Environmental impact of Li-ion battery production

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Bachelor’s thesis
LUT School of Energy Systems
Electrical Engineering

30 May 2022

ABSTRACT

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2022

Bachelor's thesis.
30 p.
Examiner: Juha Pyrhönen

This bachelors thesis is a literature review that focuses on the carbon footprint of a NMC 111 lithium-ion battery (LIB) while neglecting end-of-life and use-stages. Research for this thesis was done using reliable online sources and cross-referencing them with each other.

The goal of this thesis is to find out how much CO_2 is released in the manufacturing of a NMC 111 electric vehicle battery in kg CO_2-eq/kWh capacity. An additional interest is finding out the amount of different materials used in the production and their respective energy usage.

The overall global warming potential (GWP) of a NMC 111 LIB while not including end-of-life (EoL) emissions is between 61-106kg CO_2-eq/kWh depending on the energy source used for heating. A more precise estimate of the average energy usage is 70kg CO_2-eq/kWh - 77kg CO_2-eq/kWh with a result of 72.9kg CO_2-eq/kWh being the most accurate.

Transportation amounts for most of EoL CO_2 emissions with 12.7kg CO_2-eq/100km. Emissions from hydrometallurgy are 2.13kg CO_2-eq/kg cell and pyrometallurgy 2.1kg CO_2-eq/kg cell.

Majority of used materials (83.7%) consist of the active cathode material (28.7%), aluminium (25.3%), graphite (16%) and copper (13.7%). The amount of energy used for these four components during production is 81.14% of total energy consumption as follows, NMC powder (45%), aluminium (22.37%), graphite (9.74%) and copper (4.03%).

TIIVISTELMÄ

Lappeenranta–Lahti University of Technology LUT
School of Energy Systems
Sähkötekniikka

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Li-ion akkujen tuottamisen ympäristövaikutukset
2022

Kandidaatintyö
10 op.
Tarkastaja: Juha Pyrhönen
Ohjaaja: Juha Pyrhönen

Tämä kandidaatintyö on kirjallisuuskatsaus, joka keskittyy NMC 111 -litiumioniakun hiilijalanjälkeen jättäen huomioimatta käyttöiän loppumisen ja käyttövaiheet. Tutkimus tehtiin luotettavien verkkolähteiden avulla ja niiden ristiviittauksella.

Työn tavoitteena on selvittää, kuinka paljon hiilidioksidia vapautuu NMC 111 -sähköajoneuvon akun valmistuksessa kg CO_2-ekv/kWh kapasiteettia kohden. Lisäksi halutaan saada selville tuotannossa käytettyjen eri materiaalien määrä ja niiden energiankäyttö.

NMC 111 akun yleinen ilmaston lämpenemispotentiaali (GWP) huomioimatta käyttöiän loppuvaihetta (EoL) on välillä 61-106 kg CO_2-ekv/kWh riippuen lämmitystavasta. Tarkempi arvio keskimääräisestä hiilijalanjäljestä on 70 kg CO_2-ekv/kWh - 77 kg CO_2-ekv/kWh, tarkin tutkimuksesta saatu tulos on 72,9 kg CO_2-ekv/kWh.

Käyttöiän loppuvaiheen suurin päästötekijä on kuljetus jonka päästöt ovat 12.7kg CO_2ekv/100km. Päästöt hydrometallurgiasta ovat 2.13kg CO_2-ekv/kg kennoa kohden ja pyrometallurgiasta 2.1kg CO_2-ekv/kg kennoa kohden.

Suurin osa käytetyistä materiaaleista (83,7%) koostuu aktiivisesta katodimateriaalista (28,7%), alumiinista (25,3%), grafiitista (16%) ja kuparista (13,7%). Näiden neljän komponentin energiatarve valmistuksen kokonaisenergiatarpeesta on 81,14% ja se jakautuu seuraavasti, NMC-jauhe (45%), alumiini (22,37%), grafiitti (9,74%) ja kupari (4,03%).

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

BEV	Battery Electric Vehicle
BMS	Battery management system
CO_2	Carbon dioxide
CMC	Carboxymethyl cellulose
DMC	Dimethyl carbonate
DRC	The Democratic Republic of Congo
EC	Ethylene carbonate
EoL	End-of-life
GHG	Greenhouse gas
GWP	Global warming potential
LCO	Lithium cobalt oxide
LCA	Life-cycle assessment
LIB	Lithium-ion battery
LFP	Lithium iron phosphate
LMO	Lithium manganese oxide
NaOH	Sodium hydroxide
NCA	Nickel cobalt aluminium
NMC	Nickel manganese cobalt
PE	Polyethylene
PET	Polyethylene Terephthalate
PP	Polypropylene
PVDF	Polyvinylidene fluoride
SBR	Styrene-Butadiene

1. INTRODUCTION

This bachelor's thesis is a literature review of the environmental impact Li-ion battery production. With the increase in battery electric vehicles (BEV) around the world, it is important to know how big the greenhouse gas (GHG) emissions from the production of BEVs are. Currently 16% of worldwide GHG emissions are from transportation with CO_2 accounting for 76% of total emissions *(CAIT data: Climate Watch 2020)*. Lowering this number is a key part to achieving carbon neutrality and negativity in developed countries. One way to help achieve this goal, is by creating efficient and environmentally friendly batteries for cars, reducing the amount of GHG emissions from transportation.

Many studies have been made on the environmental impact of Lithium-ion battery (LIB) production. Most of these studies focus on the production stage of the battery. Some End-of-life (EoL) studies have also been made, but due to lack of reliable data most researchers have decided to neglect the EoL stage *(Accardo et al., 2021)*.

The battery of focus for this thesis is the nickel manganese cobalt battery chemistry (NMC 111) and the environmental effects of producing one. According to Accardo et al. (2021) due to low recycling of this battery type the environmental benefit could be a loss. The goal of this thesis is to find out how much CO_2 is released in the manufacturing of a NMC 111 electric vehicle battery in kg CO_2-eq/kWh capacity. There is also an interest in the end-of-life emissions. Other goals for this thesis include figuring out how many metals and how much of them are used in the manufacturing of a NMC battery and the energy usage they have. As this is a literature review it is important to keep in mind that the information in this thesis is based solely on other studies and only combines the results of said studies.

1.1 Methods

The methods used in this literature review consist of researching articles online, in libraries and cross-referencing them with each other. Life-cycle assessment (LCA) and EoL studies about Nickel-Manganese-Cobalt batteries are the focus of this literature review. Published works that are referred to should be at most a decade old (2010 onwards), to have the most accurate information. Structure wise this thesis will first briefly describe the different types of LIBs and the major differences between them. Afterwards the focus will be on NMC 111 batteries life-cycle assessment in the production stage.

2. ELECTRIC VEHICLE BATTERIES

Multiple different LIB chemistries have been studied for use in vehicles. The first ones to be used were Lithium Cobalt Oxide (LCO) and Lithium Manganese Oxide (LMO) cathodes. Afterwards Nickel-Manganese-Cobalt (NMC), Lithium Iron Phosphate (LFP) and Lithium Nickel Cobalt Aluminium Oxide (NCA). The biggest differences in modern LIB are reliability, stability, lifetime and cost. LFP batteries have an outstanding cycle stability and lengthy lifetime, but low energy density and therefore are losing popularity in commercial BEVs compared to NMC and NCA batteries. NCA batteries have the highest energy density but are considered less safe. NMC batteries have the 2nd highest energy density after NCA ones and are currently used in most power tools, electric bikes and other appliances. NMC and NCA chemistries are also currently the ones being worked toward the most, this can be seen by the increasing number of patents for both chemistries *(Accardo et al., 2021)*.

The three most used electric vehicle LIBs in China (as of 2017) are the LFP (52%) battery, NMC (39%) battery and LMO (3%) battery *(Han Hao et al., 2017)*. Nearly all electric vehicles today use NMC or NCA chemistries so looking at the production and GHG emissions of a NMC battery should give a good idea on the scale of emissions from vehicle batteries. The popularity of different BEV batteries is based on a study made in China, so results may differ in other parts of the world. *(Erik Emilsson & Lisbeth Dahllöf 2019).*

Modern NMC batteries along with NCA batteries require multiple different metals in order to be manufactured. The critical requirement for both the NMC and NCA is cobalt, in addition to lithium, nickel, copper and aluminium *(Erik Emilsson & Lisbeth Dahllöf 2019)*. The focus of this thesis is the cathode combination NMC111 which is made of one-third Nickel, one-third Manganese and one-third Cobalt. Cobalt is expensive and limited in supply so it determines the overall cost and sustainability of NMC batteries. Since cobalt is the limiting factor manufacturers have started to look for alternatives which decrease the amount of cobalt in batteries, shifting toward cathodes with more nickel *(Accardo et al., 2021)*.

3. PRODUCTION STAGES

LIB production roughly follows the outline in figure 1, with mining & refining being the first step then followed by battery material production, cell production & battery pack assembly, transport and infrastructure. The amount of materials used per kg of a NMC LIB can be seen in table 1. Much of a LIB (83.7%) consists of the active cathode material (28.7%), aluminium (25.3%), graphite (16%) and copper (13.7%).

Table 1. Shares of materials used in the production of a NMC 111 lithium-ion battery per kg of battery *(Accardo et al. 2021)*.

	NMC 111
Cell materials	**kg**
Active Cathode Material	0.287
Graphite	0.160
Carbon black	0.020
Binder (PVDF)	0.025
Copper	0.134
Aluminium	0.069
Electrolyte: $LiPF_6$	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
Aluminium	0.184
Steel	0.007
PET	0.005
Electronics	0.037

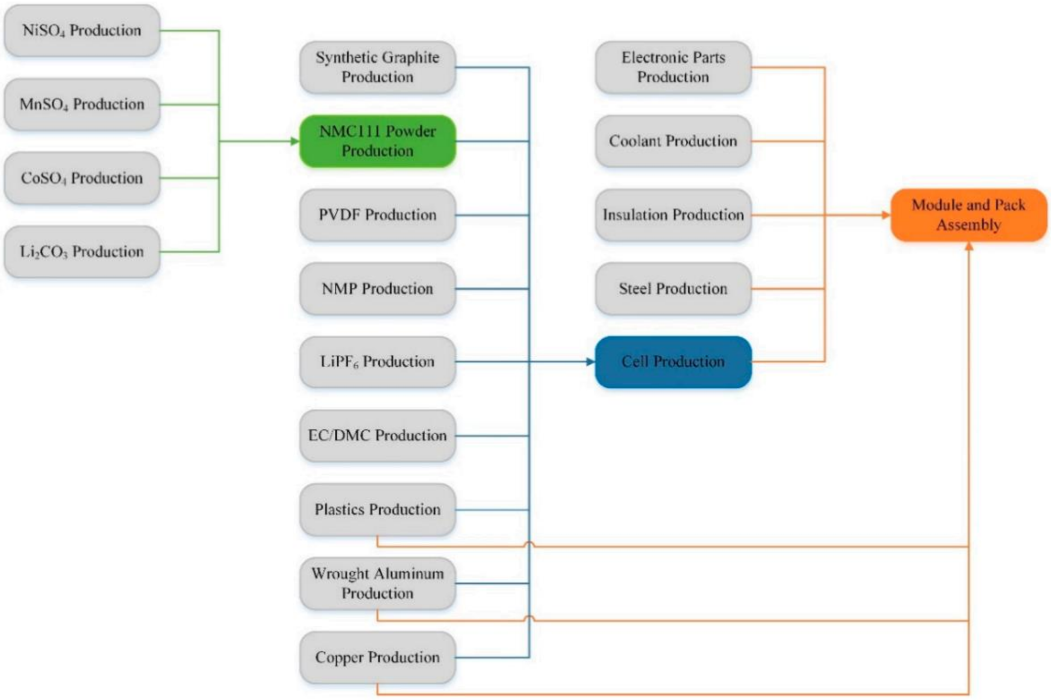

Figure 1. Cradle-to-gate NMC 111 battery production cycle *(Dai et al., 2019, p. 4).*

3.1 Mining

Cobalt is the critical mineral required to manufacture a NMC 111 battery, according to *(Tsurukawa et al., 2011)* it is mainly found as a by-product of nickel mining, except in Africa where it is mined as a primary product or by-product of copper. Its demand has tripled globally over the past decade, due to increasing demand in rechargeable batteries and catalysts *(Calvão et al., 2021)*. According to The Faraday Institution (2020) its demand is expected to double again by 2035. Global reserves of cobalt are estimated to amount 7.3Mt by USGS with the African Copperbelt holding more than half of them *(Tsurukawa et al., 2011)*. The worlds largest cobalt supplier is The Democratic Republic of Congo (DRC) where it is gathered by both artisans (20-30%) and industrial means. Most of the workers mining cobalt in DRC work in extremely poor conditions and some are forced to work by violence, in some cases child labour is also used *(Calvão et al., 2021)*.

3.2 Powder Production

The anode for LIBs is typically made of graphite, while the cathode is in the form of a powder made in a two-stage process. The first stage is the production of the precursor for the NMC powder, this begins with $NiSO_4$, $MnSO_4$ and $CoSO_4$ reacting with hydroxide. This allows the different parts of the powder to dissolve and mix properly. Sodium hydroxide (NaOH) and ammonium hydroxide (NH_4OH) are then added, after which the substance is heated to 50°C and kept at temperature for a prolonged period. This completes the coprecipitation and forms $NMC(OH)_2$ after which it is filtered, washed and dried in order to produce the NMC precursor. During the second stage the precursor is mixed with Lithium carbonate Li_2CO_3 and calcinated. *(Accardo et al. 2021).*

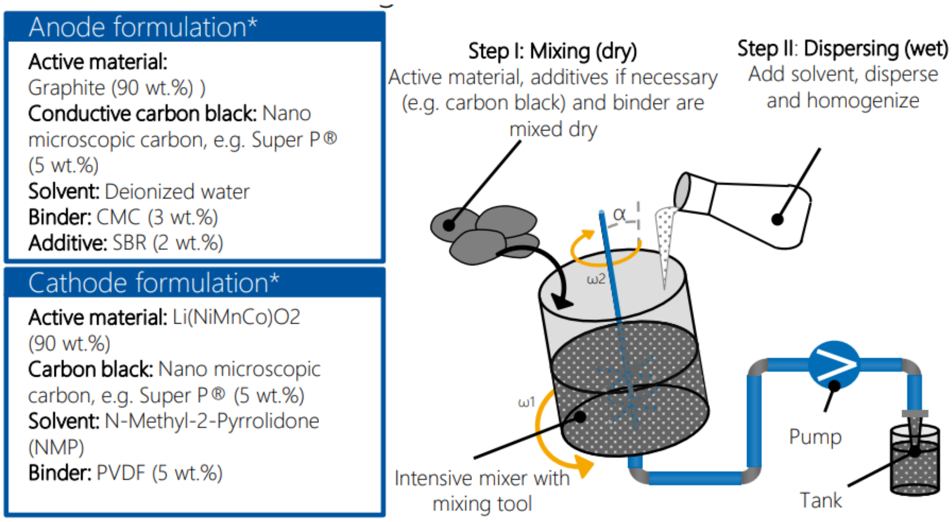

Figure 2. Mixing of materials for lithium-ion battery powder: Carboxymethyl cellulose (CMC), Styrene-Butadiene (SBR). *(Heimes et al. 2018).*

3.3 Cell production

There are three different cell designs for LIBs: pouch, cylindrical and prismatic as can be seen in figure 3. Although the designs have slight differences, the principle is the same for all the designs. As Heimes et al. (2018) stated “Regardless of the cell type, the smallest unit of any lithium-ion cell consists of two electrodes and a separator, which separates the electrodes from each other. The ion-conductive electrolyte fills the pores of the electrodes and the remaining space inside the cell.”.

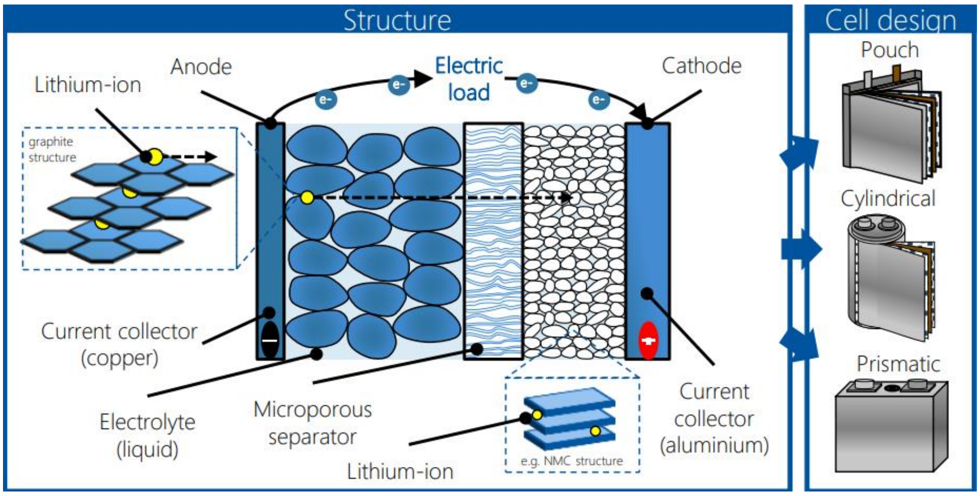

Figure 3. Cell design of a lithium-ion battery *(Heimes et al. 2018)*.

Copper foils serve as current collectors for the anode and aluminium foils for the cathode. A porous membrane separates the two electrodes from touching, while allowing the electrons to flow with as little resistance as possible *(Majeau-Bettez et al. 2011)*. The anode is graphite that has been treated at 1100°C in order to purify it from oxygen and a PVDF (polyvinylidene fluoride) binder *(Majeau-Bettez et al. 2011)*. A polymeric binder material holds the active particles together *(Dunn, J.K.J et al. 2015)*. The pores of both active materials and separator are filled with electrolyte $LiPF_6$ (Lithium hexafluorophosphate). The battery management system (BMS) monitors the battery and makes sure it works in safe parameters. It also continually optimizes performance, reports operational status to external devices and estimates the operational state. The cooling system makes sure the battery works even when not in optimal temperature and the packaging works as structural support *(Cusenza et al. 2019)*.

4. RESULTS

The active cathode material, copper, aluminium and energy use during battery production are the main environmental contributors *(Accardo et al. 2021)*. This is supported by table 2 *(Erik Emilsson & Lisbeth Dahllöf, 2019)* where the four most energy consuming materials are NMC 111 powder (45%), aluminium (22.37%), graphite (9.74%), and copper (4.03%). According to Dai et al 2019 the global warming potential (GWP) to produce a NMC 111 battery was 72.9kg CO_2-eq/kWh capacity and from only upstream materials sourcing 59kg CO_2-eq/kWh capacity. However, according to Erik Emillson & Lisbeth Dahllöf (2019) study which uses data from Dai et al 2019 the energy usage varies from 61-106kg CO_2-eq/kWh depending on the electricity mix used. A clean mix consisting of renewables having the smallest emissions of 61kg CO_2-eq/kWh and the top 106kg CO_2-eq/kWh using only fossil fuels. Emillsson & Dahllöf conclude that “When natural gas is used for heating, the emissions range from 70-77kg CO_2-eq/kWh battery capacity” which is consistent with Dai et al 2019 72.9kg CO_2-eq/kWh.

Table 2. Percentages of energy consumption per kg of battery. *(Erik Emilsson & Lisbeth Dahllöf 2019).*

	Material/process	**Share of energy [%]**
Cell Components	NMC111 powder	45.0
	Graphite	9.74
	Carbon black	1.18
	Binder Polyvinylidene fluoride (PVDF)	0.60
	Copper	3.92
	Aluminium	5.57
	Electrolyte: Lithium hexafluorophosphate ($LiPF_6$)	2.23
	Electrolyte: Ethylene carbonate (EC)	0.35
	Electrolyte: Dimethyl carbonate (DMC)	1.30
	Plastic: Polypropylene (PP)	0.67
	Plastic: Polyethylene (PE)	0.16
	Plastic: Polyethylene Terephthalate (PET)	0.12
Module components	Copper	0.09
	Aluminium	4.10
	Plastic: Polyethylene (PE)	0.07
	Insulation	0.01
	Electronic parts	2.09
Pack components	Copper	0.02
	Aluminium	12.7
	Steel	0.15
	Insulation	0.09
	Coolant	0.66
	Electric parts	9.16

4.1 Mining

The amount of GHG emissions from mining is difficult to determine. This is due to lack of reliable data which in turn is most likely due to differing laws and regulations in countries that are in the African Copperbelt. Erik Emilsson & Lisbeth Dahllöf (2019) stated ‘The only energy reported from one mine, the diesel use, was 163kWh/ton mined ore of 0.32% cobalt and the other mine reported electricity as the only energy use: 61.7kWh/ton mined ore of

0.51% cobalt...’. In addition to energy usage mining also makes the nearby land uninhabitable and reduces biodiversity by disrupting wildlife in the area. The environmental impact of mining is likely to be much more than the estimated diesel and energy usage.

4.2 Cell production

Cell production makes up 70.84% of the energy usage (table 1). Cell production needs to happen in a dry room where humidity can be properly adjusted and controlled *(Kwade et al. 2018)*. Therefore, majority of the energy used is dedicated to this dry room process, hence it has been acknowledged as the principal energy use for cell production *(Ahmed et al. 2016) (Ellingsen et al. 2014)*. Electrode drying has also been identified as a significant contributor due to requiring the same dry room methods *(Ahmed et al. 2016)*. The amount of energy used by each component can be seen in table 3. Cell components make up 645 MJ/kWh capacity battery where as Cell production and battery pack assembly 216.2 MJ/kWh.

Table 3. Energy shares for materials and cell manufacture process *(Erik Emilsson & Lisbeth Dahllöf 2019)*.

Materials and Processes		**Energy [MJ/kWh capacity battery]**
Cell components	NMC111 powder	409.9
	Graphite	88.6
	Carbon black	10.7
	Binder (PVDF)	5.5
	Copper	35.7
	Aluminium	50.7
	Electrolyte: LiPF6	20.3
	Electrolyte: EC	3.2
	Electrolyte: DMC	11.8
	Plastic: PP	6.1
	Plastic: PE	1.4
	Plastic: PET	1.1
Module components	Copper	0.8
	Aluminium	37.4
	Plastic: PE	0.6
	Insulation	0.1
	Electronic parts	19
Pack components	Copper	0.2
	Aluminium	116
	Steel	1.3
	Insulation	0.8
	Coolant	6
	Electric parts	83.4
Solvent	NMP (Recycled)	0.0
Cell Production and Battery Pack Assembly		216.2
Total		1127

Powder production consumes 45% of the energy share for the entire manufacturing process *(Dai et al, 2019)* and 63.5% for cell component energy usage. As can be seen in figure 4 most of the energy usage in powder production goes toward Co-precipitaion and Calcination with 43%**.** Nickel ($NiSO_4$ 12%), Manganese ($MnSO_4$, 1%) and Cobalt ($CoSO_4$, 24%) make up around 37% and the remaining 20% of energy usage is from Li_2CO_3 (7%), NaOH (12%) and NH_4OH (1%). The amount of energy used for making the NMC 111 powder is (table 2) 409.9 MJ/kWh capacity battery *(Dai et al. 2019)*.

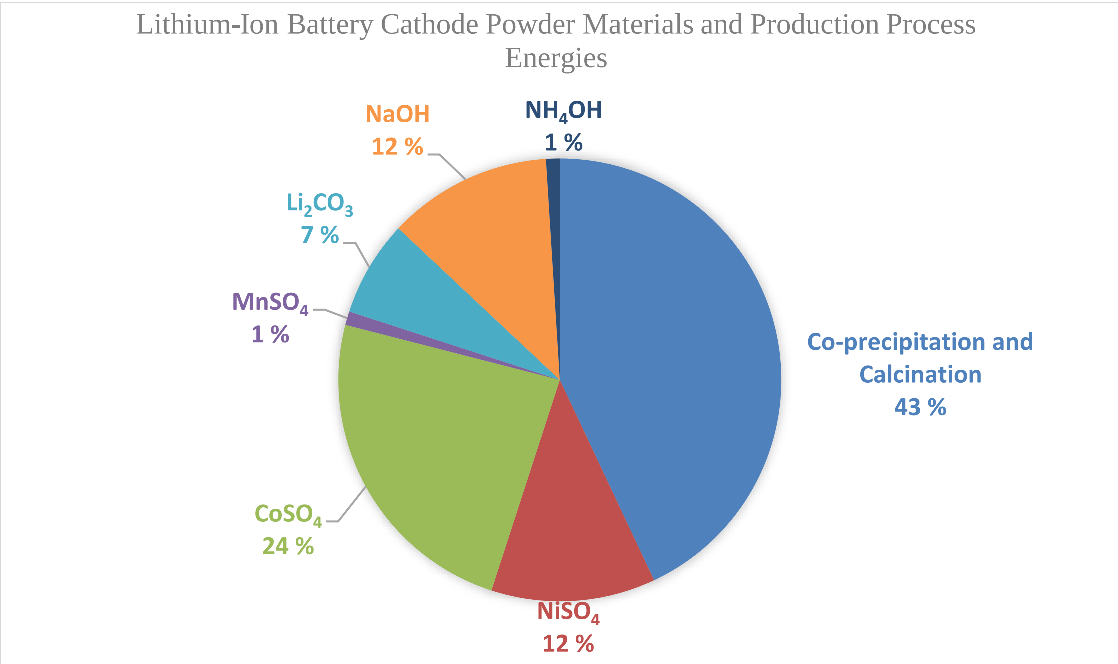

Figure 4. Percentage energy used for manufacturing of NMC 111 powder *(Erik Emilsson & Lisbeth Dahllöf 2019)*

4.3 Transportation

Analyzing the GWP of LIB transportation from factory to consumer is difficult due to differing transportation methods and routes. Depending on the location of the manufacturing plant the transportation GHG emissions can differ largely. According to Accardo et al. 2021 “The transport of batteries contributes less than 1% to all the examined categories” which is also supported by Ciez & Whitacre (2019) who state it contributes to 3.5%. Therefore, it is safe to assume that the GWP impact of transportation is a minor part of the total GWP.

4.4 End-of-life

The EoL stage consists of battery transport to EoL, recycling, incineration and landfill (figure 5). Most of the GHG emissions from EoL are generated by transportation *(Sorvisto. 2022)*. The transportation of 1kg of used LIBs amounts for 12.7kg CO_2-eq/100km *(Samarukha. 2020)*. There are two methods of recycling for NMC111 LIBs pyrometallurgy and hydrometallurgy. According to Samarukha (2020) the emissions from recycling NMC 111 batteries by pyrometallurgy are 2.1kg CO_2-eq/kg cell and by hydrometallurgy 2.13kg CO_2-eq/kg cell. However, the results for each individual battery will be different due to differences in the number of cells the battery has, transportation distance and energy source used *(Sorvisto. 2022)*.

EoL global warming potential also depends on location. Differing regulations around the world require some regions like the European Union (EU) to regain up to 95% of cobalt, copper, nickel and 70% of lithium *(European Parliament)*. Other regions like Australia only require 2% of their annual 3300 tonnes to be recycled *(Lithium-ion battery recycling. 2021)*.

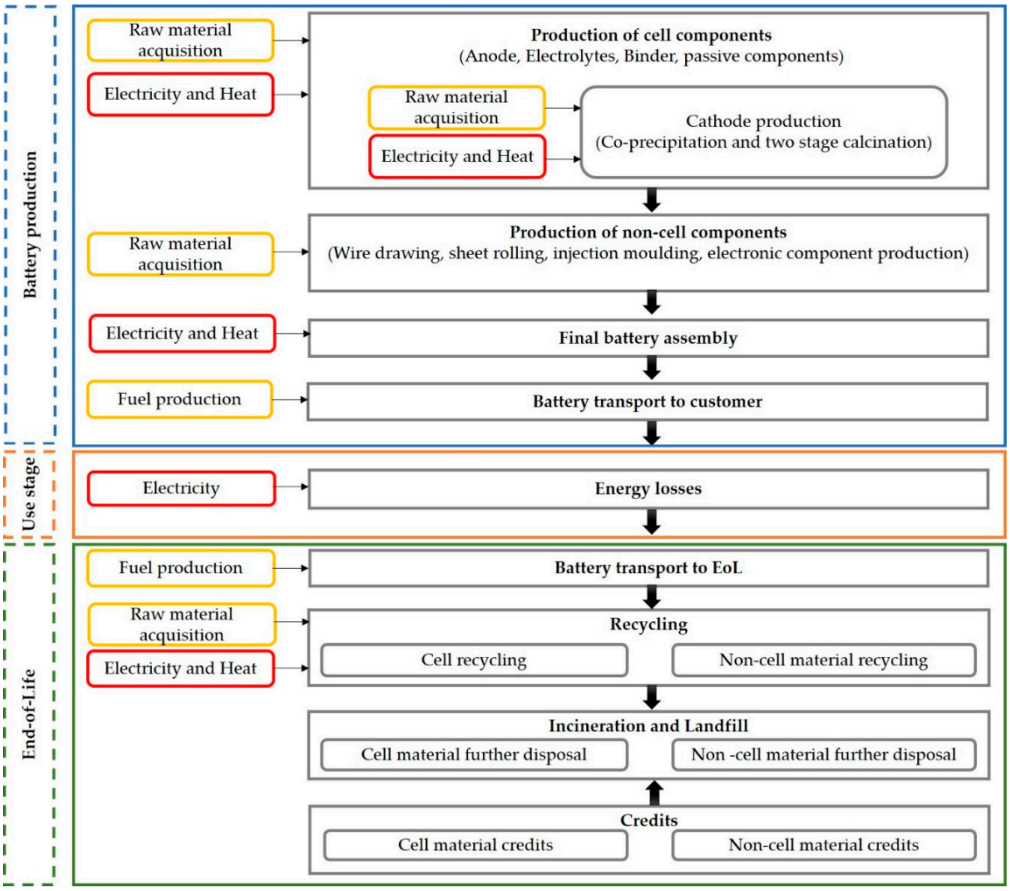

Figure 5. Different stages of a LIBs life-cycle *(Accardo et al. 2021)*.

5. CONCLUSIONS

The overall global warming potential from the production of a NMC 111 lithium-ion battery while neglecting EoL and use-stage is between 70-77kg CO_2-eq/kWh. This is subject to change depending on the energy source used for the heating of NMC 111 powder. Emissions range from 61kg CO_2-eq/kWh while using renewable energy sources to 106kg CO_2-eq/kWh when using fossil fuels. The most accurate result is from Dai et al. (2019) which is 72.9 kg CO_2-eq/kWh and fits well into the average of 70-77kg CO_2-eq/kWh. Therefore, a way to lower emissions is to use renewable energy for the production stage of LIBs.

The overall GWP including transportation and EoL is difficult to determine. Even with data of the CO_2 emissions from EoL transportation (12.7kg CO_2-eq/100km), hydrometallurgy (2.13kg CO_2-eq/kg cell) and pyrometallurgy (2.1kg CO_2-eq/kg cell) there are still too many variables to determine average emissions. These variables include location, transportation distance, energy source for recycling and number of cells the battery has. Accurate data could be gathered by individual studies for differing locations.

Outside of the active cathode materials which consist of a third Nickel, a third Manganese and a third Cobalt the most used materials in the production of a NMC 111 LIB are aluminium 25.3%, graphite 16% and copper 13.7% as can be seen in table 1. Together with the active cathode material 28.7% they make up 83.7% of the total material used in the making of a battery. The amount of energy used by these four components is NMC powder 45%, aluminium 22.37%, graphite 9.74% and copper 4.03% which totals to 81.14% of total energy consumption.

Out of the different production stages the cell and powder production are the most emission intensive contributing over 70% of the total energy usage. Transportation is stated to use only 1% *(Accardo et al. 2021)* or 3.5% *(Ciez & Whitacre 2019)* and as such is negligible in this study. Mining is highly likely to cause more GWP than results and data show. This is because of lack of regulations and data in countries where the critical minerals are mined in addition to environmental damage caused by the mine itself. The scale of environmental impact from mining will therefore be different for each location.

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