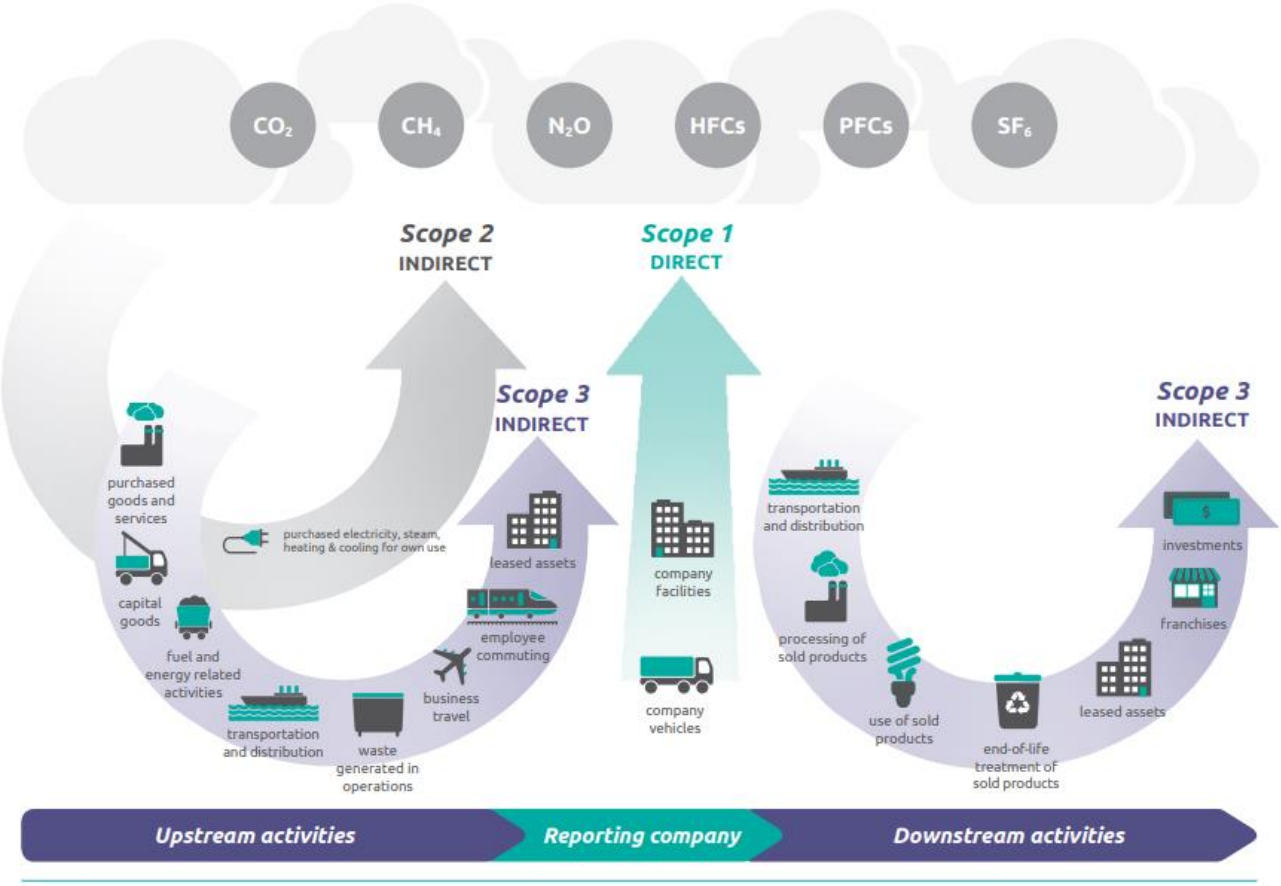

Figure 5.2:Overview of GHG Protocol Scopes [46]

Emission regarding fuel use and distance is shown in Table 5.18, This data are according to Scope 3.

Table 5.18: Emissions Based on Fuel Use and Distance [47]

Calculation Method	Greenhouse gas	Fossil Fuel emissions (Scope 3) (Metric tons)	Biofuel CO2 Emission (Metric tons)
Fuel Use	CO_2	0	0

	CH_4	0	0
	N_2O	0	0
Distance	CO_2	2.157	0
	CH_4	8.211E-05	0
	N_2O	3.292E-05	0
Total (metric tonnes CO_2e)		2.169	0

Figure 5.3 Shows emissions based on mode of transportation and as can be seen road allocated around 60% of the emission in this report.[47]

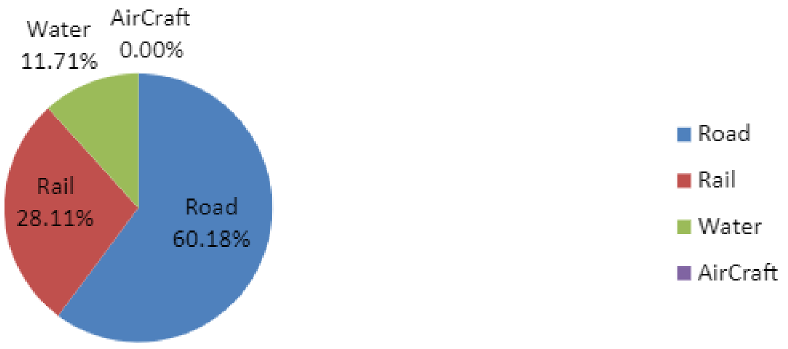

Figure 5.3: Emissions by Mode of Transport[47]

5.7 Impact Assessment (LCIA) and Interpretation for Production Step

As it was expressed in chapter 4, there are 15 impact factors, but in this study GWP is presented, because GWP is the most used impact category, and it shows no significant difference between the NMC chemistries.

CO_2-equivalents have become a tool for reporting greenhouse gas emissions, and they are used for establishing mitigation strategies, In this study GWP_{100} has been estimated, but it should be mentioned that this calculation cannot be precise, because GWP_{100} compares emissions using a single scaling variable. For representing the warming impact of different gases, GWP_{100} utilizes a single value over a 100-year time period, while using a method with time-dependent variable can show the warming impact of various gases over time, therefore it can be more precise.[1], [27]

According to Table 5.14,the GWP for battery pack production stage per kg and per kWh are 20.9567 and 136.631, respectively.

The capacity for Skagerk's battery is 576 kWh so according to the GWP from literature[1], the GWP for Skagerak's battery can be calculated as follows:

$$136.63 \times 576 = 78689\text{kg CO2eq} = 78.689 \text{ Metric ton CO2eq}$$

Also, total GWP for transportation from production site to Skagerak's company is 2.169 metric tons CO2e, and this number for Samsung SDI batteries is 1.517 metric tons CO2e.Therefore, it is obvious that production allocated the largest amount of the GWP.

Table 5.19 shows GWP of different steps for production. As can be seen, the largest GWP belongs to production part, which is 78.689 Tons CO_2eq.According to the Samsung battery the emission for battery cell of NMC111 is 39 kg/kWh, but it is not clear what stages are considered to obtain this number, the first theory is that it seems that for calculation GWP, some stages has not been considered. Second theory is that Samsung might use more efficient method for production of the batteries which needs less energy, so GWP is lower than the GWP based on literature review. As it can be seen in Table 5.14,for calculation GWP, some stages like cell production ,non-cell material production ,cathode production and final assembly have been calculated, these calculation is based on the battery for electrical car used in the research paper. Less than 36% of the (GWP) of battery manufacture is because of the production of non-cell material.

In the next step, transportation after production has been reviewed, this information was provided by Skagerak Energi. The calculations have been done for three Samsung SDI batteries, two Rittal Cabinets, KE system to Skagerak and the container. Different modes of transport have been used to transfer these components from production site to Norway and Skagerak's company. As is shown in Table 5.19 the GWP regarding transportation from production to Skagerak's site is 2.169 in total and 0.5 for each Samsung batteries. The data clearly indicates that the GWP for this step is significantly lower than the production part.[1], [41], [47]

Table 5.19: GWP of Production Part[1], [41], [47]

Stage	GWP Tons CO_2eq
Battery pack production[1]	78.69

Samsung Battery cell production[41]	22.46
Transportation after production[47]	2.169 (Total) 1.517 (for three batteries)

6 Emission Caused by Use Phase

This chapter covers the energy loss due to energy conversion and transportation required for charging the battery. For transportation stage, different fuels are reviewed. Then GWP for each part is presented.

The specification of Samsung SDI battery (94Ah cell) is used for estimation the parameters for mobile battery that will be used for the construction site. However, it should be noted that this estimation is based on some assumptions. The assumption is expressed in 6.1 and 6.2.3.

As the use phase depends on the energy used for generating electricity, there can be great differences based on location in the energy mix for producing electricity, that is why the used part is left out of LCA in most studies.[48]

6.1 Energy Loss Due to Energy Conversion

According to the Table 6.1, cycle life for Samsung SDI batteries can be assumed 6000 cycle life in the ideal situation. But to reach End-Of-Life (EOL), which in the case of batteries is the point where capacity decreases to 80% (battery still usable but not desirable), Samsung SDI predicts up to 4,600 charging cycles at 25°C. The best temperature for using the battery is 25º C, it shows the importance of the thermal management system.[49]

Figure 6.1 shows the number of cycles according to SOH, two results can be seen, SDI test result and SDI prediction are shown for 94Ah cell. As already discussed, for the cycle of the battery the range has been considered from 4600 to 6000.[50], [51]

Table 6.1:Samsung SDI specification[50]

System/Cell	DOD	SOH	Charge (C)	Discharge (C)	Cycle life	Thermal Runaway (°C)
NMC	100%	80%	1	1	4600-6000	25

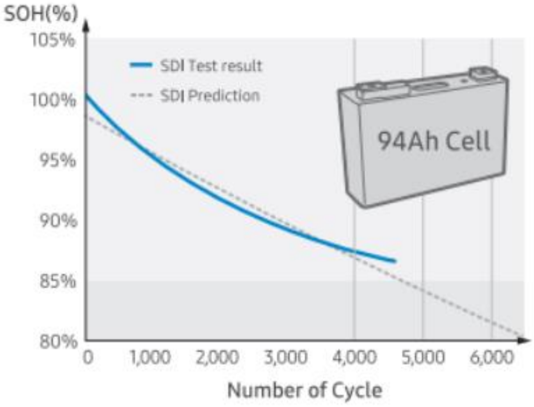

Figure 6.1:SDI Test Result and Prediction[50]

Energy transition losses is assumed 5%, so energy loss for energy conversion for Skagerrak's battery is calculated as follows:

$576\ kWh \times 0.05 \times 6000\ cycle = 172800\ kWh$ in an ideal condition

$576\ kWh \times 0.05 \times 4600\ cycle = 132480\ kWh$ when battery capacity declines to 80%

6.1.1 Energy Mix in Norway and Comparison to Other Countries

Greenhouse gas emission intensity (g CO2e/kWh) is determined as the ratio of CO_2 equivalent emissions of public electricity production (as a percentage of CO_2 equivalent emissions from the generation of heat and electricity in the public industry), and gross electricity production.[52]

Table 6.2 shows greenhouse gas emission from public electricity and heat production for some European countries which are members of the European Union, Norway, and China. According to the report that has been provided by the European Environment Agency, gas emissions from public electricity and heat production differ significantly throughout several European countries. In the European Union in 2021, Sweden with only 9 g CO_2e/kWh had the lowest level of emission, after that France with 67 g CO_2e/kWh had the second lowest level of emission, while the highest level allocated to Estonia with 946 g CO_2e/kWh. Figure 6.2 shows by 2030 , it is predicted that the high and low level of emissions of greenhouse gas for electricity sector will be 118 and 110, respectively.[48]

According to Norway Energy policy review, CO_2 emissions from electricity and heat generation were 10 g CO2/kWh in Norway, in 2020.In comparison to report related to EU countries this number shows that Norway significantly invested on renewable energy to reduce GHG emission of electricity production. Among IEA member nations, Norway produced the most renewable energy in total final energy consumption (TFEC) in 2020.Around 61% of TFEC was produced of renewable energies, while the average for IEA was around 13%. Hydropower is the most renewable energy, which 92% of electricity production.[53]

China is the largest producer of CO2 in the world.CO2 emissions of electricity is 537 g of CO2 per kilowatt hour in this country, in 2020.About 67% of electricity in China is produced from fossil fuels in 2020.This country is developing electricity production sector, therefore, around 29% of the power mix in China is produced by renewable energy in 2020.Large scale hydro projects are the reason of this development.[54]

Table 6.2: Greenhouse Gas Emission from Electricity and Heat Production by Country[48], [52]–[54]

Country	Greenhouse gas emission intensity (g CO_2e/kWh)
Norway	10
Sweden	9
France	67
Estonia	946
China	537

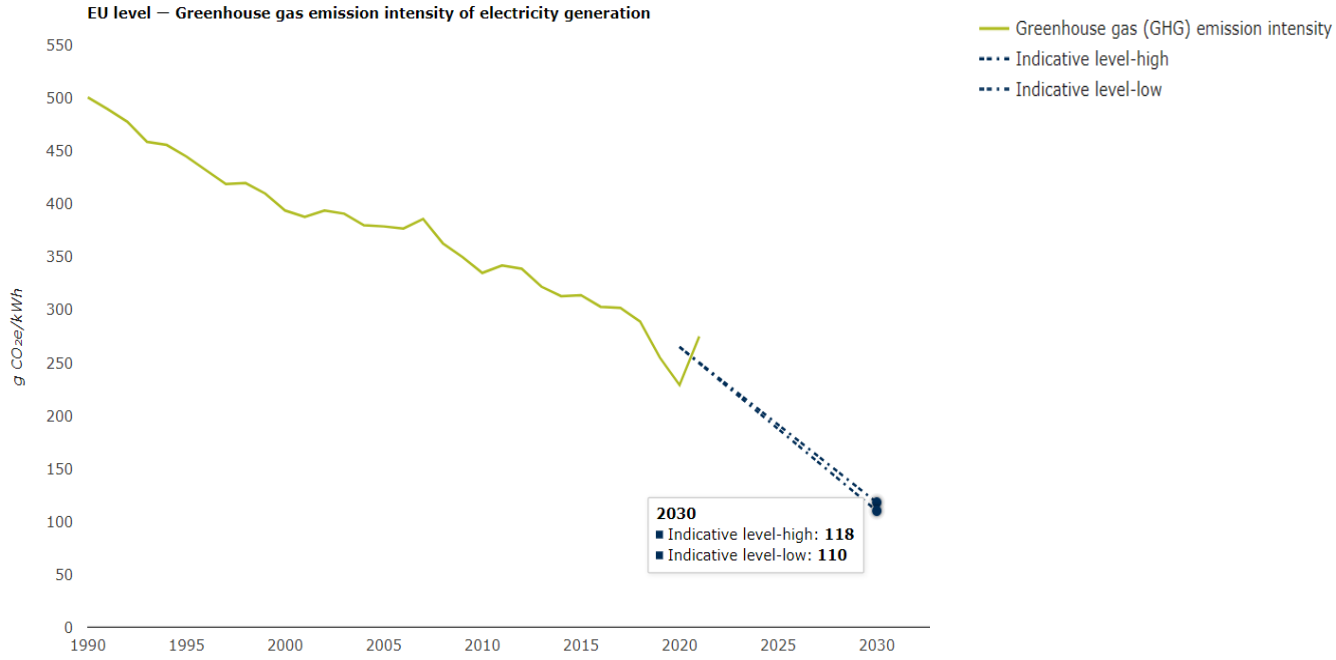

Figure 6.2:Greenhouse Gas Emission of Electricity Generation, EU Level[48]

As discussed, according to an Energy policy review , CO2 emissions of electricity and heat generation for Norway is considered 10 g CO2/kWh.[53]

So GWP for this step is calculated as follows:

For 6000 cycle life 172800 $kWh \times 0.01 \frac{kgCO2eq}{kWh} = 1728 kgCO2eq$=1.73 $tonsCO2eq$

For 4600 cycle life 132480 $kWh \times 0.01 \frac{kgCO2eq}{kWh} = 1325 kgCO2eq = 1.32\ tonsCO2eq$

By considering China’s energy mix, the calculation will be different , according to Table 6.2 greenhouse gas emission from electricity and heat production for China has been reported 537g CO_2e/kWh[54], so the calculation based on energy mix in Norway is as follows :

For 6000 cycle life : $172800\ kWh\ \times 0.537 \frac{kgCO2eq}{kWh} = 92793 kgCO2eq$=92.80 $tonsCO2eq$

For 4600 cycle life : $132480\ kWh\ \times 0.537 \frac{kgCO2eq}{kWh} = 71142 kgCO2eq$=71.14 $tonsCO2eq$

As cab be seen by using China’s energy mix, GWP for this step significantly increased, but by using Norway’s energy mix the emission will be decreased around 94%.

6.2 Transportation During Lifetime

This step is related to transportation for charging the battery. As Skagerak is using biogas, GWP of different biogases are calculated and then the difference between diesel and biogas is discussed.

6.2.1 Biogas

Biogas is a combination of methane, CO_2 and small quantities of other gases that is created by the anaerobic digestion of organic materials in an oxygen-free environment. The specific composition of biogas is determined by the kind of feedstock and the production process, which includes the primary technologies listed below.[55]

- Bio digesters
- Landfill gas recovery systems
- Wastewater treatment plants

6.2.2 Tank-to-Wheel Data

Tank-to-wheel (TTW) indicates the use of fuel and emissions during driving and used phase. Tank-to-wheel data for methane-fueled heavy-duty vehicles are according to Euro VI engines, which represents long haulage / regional trucks equivalent to a total gross weight of 30 tons. Two different types of trucks were studied by research paper, one equipped with an internal combustion, spark-ignited (SI) engine manufactured by Scania (methane otto engine), and one with a prototype, dual-fuel (DF) methane diesel engine by Volvo. The methane otto engine is fueled with CBG/CNG, but calculations are also done for LBG/LNG. The dual-fuel methane diesel engine is fueled with LBG/LNG mixed with a minor portion of diesel. equivalents. All the characterization parameters apply to the global warming potential (GWP) within a 100-year period.[56]

Table 6.3 indicates TTW GHG emission for heavy-duty vehicles. All vehicles are following the Euro VI standard. Crankcase ventilation is considered for measuring emission levels of methane. The emissions of CH_4 and N_2O are much greater for cold engines than for warm engines, but long-distance travel is considered, therefore, emission data from warm engines is used in the calculations.

Bio-methane is considered as biogas, if it is formed through anaerobic digestion, it is shown as (AD), if it produced through thermal gasification, it is shown as (TG).

Compressed and liquefied methane of fossil origin are referred to as compressed natural gas (CNG) and liquefied natural gas (LNG), respectively.

Compressed and liquefied methane of renewable origin are presented as compressed biogas (CBG) and liquefied biogas (LBG), respectively.[56], [57]

6.2.3 GWP Calculation Based on Different Fuels

The fossil fuel reference systems according to [58] used the characterization factors 25 g for CH4 and 298 g for N2O CO_2-equivalents. All the characterization parameters apply to the global warming potential (GWP) within a 100-year period.[56]

Table 6.3:TTW GHG Emission for Heavy-Duty Vehicles [56], [58]–[62]

Engine	GHG emissions								
Item	CH4		N2O		CO2		GWP (CO2-eq)		Type of Fuel
Unit	g/MJ	g/km	g/MJ	g/km	g/MJ	g/km	g/MJ	g/km	
CNG (SI)	0.007	0.08	0	0	56.2	641	56.4	644	Fossil fuel
CBG(SI)	0.007	0.08	0	0	0	0	0.24	2.7	Renewable
LNG(DF)	0.056	0.54	0.006	0.058	57.1	552	60.8	588	Fossil fuel
LBG (DF)	0.056	0.54	0.006	0.058	3.7	35	7.4	71.6	Renewable
Diesel	0.002	0.019	0.006	0.058	73.2	709	75.0	727	Fossil fuel

Some assumptions are considered to calculate GWP for the Skagerak’s battery according to different kinds of fuel. Lifetime is considered to be between 4600-6000 cycles based on Samsung SDI battery (94Ah cell). According to one of student project [17],total distance traveled for one vehicle was reported 13.1 km, so based on that, the transportation for charging the battery assumed to be 20km per cycle.

Table 6.4 indicates GWP for each fuel for 20 km/Cycle in an ideal condition where the number of cycles is 6000 and GWP is calculated for 4600 cycles while other condition are the same.

Table 6.4:GWP for Different Fuels[56]

Engine	Type of Fuel	GWP g/km	GWP tonnsCO_2eq for 6000 cycles	GWP tonnsCO_2eq for 4600 cycles
Diesel	Fossil fuel	727	87.24	66.88
CNG (SI)	Fossil fuel	644	77.28	59.25
LNG(DF)	Fossil fuel	588	70.56	54.09
CBG(SI)	Renewable	2.7	0.32	0.25
LBG (DF)	Renewable	71.6	8.59	6.59

As it can be seen there is a significant difference for GWP depending on the type of fuel when they are produced from fossil sources or renewable sources. Diesel has the largest GWP which is reported 727 g/km, while GWP of renewable fuels like CBG and LBG are 2.7 and 71.6 g/km, respectively. If CBG is used as a fuel instead of diesel, GWP will be 99% lower and if LBG is used, emission of greenhouse gas will be 90% lower than when diesel is utilized, even using LNG instead of diesel results in lower emission around 19%. CBG indicated the best performance and the lowest level of GWP, as can be seen in table 6.3, regarding CBG, emission of N_2O and CO_2 are zero and GWP for this fuel is calculated only based on CH_4 emission. GWP of diesel is 270 times higher than CBG, therefore, using renewable origin fuels like CBG and LBG will significantly decrease the amount of GWP in transportation step for charging the battery.

6.3 GWP Comparison for Different Stages

GWP regarding energy loss and energy conversion has been estimated. As mentioned earlier, calculation GWP for use phase cannot be precise and accurate, as these calculations depend on energy used to produce electricity, which is known as energy mix, energy mix can be affected by location, so in lots of projects, LCA is defined to study only the production step. To estimate energy loss for the battery used in the construction site, specification of Samsung SDI battery has been used. As discussed, ideal cycle life for this specific battery is reported 6000, but according to the Samsung report, they predict 4600 charging cycles when SOH is 80%, also the optimal temperature in used phase is reported 25°C.According to data that Skagerak provided, battery capacity is 576 kWh and the energy transition losses is assumed 5%.To estimate GWP for this step ,energy mix in Norway used, which is 10g CO2e/kWh. Therefore, energy loss during lifetime is 1.32 and 1.73 for 4600 and 6000 cycles, respectively.

As stated in the earlier discussion, significant difference for GWP depending on the type of fuel, is clear. Diesel has the largest GWP which is reported 87.24 tons CO_2eq for 6000 cycles, while GWP of CBG is 0.32 for the same number of cycles, which is considered as renewable origin fuel. GWP of diesel is 270 times larger than CBG. Therefore, it is evident that use of renewable origin fuels like CBG and LBG will greatly reduce GWP in transportation step for battery charge. In conclusion, the GWP regarding used phase allocated the lower numbers in comparison to the production step.

Table 6.5:GWP Comparison for Use Phase[53], [54], [56]

Stage	GWP Tons CO_2eq	
Number of cycles	4600 cycles	6000 cycles
Energy loss during lifetime by using Norway’s energy mix	1.32	1.73
Energy loss during lifetime by using China’s energy mix	71.14	92.8
Transportation during lifetime(CBG)	0.25	0.32
Transportation during lifetime(LBG)	6.59	8.59
Transportation during lifetime(Diesel)	66.88	87.24

7 Discussion

The main objective of this study is analyzing simplified Life Cycle Assessment (LCA) for Skagerak's pilot project. Because of lack of real data, data for the production part has been sourced from various research papers. Also for use phase, the specification of Samsung SDI battery (94Ah cell) has been used.

NMC batteries are categorized as a rechargeable battery and have high energy density, therefore, they can save a large amount of energy with a low weight and volume. In order to compare NMC with different chemistries, it is noted that NMC111 has the highest GHG emissions, while nickel-rich batteries have lower GHG emissions and greater recycling advantages.

As it was mentioned the objective is analyzing Life Cycle Assessment (LCA) for Skagerak batteries. LCA is used to identify GHG emissions and other environmental impacts. In order to present the environmental impact, the product life cycle from production to use phase is assessed. As discussed, there are 15 impact factors. Since GWP is the most used impact category, for this study GWP is chosen as impact factor for production and use phases. In this study GWP_{100} has been presented but it is necessary to consider that calculation cannot be precise. GWP_{100} uses a single value over a 100-year time period for presenting the warming impact of different gases, while using a method with time-dependent variable can be more precise.

To analyze life cycle assessment of mobile battery used in Skagerak's pilot project, the first step is production phase. For calculation of GWP related to production part, real data were not accessible to define different steps like products and processes, so the information for production stage have been extracted from different research papers. The supply of raw materials, component manufacturing, cell and pack battery assembly, and infrastructure are all defined in the NMC production step. To determine the required energy for each LCA step of NMC 111 battery, the Ecoinvent 3.6 database has been used in research papers.

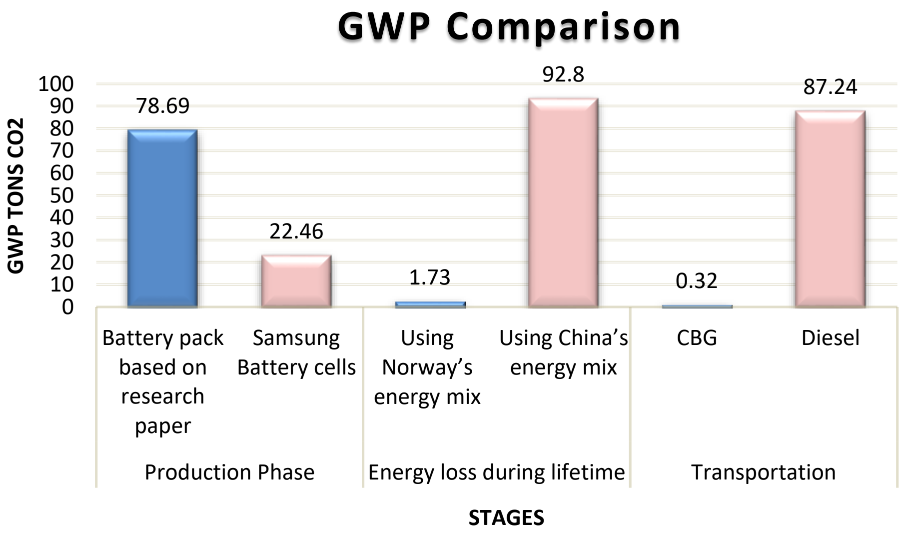

Figure 7.1:GWP comparison for different stages

Figure 7.1 shows GWP for different stages in production stage, use phase and the transportation for charging the batteries.

First, the energy consumption for the production stage of the battery has been used from research papers, then global warming potential related to the production phase has been estimated. Battery containers and charging containers were not considered. After that, the energy consumption during transportation based on the information provided by Skagerak has been presented. Production part has the highest GWP, which is 78.689 Tons CO2eq per battery pack production.

According to the Samsung battery the emission for battery cell of NMC111 is 39 kg/kWh, but it is unclear what stages were considered to achieve this number. There are two theories, first it seems that some stages have not been considered for GWP calculation, second theory is that Samsung might use an efficient method to produce the batteries which consume less energy, so GWP is lower than the GWP based on literature. For GWP calculation according to the battery for electrical car used in the research paper, some stages like cell production, non-cell material production, cathode production and final assembly have been calculated. Figure 7.1 shows GWP of production phase based on data from research papers in comparison with GWP according to Samsung report. As can be seen there is a significant difference.

Total GWP for transportation from production site to Skagerak's company is 2.169 metric tons CO_2eq.This step is considered as a part of production phase. The calculations have been done for three Samsung SDI batteries and two Rittal Cabinets, KE system to Skagerak and the container. GWP for three Samsung SDI batteries is 1.517 metric tons CO2e.The data clearly indicates that the GWP for transportation from production site to customer is significantly lower than the production part.

As discussed, battery production has the highest GWP, so for reducing GWP of production part, some solutions must be considered. More efficient methods for production should be utilized, for producing required energy for this step, renewable energy sources should be used to decrease carbon footprint. Also improving battery design can help to decrease materials and energy consumption during production. As earlier mentioned, NMC 111 has the highest GHG in comparison to Nickel-rich batteries, and also Nickel-rich batteries have greater recycling benefits.

Even though GWP for transportation from production site to Skagerak's company is much lower than battery production, producing the battery in Norway could still decrease around 2 metric tons CO_2eq.

When it comes to GWP calculation, the steps used to calculate it must be clear, otherwise it will not be possible to make a correct comparison, so finding solutions to improve methods and reduce emissions will be impossible.

Next step is use phase. It includes energy loss due to energy conversion and transportation for charging. It should be taken into account that the use phase depends on the energy used for producing electricity, therefore, there can be great differences based on location in the energy mix for producing electricity. For transportation stage (charging the battery), different fuels and their GWP has been presented. To estimate parameters, the specification of Samsung SDI battery (94Ah cell) has been used. As discussed, ideal cycle life for this specific battery is reported 6000, but according to the Samsung report when SOH is 80%, the life cycle reduces to 4600, moreover, the optimal temperature has been considered 25°C. The capacity of Skagerak battery is 576 kWh and the energy transition losses has been assumed 5%. To estimate GWP for this step, first energy mix in Norway used, which is 10g CO_2e/kWh. Therefore, energy loss during lifetime has been calculated 1.32 and 1.73 for 4600 and 6000 cycles, respectively. Then GWP for this stage has been calculated based on China's energy mix and the number for 6000 cycles and 4000 cycles are 92.8 and 71.14 tons CO2eq, respectively. Figure 7.1 indicates that energy mix in Norway in this step can significantly decrease GWP, reduction of around 94%.As can be seen, GWP for use phase by using energy mix in China is even higher than production stage. Therefore, it is vital to use energy mix in Norway to achieve the goal of reducing GWP for energy loss due to energy conversion. Also during use phase, it is vital to use machines that operate on electricity than diesel or other fossil fuels. Using electrical machines can minimize emission during use phase.

As discussed, there are significant differences for GWP depending on the type of fuel. Diesel showed the largest GWP which is 87.24 tons CO_2eq for 6000 cycles, while GWP of CBG is 0.32 for the same number of cycles, CBG is considered as renewable origin fuel. GWP of diesel is 270 times larger than CBG. Therefore, it is evident that use of renewable origin fuels like CBG and LBG will significantly decrease GWP in transportation step for battery charge. Figure 7.1 indicates that GWP is notably high, when diesel is used as a fuel. This GWP can even exceed GWP caused by production stage, so it is necessary to use biogas for transportation for charging the battery, another factor that can effect GWP for transportation is distance, in this study 20 km was assumed, but reducing the distance to charging station can decrease GWP caused by transportation for charging the battery, therefore, decrease the total GWP for the use phase.

In conclusion, it is obvious that the GWP regarding use phase is lower in comparison to the production step, but still it causes emission, so considering the mentioned solutions can be helpful to decrease GWP.

8 Conclusion

The study's main goal was estimating GWP of Skagerak's battery, which is used to power construction site, GWP for both production phase and use phase has been assessed. The results show that production phase has the highest GWP.GWP regarding energy loss due to energy conversion and transportation required for charging the battery are lower in comparison to production step. Also, the results indicated that GWP can be significantly affected by the type of fuel used for transportation and it is obvious that biogas can significantly reduce emissions.

In conclusion, for reducing energy consumption and its impact on the environment, it is vital to pay attention to production phase and improve the method of production by using energy efficient methods and cleaner production technologies. Also, it is undeniable that using renewable fuels can significantly decrease the GWP of transportation for charging the batteries.

8.1 Future work

1. Access to Real Data

Since the data used for production phase were based on literature review, and use phase were assessed based on some assumptions, not based on real data, therefore, the results cannot be precise. For improving the accuracy of results, access to actual data is necessary. Also accessing real data can be used to define all necessary steps in LCA, so analyzing detailed LCA through OpenLCA or other related software will be possible. Moreover, container and charging container were not considered in this project, but by considering these components in the analysis, more accurate and precise results will be possible.

2. Evaluate the Environmental Impact of Other Li-ion Batteries.

As each battery has a different environmental impact, investigating different kinds of battery like LFP(LiFePO4) and NMX (free of Cobalt batteries) can be helpful to make a better decision for choosing battery for construction site.

3. Investigate other impact factors.

In this study GWP of battery has been reviewed, but other impact factors POP (Photochemical Ozone Creation Potential), AP (Acidification Potential) and ADP (Abiotic Depletion Potential) can provide a more comprehensive evaluation.

4. Evaluate End of Life

This project studied production and use phase based on literature review and some assumption, but end of life of batteries, including recycling, reuse and disposal have impact factors, so including this part can improve the evaluation the overall environmental impact of batteries.

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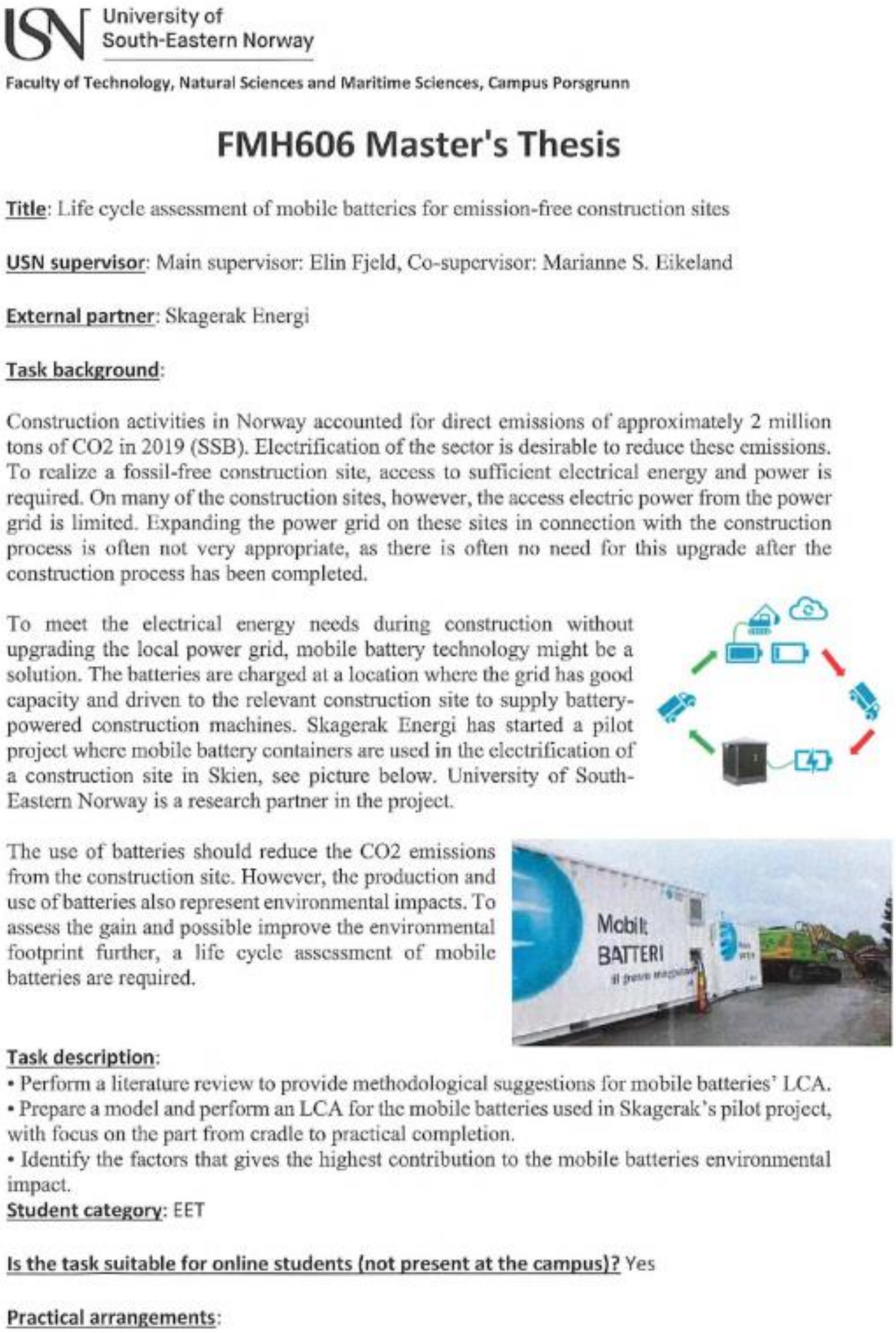
Appendices

Appendix A – Project description:



University of South-Eastern Norway

Faculty of Technology, Natural Sciences and Maritime Sciences, Campus Porsgrunn

FMH606 Master's Thesis

Title: Life cycle assessment of mobile batteries for emission-free construction sites

USN supervisor: Main supervisor: Elin Fjeld, Co-supervisor: Marianne S. Eikeland

External partner: Skagerak Energi

Task background:

Construction activities in Norway accounted for direct emissions of approximately 2 million tons of CO2 in 2019 (SSB). Electrification of the sector is desirable to reduce these emissions. To realize a fossil-free construction site, access to sufficient electrical energy and power is required. On many of the construction sites, however, the access electric power from the power grid is limited. Expanding the power grid on these sites in connection with the construction process is often not very appropriate, as there is often no need for this upgrade after the construction process has been completed.

To meet the electrical energy needs during construction without upgrading the local power grid, mobile battery technology might be a solution. The batteries are charged at a location where the grid has good capacity and driven to the relevant construction site to supply battery-powered construction machines. Skagerak Energi has started a pilot project where mobile battery containers are used in the electrification of a construction site in Skien, see picture below. University of South-Eastern Norway is a research partner in the project.

The use of batteries should reduce the CO2 emissions from the construction site. However, the production and use of batteries also represent environmental impacts. To assess the gain and possible improve the environmental footprint further, a life cycle assessment of mobile batteries are required.

Task description:
- Perform a literature review to provide methodological suggestions for mobile batteries' LCA.
- Prepare a model and perform an LCA for the mobile batteries used in Skagerak's pilot project, with focus on the part from cradle to practical completion.
- Identify the factors that gives the highest contribution to the mobile batteries environmental impact.

Student category: EET

Is the task suitable for online students (not present at the campus)? Yes

Practical arrangements:

Supervision:
As a general rule, the student is entitled to 15-20 hours of supervision. This includes necessary time for the supervisor to prepare for supervision meetings (reading material to be discussed, etc).

Signatures:

Supervisor (date and signature): ELIN FJELD, MARIANNE S. EIKELAND

Student (write clearly in all capitalized letters): SAFA KHODABAKHSH

Student (date and signature): 31.01.2023