Possibilities of minimising cobalt usage in the electric passenger car industry

A comparison between different lithium-ion cathodes and their potential to lower the cobalt usage within the electric passenger car industry in the near future.

Jakob Busck, Marcin Kryger, Daniel Näs, Filip Rosén, Karl Steen and Erik Wallin

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
www.chalmers.se

Bachelor thesis report 2024

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Cover: Batteries from laboratory production. © Marcin Kryger, 2024.

Typeset in LaTeX
Gothenburg, Sweden 2024

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Abstract

Lithium-ion batteries are an essential and important part of the future, and play a crucial role in fulfilling the Paris agreement and the building of a sustainable future. Battery electric cars are pointed out as a key solution to electrify the transport industry and the majority of electric cars today are equipped with NMC batteries. Due to shortage and the complex supply chains, high price and the poor working conditions associated with cobalt mining, the industry works to phase out cobalt and replace cobalt-rich NMC batteries with different cathode chemistries containing less cobalt. By using literature studies and manufacturing coin cells with different cathode chemistries, this report aims to investigate whether alternative cathodes can be used today or within the near future. The investigated cathodes were examined in terms of cost, performance, safety, environmental- and social sustainability. Moreover, interviews with two representatives from the industry were conducted to discuss industry information and deepen the general comprehension of large scale battery production. The conclusion that could be drawn was that there are several possible alternative cathode chemistries without cobalt. However, all examined cathode chemistries have advantages and limitations that make different cell chemistries better suited depending on the usage.

Keywords: lithium-ion, lithium, battery, NMC, LFP, LFMP, cobalt, cathode.

Sammandrag

Litiumjonbatterier är redan idag av stor vikt och kommer utgöra en viktig del av framtidens energisystem. För att kunna nå Parisavtalets utsläppsmål för att reglera global uppvärmning krävs hållbart producerade lithiumjonbatterier. För eldrivna personbilar är litiumjonbatterier med den koboltrika cellkemin NMC vanligt förekommande. På grund av komplexa logistikkedjor, höga kostnader och dåliga arbetsförhållanden inom koboltsgruvindustrin, försöker elbilsindustrin byta ut de koboltrika katoderna mot andra katodmaterial som innehåller mindre kobolt. Genom en litteraturstudie och tillverkning av battericeller försöker rapporten besvara vilka katodmaterial som kan ersätta de koboltrika battericellerna inom en snar framtid. De undersökta katoderna undersöktes i termer om kostnad, prestanda, säkerhet, social och miljömässig hållbarhet. Intervjuer från industrirepresentanter genomfördes för att komplettera litteraturstudien och få den senaste informationen samt besvara komplexa och tvetydiga frågor som litteraturstudien hade svårt att besvara. Slutsatsen som kan dras är att det finns alternativa cellkemier som minskar koboltanvändningen. Alla undersökta katodmaterial har för- och nackdelar vilket lämpar olika cellkemier till olika användningsområden.

Acknowledgements

The authors would like to thank several people that has, in different ways, contributed to this thesis.

Primarily, we wish to thank our supervisor Jinhua Sun and examiner Uta Klement for continuous supervision and help throughout the project from the first to the last day of work. Their continuous feedback, guiding and help to connect with industry representatives have been a fantastic help, for which we are extremely grateful.

We would also like to thank Tianlin Zhang for his constant supervision and help while producing batteries in the graphene laboratory.

Finally we wish to extend a thank you to Niels Boardman Jonson from Mattr Collective AB and the anonymous battery engineer working for a major battery manufacturer. Their help to interpret and understand ambiguous information and gain knowledge about the industry have been priceless, for which we are immensely grateful.

Jakob Busck, Marcin Kryger, Daniel Näs, Filip Rosén, Karl Steen and Erik Wallin, Gothenburg, May 2024.

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BOM	Bill Of Materials
CMC	Carboxymethyl Cellulose
DOD	Depth Of Discharge
EFC	Equivalent Full Cycles
LCA	Life Cycle Assessment
LLOs	Lithium-rich Layered oxides
LFMP	Lithium-Iron-Manganese-Phosphate
LFP	Lithium-Iron-Phosphate
NMP	N-Methyl-2-Pyrrolidone
NMC	Nickel-Manganese-Cobalt-oxides
PVDF	Polyvinylidene Fluoride
SEI	Solid Electrolyte Interface
SBR	Styrene-Butadiene Rubber

Contents

List of Acronyms **xi**

List of Figures **xv**

List of Tables **xvii**

1 Introduction **1**
- 1.1 Background 2
- 1.2 Purpose 2
- 1.3 Goals 2
- 1.4 Limitations / Demarcations 3

2 Theory **5**
- 2.1 Cell chemistry 6
  - 2.1.1 Cathode material 7
  - 2.1.2 Anode material 7
  - 2.1.3 Electrolyte 7
  - 2.1.4 Future battery concepts 8
- 2.2 Cell geometry 8
  - 2.2.1 Cylindrical cells 8
  - 2.2.2 Prismatic cells 9
  - 2.2.3 Pouch cells 9
  - 2.2.4 Coin cells 9
- 2.3 Relevant battery metrics 10
- 2.4 Manufacturing process 10

3 Methods **13**
- 3.1 Literature review 13
- 3.2 Interviews 13
  - 3.2.1 Niels Boardman Jonson from Mattr 14
  - 3.2.2 Anonymous battery engineer working for a major battery manufacturer 14
- 3.3 Usage of AI 14
- 3.4 Manufacturing of batteries in laboratory 14
  - 3.4.1 Making of cathode slurry 14
  - 3.4.2 Coating of the electrode 15
  - 3.4.3 Preparation of electrode and separator 16

3.4.4 Assembling of batteries 16
3.4.5 Testing of the batteries 17

4 Results **19**
4.1 Battery choice 19
4.2 Performance 21
4.3 Safety 24
4.4 Cost 24
4.4.1 Material cost 25
4.4.2 Manufacturing cost 25
4.4.3 Battery pack market price 26
4.5 Manufacturability Challenges 27
4.6 Sustainability 27
4.6.1 Environmental sustainability 27
4.6.2 Social sustainability 31
4.7 Results from laboratory produced batteries 34
4.7.1 LFP 34
4.7.2 NMC-811 36
4.7.3 NMC-111 37
4.8 Future technologies reducing the use of cobalt 39
4.8.1 Structural batteries 39
4.8.2 LFMP battery cells 39

5 Discussion **41**
5.1 Potential means of decreasing cobalt reliance 41
5.2 Comparison of cell performance 41
5.3 The balancing act of sustainability, manufacturing and cost factors . 43
5.4 Laboratory experiment 46
5.5 Future Outlook 46
5.6 Ethical aspects 48

6 Conclusion **49**

Bibliography **51**

A Appendix 1 **I**

List of Figures

2.1 The construction of a battery cell. [1], CC BY-NC-ND 5
2.2 Intercalation: atoms intercalated between layers of graphite. [2], CC BY-SA 6
2.3 Overview of the manufacturing process. [3], CC BY-NC-ND 12

3.1 The coating machine 15
3.2 Dried cathode 15
3.3 Weighed and named cathodes 16
3.4 Punching holes in cathode 16
3.5 Application of electrolyte on separator 17
3.6 The figure shows how a manual hydraulic press was used to enclose the active material ans separator within the battery enclosure. The press was also placed within the argon fill argon filled glove box. . . 17
3.7 The figure shows a completely assembled NMC-811 cell. 18
3.8 Landt battery testing machine 18

4.1 The figure depicts the decrease in capacity over EFC. [4], CC BY-NC-ND 22
4.2 Cost of different NMC-chemistries. [5], CC BY 25
4.3 Cost and energy consumption breakdown of LIB manufacturing processes. [3]. CC BY-NC-ND 26
4.4 Assessment results for selected social risk of different supply chain configurations. [6]. CC BY-NC-ND 33
4.5 Applied charge/discharge (blue and green), the battery's capacity and the efficiency 34
4.6 Several cycles with voltage and current over time 35
4.7 Voltage as a function of capacity for a LFP battery 35
4.8 Applied charge/discharge (blue and green), the battery's capacity in blue and the efficiency 36
4.9 Several cycles with voltage and current over time 36
4.10 Voltage as a function of capacity for a NMC-811 battery 37
4.11 Applied charge/discharge (blue and green), the battery's capacity in blue and the efficiency 37
4.12 Several cycles with voltage and current over time 38
4.13 Voltage as a function of capacity for a NMC-111 battery 38

List of Tables

2.1 The table describes different battery metrics 10
2.2 Percentages of cost and energy consumption for each step in the manufacturing process, reprinted from [3]. 11

4.1 Cell performance data compiled by [7] 21
4.2 Cell performance data compiled by [7] 21
4.3 Cycles at 80% of capacity for LFP and NMC cells, using the data from [4]. 22
4.4 Data of Pack Specific Energy for different battery cells, reprinted from [8]. 23
4.5 BOM of different of different cells in battery packs, reprinted from [8]. 28
4.6 Production activities in the supply chain of a lithium-ion battery pack with corresponding SHDB sectors and production shares of countries for three alternative configurations, reprinted from [6]. 32

1

Introduction

Lithium-ion batteries are essential in today's digital world, and as they were commercialised they became a significant advancement in energy storage technology. The development began as early as in the beginning of the 1900s but the development accelerated in the 1970s when pioneering work by M. Stanley Whittingham introduced the concept of lithium-based rechargeable batteries [9]. Whittingham's battery utilised titanium disulfide as the cathode and lithium metal as the anode.

In the 1980s, John B. Goodenough and his team made a breakthrough by using lithium cobalt oxide as the cathode, which significantly increased the battery's potential voltage. This innovation paved the way for commercial applications. However, due to lithium's reactive nature, safety concerns still remained.

The final major leap was made in the late 1980s when Akira Yoshino replaced the anode from lithium metal to a carbon material, graphite, which could intercalate lithium ions without the risks associated with metallic lithium. This led to the first commercially viable lithium battery launched in 1991.

In 2015 the United Nations climate conference was held in Paris where the participating countries signed the Paris agreement to counteract global warming. To fulfill the agreement and cope with the issue of global warming, the transport industry has taken a number of steps in order to reduce their emissions their dependency on fossil fuels. According to the Environmental Protection Agency [10], the transport industry is responsible for 15% of the global green house emissions. In order to reduce these emissions and fulfill the Paris agreement, battery electric cars have been pointed out as one of the key solutions. Today, lithium-ion batteries are taking up the mantle to power the solution of the greatest problem in our time, and their prevalence is only expected to increase.

1.1 Background

Most of the electric cars produced today use a lithium-ion battery due to high energy density and several other desirable properties [11]. A battery consists of an anode, a cathode, electrolyte and a separator, where the battery cell chemistry is commonly named after its cathode materials. The most common chemistry used in lithium-ion batteries today is composed of Nickel-Manganese-Cobalt-oxides abbreviated NMC, which uses significant amounts of cobalt [12].

Within the cobalt mining industry, poor working environments with miners breathing in potentially lethal cobalt-lathed dust, as well as instances of child labour, have been reported [13]. This is considered a major problem for the electric vehicle industry, in part due to a shortage of cobalt and ethical concerns regarding production and mining. Furthermore, another relevant problem is geopolitical and strategic issues related to the location of the cobalt reserves. In addition, a low usage of cobalt in the cathode is aimed for due to the cost [14]. Therefore western world battery manufacturers aim to drastically reduce the use of cobalt without compromising the battery performance [15].

1.2 Purpose

The purpose of this study is to research the possibilities to minimise cobalt usage in commercialised lithium-ion batteries within the electric passenger car industry. This is done by reviewing and comparing different lithium-ion battery cells that are currently on the market or could be introduced in the near future, focusing on the choice of the cathode material.

1.3 Goals

The goals of this project is to primarily identify potential candidates for replacing cobalt-rich battery chemistries, mentioned candidates should be currently available on the market or likely to be commercialised soon.

After identifying the candidates, the goal is to analyse the characteristics of these candidates in order to compare them to the currently used cobalt-rich battery types. The candidates will be evaluated in terms of cost, performance, safety, environmental- and social sustainability.

The third goal is to compare these candidates with the currently used cobalt-rich battery types. The comparison aims to show both positive and negative differences, and the potential problems of transitioning to cobalt-reducing alternatives will be discussed.

The final goal is to identify in which electric car areas a transition to cobalt reducing alternatives is possible. To conclude which candidates are able to replace the cobalt-rich batteries in the near future.

1.4 Limitations / Demarcations

The main focus will be the automotive industry, more specifically to electric passenger cars since battery technology in electric vehicles can be applied within other areas. The analysis will also be focused on a Swedish perspective to further limit the project scope.

The project will focus on several geometries and cell types. However, in the laboratory in which the cells will be manufactured, only coin cells can be produced. There will also only be three different cell types that will be manufactured in the lab, NMC-111, NMC-811 and LFP, see 2.2.3.

2

Theory

A lithium-ion battery consists of several battery cells which store energy chemically and this energy is then extracted through chemical reactions creating electricity, which can be used to power for example electric cars [16]. A lithium-ion battery cell consists of a cathode, an anode, their respective collectors, electrolyte and a separator [16]. A battery cell and its respective parts are shown in figure 2.1 below. The cathode is the positive pole and the anode is the negative pole which are separated by a separator. The separator needs to be electrically insulating to hinder short-circuiting. In between the poles and the separator is the electrolyte [1]. It permits the ions to travel from the cathode to the anode [17]. Lithium is used as the electrolyte that enables the free ions.

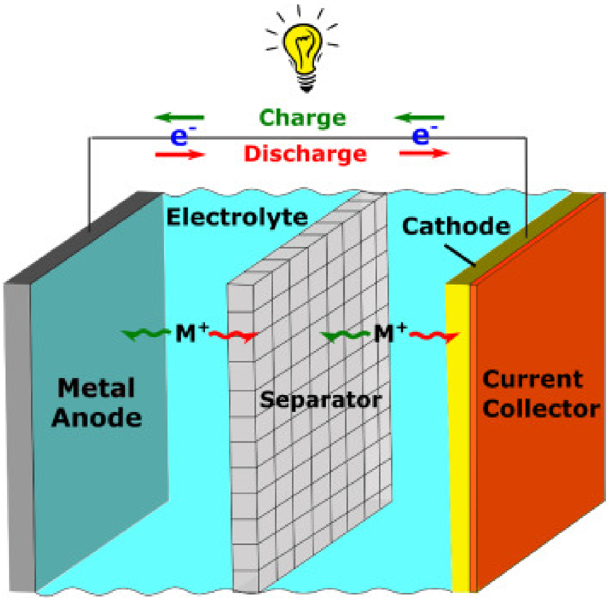


Figure 2.1: The construction of a battery cell. [1], CC BY-NC-ND

Intercalation refers, in this case, to the reversible insertion of an ion between two other molecules in a layered structure without significantly disturbing the lattice structure of the host material. This means lithium-ions being embedded and de-embedded traveling between the poles. The ability of a material to undergo intercalation without substantial changes to its crystal structure is an important factor for the battery's performance in terms of number of possible cycles and capacity [18].

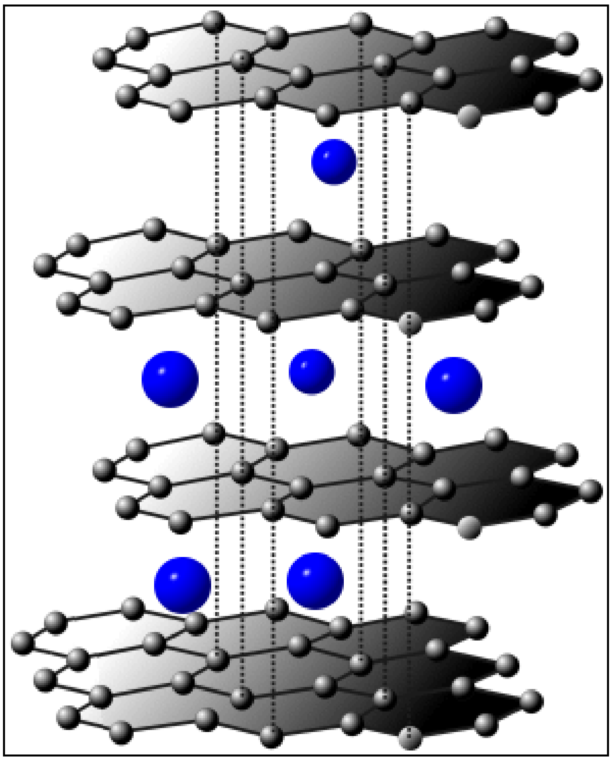


Figure 2.2: Intercalation: atoms intercalated between layers of graphite. [2], CC BY-SA

The main principle when the battery is charged and discharged is intercalation. When discharging (use of battery), positive lithium-ions are generated at the anode and then move through the electrolyte and the separator to the cathode [17]. The cathode and the anode has micro-pores where the transported ions can be embedded. The generated ions cause an electron movement through an external circuit from the anode to the cathode. The electrons that flow through the external circuit will power an electric load, for example a car [16]. The process is reversible, which means that charging works the same way but is reversed [17].

The theory of how a battery is constructed shows the possibilities to minimise cobalt usage in a battery-cathode. Several cathode materials will be listed in the section, as well as how a battery works and important metrics.

2.1 Cell chemistry

A battery cell can be made up out of different materials in the cathode and the anode, while the electrolyte is always lithium in lithium-ion batteries. This section will list different materials used in the cathode and the anode, as well as discuss different battery concepts.

2.1.1 Cathode material

The cathode is what the battery cell is named after and has the largest impact on how the cell will behave. The main reason why lithium-ion batteries contain cobalt is because of NMC battery cells. The NMC battery cathode consists of nickel, manganese and cobalt oxide and NMC is an abbreviation of the materials it contains [19]. Three commonly used compositions in commercially manufactured batteries are NMC-111, NMC-622 and NMC-811. The numbers after the cell name represent the proportions of the three different materials in the cathode.

An alternative cathode material for lithium-ion batteries used in the industry today is LFP which consists of lithium iron phosphate ($LiFePO_4$) and LFP is an abbreviation of the materials it contains [20]. In LFP cells, the atoms are arranged in a crystalline structure forming a three dimensional network with lithium-ions.

2.1.2 Anode material

The most common anode material and the one used for the cells manufactured commercially is graphite carbon with a metallic backing in the middle of the battery, usually a kind of copper foil. Graphite is used for its layered structure which enables the intercalation and de-intercalation of the lithium-ions [21].

Possible alternative anode materials for lithium-ion batteries include silicon, along with germanium, tin, and antimony, which is considered due to its high theoretical capacity, which surpasses that of graphite [22]. Despite the superior theoretical performance of these alternatives, they are not widely used commercially. The primary concern with silicon and its counterparts is their significant volumetric expansion during the intercalation of lithium, which poses challenges for battery durability and efficiency [23]. This issue of volumetric expansion is common among all these materials, hindering their practical application in spite of their higher theoretical capacities compared to graphite.

2.1.3 Electrolyte

The primary function of the electrolyte is to act as a conductive medium which allows the lithium-ions to move freely between the electrodes. The electrolyte also prevents direct flow of electrons which enables the battery to store and release energy.

Common materials used as electrolytes is often lithiumbased salts such as hexafluorophosphate ($LiPF_6$), lithium tetrafluoroborate ($LiBF_4$), and lithium perchlorate ($LiClO_4$). They offer different advantages in terms of thermal stability and ionic conductivity [24]. The lithium based salts is dissolved with an organic solvent, which can be for example ethers, esters, and carbonates. The choice of solvent is also of significance since it shall remain stable across the battery's operational temperature range, and be compatible with the used electrode materials.

2.1.4 Future battery concepts

Lithium-rich layered oxides (LLOs) are a prominent class of cathode materials in the field of lithium-ion batteries due to their high capacity and energy density [25]. These materials distinguish themselves by having excess lithium in the layered structure of transition metal oxides. This configuration allows more lithium ions to participate in the electrochemical reaction during charging and discharging, thereby enhancing the battery's capacity and energy output.

Another promising future cathode material is the Lithium-sulphur cathodes that offer higher energy density compared to traditional lithium-ion batteries [26]. The cathode material in lithium-Sulfur batteries is composed of sulfur, which is abundant, lightweight, and capable of providing a significantly higher capacity than ordinary metal cathodes in use.

Recently, the research has seen potential in a completely different battery concept known as "Solid state electrolytes" [27]. In solid state batteries, a solid electrolyte is used which has several advantages compared to a liquid electrolyte. For example, the technology is promising to have a significantly higher capacity of energy storage. Since the electrolyte is solid, safety concerns such as leakage and flammability could possibly be eliminated or at least minimised.

Battery research is constantly changing and improving, and these battery concepts might be relevant in the future. This project focuses on the near future and these concepts are too far from being introduced into the market. They will therefore not be further evaluated.

2.2 Cell geometry

The cell geometry of a battery can affect all crucial performance factors of a battery, therefore a literature study was conducted that aimed to gain a better understanding of advantages and disadvantages of four common cell geometries with different possibilities to applicate in the electric car industry.

2.2.1 Cylindrical cells

Cylindrical cells are one of the most commonly used cells today. They are durable, fairly simple to manufacture and has an efficient thermal management [28]. The thermal management is dependent of the shape and structure of the battery as the circular cross-section helps evenly distribute heat in the cell. Their efficient thermal management makes them ideal for use in high drain applications, such as in the electric car industry where you want the opportunity of a quick discharge which will increase the battery's temperature.

The round shape of cylindrical cells can however also lead to less efficient packing within a battery pack, resulting in unused space. Unused space can be a disadvantage in applications where space and weight are critical factors for example the car industry. Even though cylindrical cells can handle heat better than other cell types, it could still be a problem in high density battery packs as those found in electric cars. Therefore additional cooling systems might be needed which further increases the complexity of the battery pack [28].

2.2.2 Prismatic cells

Prismatic cells has a rectangular shape and are enclosed in a hard metal case. Its shape makes them ideal for stacking in battery packs which makes them good in applications where space is limited. Even though prismatic cells have high energy density and are easier to cool than cylindrical cells they may be more prone to swelling which is a problem [29].

2.2.3 Pouch cells

Pouch cells are enclosed in an aluminum-plastic composite film which both works as sealing and packaging. The flexible pouch allows the battery to expand slightly during charging and discharging which makes the battery good for applications where space is limited since the pouch cell can be shaped into diverse shapes and sizes because of its flexible package.

An advantage with pouch cells is that they often offer higher energy density compared to other cell types due to efficient space utilisation and less dead weight from packaging. The flexible pouch packaging also allows custom shapes and sizes, enabling designers to maximise battery volume in the available space, which is particularly advantageous in applications with irregular shapes or tight space constraints [30].

2.2.4 Coin cells

Coin cells are constructed with a simple design consisting of two electrodes separated with an isolator and an electrolyte, all encased in a metal shell. One of the main advantages of lithium-ion coin cells is their ability to provide a high energy density relative to their size, which allows them to operate efficiently in devices requiring minimal power over extended periods for example watches, pacemakers and hearing aids. Other advantages with the coin cell include its long shelf life, reliability and wide temperature range.

2.3 Relevant battery metrics

To be able to compare the different cell chemistries, different battery metrics need to be analysed. Those that are the most important to the comparison are explained below in table 2.1. The unit of EFC is short for Equivalent Full Cycles and one unit of EFC is equivalent to a full charge and discharge of a battery [4].

Table 2.1: The table describes different battery metrics

Metric	**Description**	Unit
Nominal voltage	Often printed on the battery and indicates the typical voltage during use [31].	[V]
Specific capacity	The amount of charge stored in a battery per mass [14].	[mAh/g]
Energy density	Represents the energy per volume of a battery [1]. It is also called volumetric energy density [14].	[Wh/L]
Specific energy	The energy in a battery per mass. It is also called gravimetric energy [14].	[Wh/kg]
Cycle life	Describes how many times a battery endures being charged and discharged in its useful life [1].	[EFC]
Specific power	Represents a battery's power per mass.	[W/kg]

Some important notes considering the battery metrics is that a longer cycle life means less frequent battery replacements for electric car customers which decreases the operating cost [14]. A higher specific energy for a given energy capacity leads to a lighter battery pack, which allows for battery energy efficiency and longer driving ranges for electric vehicles. An electric vehicle's acceleration and its fast charging capabilities is closely linked to specific power.

2.4 Manufacturing process

The manufacturing process of lithium-ion batteries can be divided into different stages and looks very similar in large as well as small scale operations. The manufacturing process also looks very similar between the different types of cells, whether it is a pouch, prismatic or cylindrical cell.

The first stage is slurry mixing which is a process where you mix an active material and a conductive additive with a binder to form a uniform slurry. Usually N-methyl pyrrolidone (NMP) is used to dissolve polyvinylidene fluoride (PVDF) which is the most commonly used binder for the cathode slurry. Styrene-butadiene rubber (SBR) is often used as binder for the anode and is disolved in water and carboxymethyl cellulose (CMC) [3].

The slurry is then coated on a current collector which is made of aluminium foil for the cathode and copper foil for the anode. The slurry coated strip is then dried so that the solvent can evaporate. NMP solvent is very toxic and has strict regulations for emissions, for this reason a solvent recovery process is needed during the drying process. This process is very energy intense and is responsible for the majority of the energy consumption for the whole manufacturing process (see table 2.2). The recovered NMP is reused for future battery production and generally 20 to 30 percent of the solvent is lost in the recovery process [3].

Table 2.2: Percentages of cost and energy consumption for each step in the manufacturing process, reprinted from [3].

Manufacturing process	Cost [%]	Energy consumption [%]
Slurry mixing	7.9	0.83
Coating/Drying	14.96	1.36
Solvent recovery	4.60	46.84
Calendering	5.19	2.86
Slitting	3.09	5.35
Vacuum drying	3.20	5.80
Stacking	8.65	1.88
Welding	7.34	5.20
Enclosing	12.45	0.53
Formation/Aging	32.61	29.37

The next step is calendering. This is done to compact the electrode which in turn impacts the porosity and density, thus impacting the electrochemical properties of the electrode. After this the sheets are stamped or slitted into the right dimensions for the battery cell. Now it is time to remove any moisture left by using a vacuum oven. After the vacuum oven the electrode are checked for moisture levels.

When the electrode is prepared, it is time to prepare the inner structure of the cell. They are stacked or wound depending on the type of cell is being manufactured. Aluminium and copper tabs are then welded on to the respective cathode and anode current collector. Generally this is done using ultrasonic welding but other methods like resistance welding can also be used. The cell stack is then put in its enclosure and filled with electrolyte before it is sealed.

Before the cell is ready for use, it has to go through some electrochemistry activation steps called formation and aging. First the cell is charged at a slow rate to ensure that the copper current collector is protected from corrosion and then the cell will rest for a while for electrolyte wetting. The cells are then charged and discharged multiple times at a slow rate that will increase gradually to ensure that there is a stable solid electrolyte interface (SEI) layer on the anode. An SEI layer will help protect the anode from overpotential during fast charging and can prevent consumption of electrolyte which is crucial since electrolyte can't be added after the cell is sealed.

After the formation cycles the cells are stored on aging shelves to complete the electrolyte wetting and SEI stabilisation processes. During the formations cycles, gas is generated inside the cells which will need to be let out for safety reasons. This step is called degassing and is done two times, once after formation and once after aging before the cell is sealed. The formation and aging processes generally takes multiple weeks which is a major bottleneck in battery manufacturing. It also means that this step i very costly and very energy demanding (See table 2.2) [3]. See an overview of the entire manufacturing process in figure 2.3.

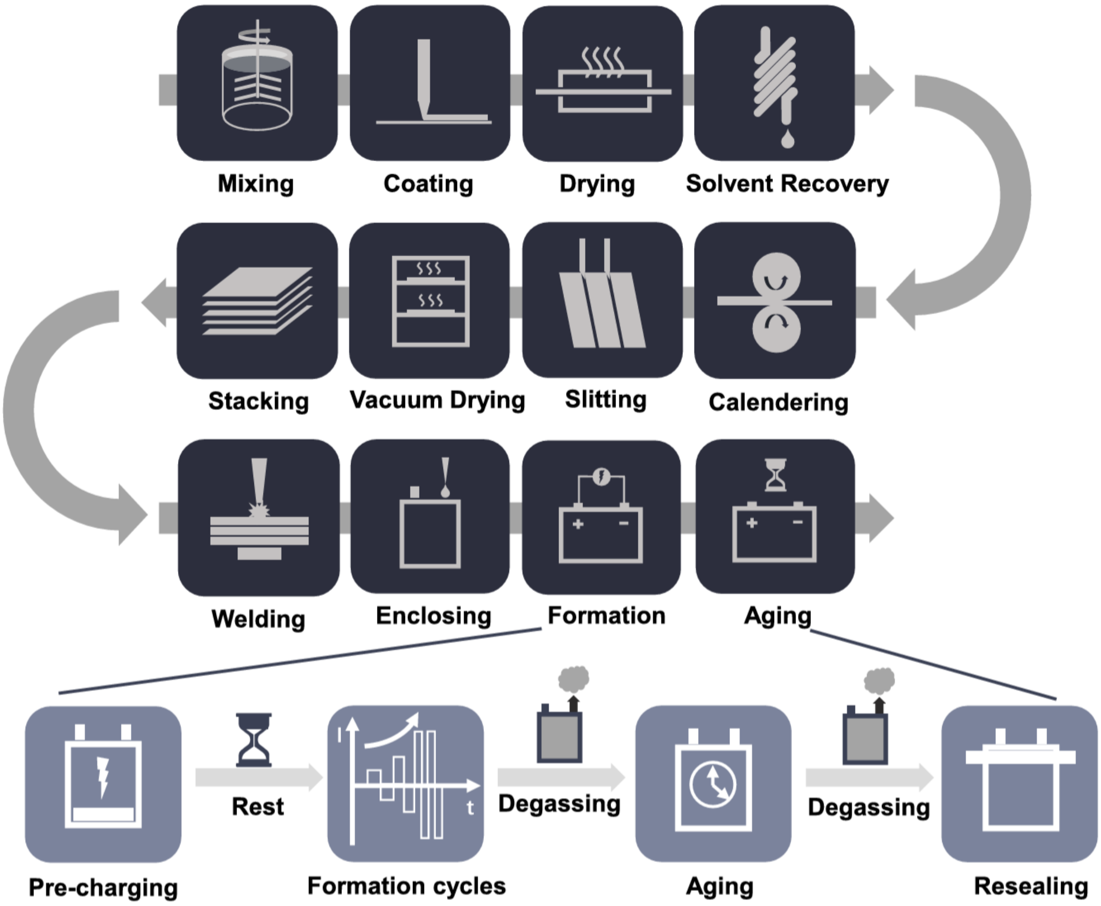


Figure 2.3: Overview of the manufacturing process. [3], CC BY-NC-ND

3

Methods

The projects primarily focus was on literature research with a practical element where batteries was manufactured. The laboratory work was conducted to understand better how the batteries are manufactured, with the additional benefit of broadening the understanding of the subject. The results from the theoretical study as well as the practical lab is useful to be able to review the possibilities of lithium-ion batteries without cobalt.

3.1 Literature review

With the literature review, a thorough research was made of lithium-ion batteries. This was done by examining lots of different types of academic and trustworthy sources. The data is used both in the theory and in the results were analysed, presented and reasoned about in the discussion.

Technologies around battery is a hot research topic that's constantly evolving. A risk with this is that the research articles are not capable to stay on top of the new innovations due to the time put in to the writing and confirmations needed. Therefore research article's has to be complimented with an excessive analysis of for example news articles and conference papers in order to review the latest technologies.

The used databases are the Library of Chalmers, Google Scholar, Scopus and Web of science to search for information. Keywords such as Lithium-ion batteries, Cathode material and electric cars were used to narrow down the search. These keywords were also combined with other specific words to find more precise information. Different search-functions such as year and type of text was also used depending on what information was sought or required.

3.2 Interviews

Interviews were conducted to find relevant and useful information not found in existing literature. All interviews were transcripted and are placed in appendix A. This information was later referred to and used in the results.

3.2.1 Niels Boardman Jonson from Mattr

Mattr Collective AB is a company that specialises in lithium-ion batteries offering services such as consultancy and custom battery production. He is also currently employed as an electrical engineer working on drive-train and power electronics. He has also previously worked at RGNT motorcycles as a Lead Electrical Engineer with expertise in product ownership and development of the electrical system and high voltage lithium-ion battery packs. Re-designing and optimising components for improved performance, energy efficiency, and cost reduction. The interview was done in a teams-call in Swedish. With permission from Niels, teams automatic transcript function was used to save the information as notes. The automatic transcription was later fixed of imperfections manually. The topic of the meeting was mostly how NMC and LFP battery packs differ in terms of safety and limiting factors for the electric car industry.

3.2.2 Anonymous battery engineer working for a major battery manufacturer

This interview was done in person in English with a battery engineer working for a major battery manufacturer who wishes to be anonymous. The engineer works with both NMC and LFP chemistries at the company. The company is a battery manufacturer that specialises in lithium-ion batteries for electric vehicles and energy storage. The topics of this interview was about different types of NMC- and LFP cells and how they differ in terms of manufacturability and materials.

3.3 Usage of AI

The usage of AI during this project was approached with careful consideration and the entire report represents original work. In the case of AI usage, compliance to the regulations set forth by Chalmers University of Technology and the examiner was ensured.

3.4 Manufacturing of batteries in laboratory

The laboration and manufacturing of the batteries includes all the steps of battery manufacturing in an industry, only on a smaller scale. Therefore the laboration will be used to compare manufacturability and cost to the greatest possible extent. It will be further complimented with information from the literature review and the conducted interviews.

3.4.1 Making of cathode slurry

The three fabricated cells were NMC-111, NMC-811 and LFP which each is the active cathode material. The active material was also mixed with a conductive agent made out of carbon black and a binder called PVDF (polyvinylidene fluoride). The active material, carbon black and the binder was weighed with the proportions as in the name of the chemistry, for example NMC-811 had 800 μg of active cathode material, 100μg of carbon black and 100 μg of binder. The weighing was done using a digital scale, a plastic tray for weighing and a spatula which was cleaned with ethanol between the substances, the powders were then put in a glass cup. Then a solvent called NMP was added to each sample using a pipette along with a magnet making mixing possible. The mixing went on for 3 days until it became a slurry and was then checked if it was viable. Then the magnet was removed and it was time for coating of the cathode.

3.4.2 Coating of the electrode

To prepare for the coating, an aluminium sheet with one side pre-coated with carbon was cut into a rectangle approximately 20 $[cm] \cdot 40$ $[cm]$ and put on the coating machine carbon side facing up. The aluminium sheet will act as the current collector for the cathode. The sheet was held down using the vacuum-function on the machine, and one of the samples at a time was applied using a pipette, see figure 3.1. Afterwards the desired speed was set and the metal "coater" that controls the thickness of the coating was put on the machine and adjusted to a thickness of 150 $[\mu m]$. The machine was turned on and the slurry was coated on the current collector.

When the coating was finished the coated sheets were on cardboard pieces and placed in a fume hood to dry. This because the used solvent NMP is toxic. After 48 hours when the coating had dried they were put in a vacuum oven at 120 $[°C]$ for 24 hours.

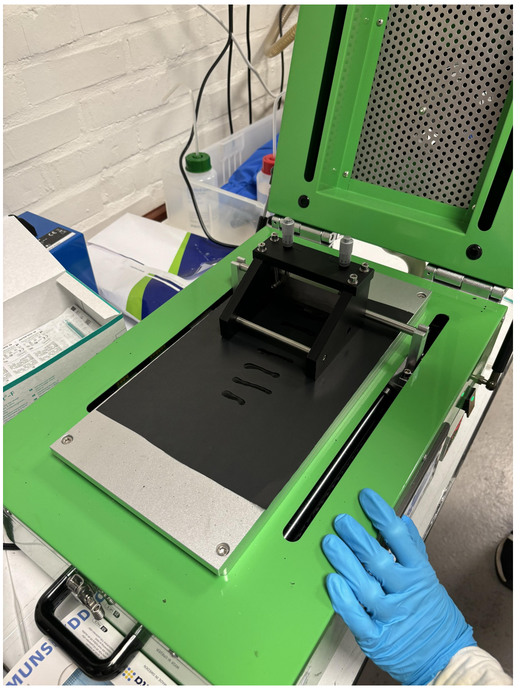


Figure 3.1: The coating machine

Figure 3.2: Dried cathode

3.4.3 Preparation of electrode and separator

When the slurry was finished out of the oven it was prepared along with the separator before assembling. A punching machine with the diameter 12 $[mm]$ was used to punch out one piece of cathode for each battery. Each piece was weighed, documented and put in a plastic bag, marked with the weight and its chemistry, see figure 3.3. In total 24 batteries were produced, 8 for each chemistry. The separator was a thin plastic tape made from polypropylene. It was placed between two pieces of paper to ease punching out the holes. The diameter for the separator was set to 16 $[mm]$ and one piece of separator was made for each battery.

Figure 3.3: Weighed and named cathodes

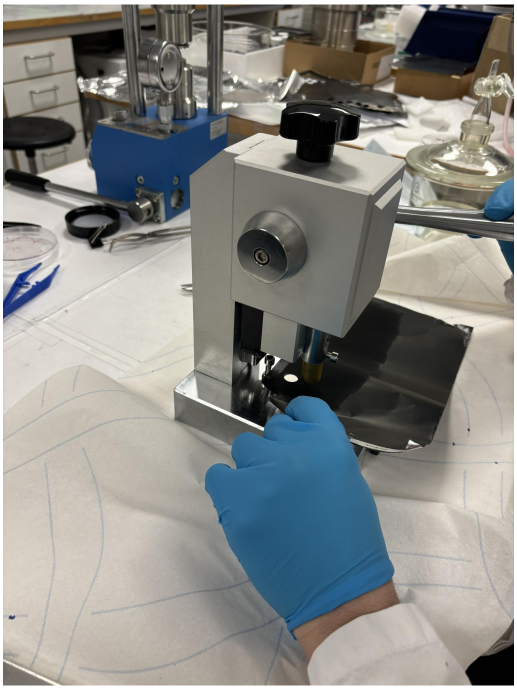


Figure 3.4: Punching holes in cathode

3.4.4 Assembling of batteries

In total 24 coin cell batteries with 8 pieces of each chemistry was made. The assembled batteries were half cells with the electrolyte (lithium) acting as an anode instead of a graphite carbon anode. This because it is cheaper and easier when researching and developing batteries but not done in the industry. To prevent the lithium from oxidising the batteries were assembled with an argon atmosphere in a glove box. The electrodes and separator were put in the box through an air vent and then the chamber was vacuumed, all the other tools and battery components needed were already in the box.

The components were the outer case (top and bottom), lithium in the shape of a circle, electrolyte, cathode, separator, a spacer and a spring. There is no anode because of the half cell thus the lithium is acting as the missing electrode. The following order is the order of assembly starting with the bottom cover at the bottom constructing upwards: bottom cover, cathode, electrolyte (2 drops), separator, electrolyte (2 drops), lithium, spacer, spring and top cover. The electrolyte was applied with a pipette, see figure 3.5 and all components were handled with a metal tweezers except the metal parts which were handled with a plastic tweezer to prevent short-circuiting. All components were placed in the middle to prevent them from affecting each other except from the electrolyte touching every component. After the top cover was on, a manual coin cell press was used to press the battery together. The spring made so that the components were pressed together and the cover had a plastic seal preventing any leakage when pressed together at 1500 [psi] which translates to roughly 10 [MPa].

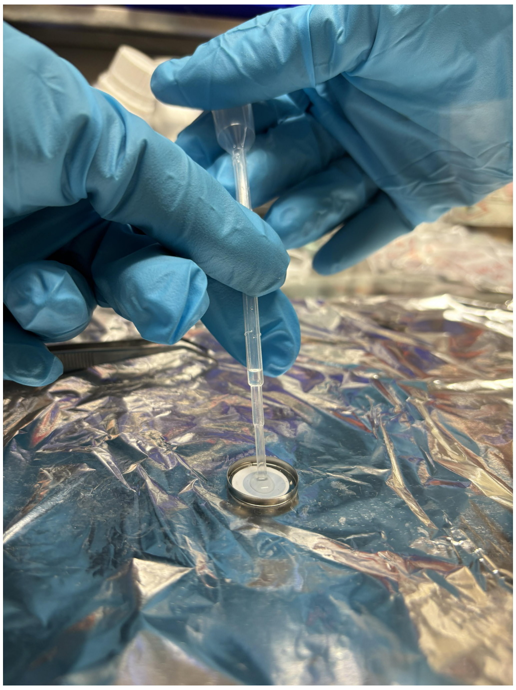


Figure 3.5: Application of electrolyte on separator

Figure 3.6: The figure shows how a manual hydraulic press was used to enclose the active material ans separator within the battery enclosure. The press was also placed within the argon fill argon filled glove box.

3.4.5 Testing of the batteries

The assembled batteries were then put in the *Landt battery testing machine* to run a few cycles to see that it did not short circuit. Then the active material of each coin cell needed to be determined. This was done by subtracting the weight of the cathode with the weight of the current collector. Then the coating was multiplied with $0,8$ because 80% of it's total weight is the active material, see equation 3.1.

$$m_{active\,material} = (m_{tot} - m_{current\,collector}) \cdot 0,8 \tag{3.1}$$

The weight of the active material was inserted into the testing machine via a computer and also a C-rate was put to different values, for example $0,1$, $0,5$ and 2. C-rate is the measure for how fast a battery is charged and discharged (a cycle), a C-rate of 1 means that the battery is charged and discharged in 1 hour.

Figure 3.7: The figure shows a completely assembled NMC-811 cell.

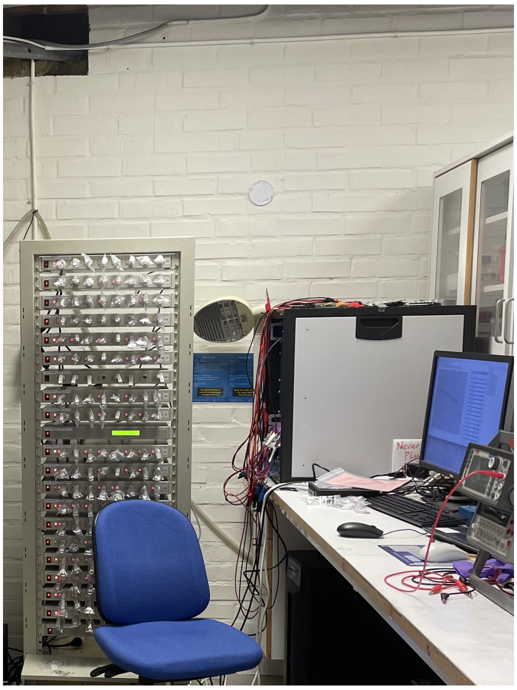


Figure 3.8: Landt battery testing machine

4

Results

The literature review carried out in this project rendered a comprehensive overview of how the compared battery chemistries differ in regard of various metrics. This data was used as a benchmark to compare against during the experimental evaluation, as well as the foundation for the subsequent discussion and analysis regarding the future potential of decreasing cobalt usage in batteries within the automotive industry. The literature review was also complimented with a series of interviews that allowed to gather information which was not readily available in the compiled literature.

4.1 Battery choice

According to Boardman [32], a battery pack in a car is often designed after its limited space where the battery box is universal in size for all range models. This means that when using different cell chemistries like NMC and LFP, only the hardware and software within the box itself is changed.

When choosing the cell chemistry, everything is a balancing act since every factor affects every other factor. Increasing energy density will decrease safety, since the battery will get more volatile. A good analogy is that when the energy increases, the closer to battery gets to a dynamite. Another clear balancing act is power to cyclic life, since the heat generated by high power will decrease the cyclic life. Boardman also states it is impossible to have high power and high energy density in one cell at the same time. This is because different sizes of the grains in the crystals will give different effects. Large grains will be able to store alot of electrons, thus giving high energy density. Small grains won't have the same capability of storing electrons, but the electrons will be able to navigate around the grains easily, giving high power.

Since everything is a balance, it is not possible to increase every factor to its maximum. It is always an optimisation problem that will be different for every situation. Hard and soft limits are often used to choose a chemistry. For example if a car is designed to be a sports car, the power of the motors and the capacity to utilise it usually is a hard limit. There needs to be soft limits aswell that can be tweaked so that the hard limits can be achieved. Cyclic lifetime is a good example of a factor that is often seen as a soft limit. It is always good to have more, to little is to little, but somewhere in between is probably going to give the best balance for the other factors.

According to [33], which battery chemistry is chosen for which automotive application largely depends on what range is expected from the vehicle, this can be considered a crucial metric. LFP batteries could be suitable for an application such as taxis, given the long cycle life of the cells. For premium vehicles NMC currently appears to be a more suitable option due to the much higher range capability it enables. However, already today LFP is taking some market share from the NMC market, especially from lower capacity chemistries such as NMC-111, which in turn will likely be succeeded by LFMP. In sportscar applications NMC-811+ chemistries are preferable, due to the range they offer given their superior energy density. This metric can be as high as 300 [Wh/kg] for NMC-811+, as opposed to around 170 [Wh/kg] obtained with the LFP chemistry, or the slightly improved 210-220 [Wh/kg] made possible by LFMP.

4.2 Performance

In an experimental study conducted on cells of the 18650 type [7] compiled a list of manufacturer specified battery metrics along with measured data they had gathered throughout a series of experiments. The data they compiled is represented in table 4.1.

Table 4.1: Cell performance data compiled by [7]

Cell Chemistry	LFP	NMC
Anode	Nano-Carbon	Graphitic Carbon
Cathode	$LiFePO_4$	$LiNi_{0.80}Mn_{0.15}Co_{0.05}O_2$
Nominal Capacity [Ah]	1.1	3.0
Nominal Voltage [V]	3.3	3.6
Measured Capacity [Ah]	1.062 ± 0.006	2.8 ± 0.1
Measured Energy Density [Wh]	3.50 ± 0.02	10.1 ± 0.4
Maximum Discharge Current [A]	30	20
Operating Temperature Range [°C]	−30 to 60	0 to 50
Nominal Volume [mL]	16.5	16.5
Measured Mass [g]	39.4	44.9
Cost Per Cell [$]	9.95	6.00
Energy Density [Wh/L]	212.1	612.1
Specific Energy [Wh/kg]	88.9	224.8
Cost Per Capacity [$/kWh]	2,843.8	594.0

A similar but less extensive dataset was obtained from a study on battery degradation [4] which provided an additional source on some of the metrics presented in table 4.1. The data they recorded can be seen in table 4.2, which are solely manufacturer specified metrics.

Table 4.2: Cell performance data compiled by [7]

Cell Chemistry	LFP	NMC
Nominal Capacity [Ah]	1.1	3
Nominal Voltage [V]	3.3	3.6
Voltage Range [V]	2 to 3.6	2 to 4.2
Max Discharge Current [A]	30	20
Acceptable Temperature [°C]	−30 to 60	−5 to 50
Nominal Mass [g]	39	47

The study on battery degradation investigates how the chemistry and cycling conditions affect the degradation of lithium-ion cells [4]. Therefore, the different cell chemistries LFP, NMC and NCA are compared. The NMC cell used is a nickel enriched version of NMC811. In the experiments, the batteries are cycled until the discharge capacity retention or "% Initial Capacity" reaches 80%. This is because manufacturers often specify 80% of capacity to be the end of life of the battery in their specification sheets. Equivalent full cycles (EFC) is used to describe the number of cycles. This makes it possible to make a fair comparison of different depth of discharge (DOD). An overall picture of cycle-induced aging is shown in figure 4.1. After the cells had reached 80% of the initial capacity, the cycles ranged from 2500 to 9000 EFC for LFP vs 200 to 2500 EFC for NMC, see table 4.3. In addition, most of the LFP cells had not reached 80% of its capacity by the end of the study and had to be interpolated.

Table 4.3: Cycles at 80% of capacity for LFP and NMC cells, using the data from [4].

Battery type	LFP	NMC
Cyclic Life(EFC)	2500-9000	200-2500

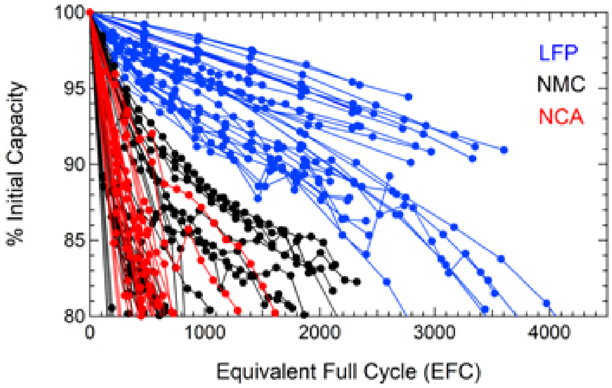


Figure 4.1: The figure depicts the decrease in capacity over EFC. [4], CC BY-NC-ND

Three factors which might change the amount of EFC for the different battery cells are introduced; temperature, DOD and discharge rate [4]. Battery cells have a tipping point in temperature were they have their lowest degradation rate. If the temperature increases or decreases from this tipping point, the degradation rate of the battery cell will increase. For LFP cells the tipping point is at temperatures of 5 $[°C]$- 10 $[°C]$ and for NMC cells the tipping point is at 35 $[°C]$.

In regard of different DOD, LFP cells are stable and the degradation rate does not change from using different DOD [4]. NMC cells on the other hand have a problem when the DOD is 0-100%. This is because NMC cells have a much higher degradation rate when the state of charge(SOC) is close to 100%. The discharge rate does not affect LFP and NMC cells differently. Higher discharge rates are expected to increase the degradation rate.

Specific energy for each cell chemistry as provided in the BOM [8], the data is derived from BatPaC version 4.0.

Table 4.4: Data of Pack Specific Energy for different battery cells, reprinted from [8].

Battery type	LFP	NMC111	NMC622	NMC811
Pack Specific Energy (Wh/kg)	174.1	214.8	240.7	247.9

Table 4.4 represent the different specific energies in various cells were LFP has the lowest and NMC-811 has the highest.

According to [33], cobalt content relates to the conductivity of the cathode material. Adding cobalt to the material enhances it's conductive properties and is considered necessary to create a functioning NMC cell that's practically usable. There is potential to decrease the usage of this metal by tweaking the chemistry in a way that still retains some cobalt, but considerably less. This is for example true when comparing the NMC-111 and NMC-811 chemistries, where the 811 has a significantly smaller cobalt quantity within the battery. Moving to completely cobalt-free NMCs however does not currently appear to be a feasible option, although the technology could be promising for the future.

Manganese helps increase the maximum and nominal cell voltage of the battery, which is very apparent when comparing the LFMP chemistry to ordinary LFP cells. The higher nominal voltage of LFMP cells allows for higher capacity extraction. The reason manganese percentage in NMC batteries is often lowered along with the cobalt amount is simply to obtain a higher Nickel concentration which increases the capacity [33].

As explained by [33], higher power output from battery cells is obtained more by modifying the form of the electrodes rather than just altering the chemistry itself. If high power is in demand for an application the path of discharge for the ions needs to be made shorter, which makes for a more difficult manufacturing process as several thinner electrodes will need to be manufactured in place of fewer thicker ones found in lower power applications.

The internal resistance of the cells is directly correlated to how easily the charges can be transferred within the cell. This quantity is affected by the composition and structure of the entire cell, not just the cathode and the material it's composed of [33].

4.3 Safety

One safety issue with lithium-ion batteries is that they can fail and cause a thermal runaway leading to a battery fire. This can occur if the battery is exposed to thermal-, electric- or mechanical abuse [34]. A thermal runaway is the effect describing an exponential increase of temperature in a cell causing it catch fire. If the cell-fire spreads to other neighboring cells, a chain reaction starts causing a battery fire. This fire endangers the car itself, critical infrastructure and human health [35]. A battery-fire can release particulate emissions, heavy metals and harmful organic materials from the combustion into the air. This can seriously harm the environment and human health. Furthermore the groundwater and soil can get contaminated depending on what suppression method is used and also the scale of the fire determine the environmental impact [34].

According to Boardman [32], in order to avoid battery fires there will almost always be thermal barriers, this leads heat away to avoid chain reactions of fires in the cells. A mechanical barrier also exist to avoid short circuits. There is also a need to have gas valves, otherwise there is a risk that the built up pressure creates a bomb. The ordinary cooling system is also turned on to the max in case of a cell fire to decrease the temperature as much as possible [32].

In cylindrical cells, air gaps are often used between the cells. The air gaps prevents a potential fire in one cell to spread to neighboring cells, thus avoiding chain reactions. If the air gaps are well designed, no other extinguishing method is necessary. If a cell catch fire, smaller air gaps are needed for LFP cells than NMC cells which has bigger gaps because LFP are less volatile. This means that more LFP cells can be placed in the same space than NMC cells can [32].

For prismatic cells, air gaps are not used as often as in prismatic cells, instead the cells are placed across from each other. In this case an extinguishing method or a chain reaction prevention method is needed. A method that can be used is to pump a foam or a coolant into the battery package in order to lower the temperature as much as possible, preventing the fire to spread and avoiding a chain reaction [32].

4.4 Cost

The cost of manufacturing a lithium-ion battery cell can be broken down to six parts, the cathode, manufacturing and depreciation, anode, separator electrolyte and battery housing. In large scale manufacturing of battery cells the material has a significant impact on the overall cost [36]. Both LFP and NMC cells contains distinctive compositions of material which based on what type of cell chemistry is used, contains various amounts of fundamental materials like lithium, cobalt, nickel and manganese. The cathode material cost varies depending on which cell, but in some cases it can be as high as half of the over all cost. The material cost can variate alot depending on what type of cell chemistry is used, for an average NMC Cathode materials is approximated to be as high as 51% of the over all cost [37]. Manufacturing and depreciation is approximated to be responsible for 24% of the overall cost. This includes producing the electrodes, assembling the different components, and finishing the cell. The last big cost is the anode which is approximated to be 12% of the total cost. Lithium-ion cells typically has natural or synthetic graphite for there anode, which tends to be less expensive than other battery commodities.

4.4.1 Material cost

This section will be a more careful assessment of the raw materials including supply chains and extraction. As seen in figure 4.2*c* the main cost for producing an NMC-battery is the raw material cost. This is for NMC-811 which is one of the chemistries that were fabricated in the lab. A similar method that is being used in large factories is also used in fabrication of batteries in the lab. It is indicated in figure 4.2*a* that the cathode is the most expensive in $[USD/kWh]$ [5]. This is also in accordance with the interviews.

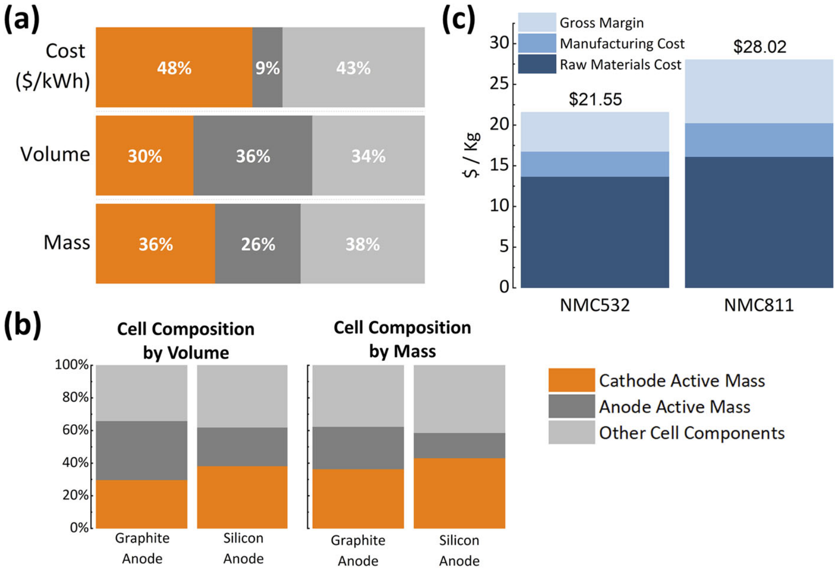


Figure 4.2: Cost of different NMC-chemistries. [5], CC BY

The price of active cathode materials for LFP is 43% lower than for the NMC-811 in $[USD/kWh]$. Also the cost of active materials for LFP was approximately 10 $[USD/kg]$ compared to NMC which was 35 $[USD/kg]$ during 2022. LFP contains iron which has a considerably lower cost than for nickel and cobalt [14]. Additional, in 2023 LFP cells were 32 % cheaper compared to NMC cells on average [38].

4.4.2 Manufacturing cost

The manufacturing of lithium batteries encompasses a series of intricate processes, each contributing to the overall production cost. To gain insights into the cost distribution, a comprehensive analysis was conducted, as illustrated in figure 4.3 A. The data shows the financial outlay associated with all the individual manufacturing steps needed to manufacture a lithium-ion battery.

To understand the actual cost of manufacturing a battery, the cost is split in to two separate segments. Firstly we look at the cost of the actual work as seen in figure 4.3 A. Secondly the energy consumption of each of the steps during the process is shown in figure 4.3 B.

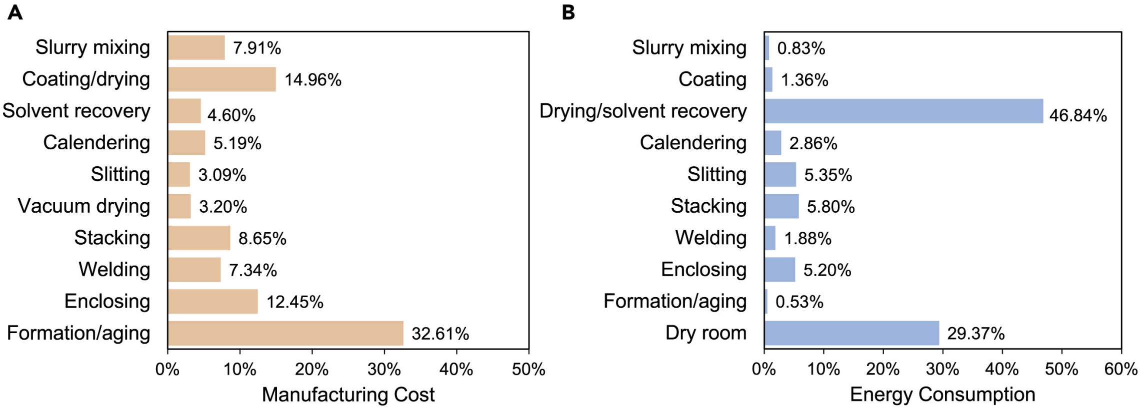


Figure 4.3: Cost and energy consumption breakdown of LIB manufacturing processes. [3]. CC BY-NC-ND

In parallel with costs, energy consumption constitutes a critical aspect of lithium battery production, as depicted in figure 4.3 B. The data, sheds light on the energy requirements associated with diverse manufacturing processes.

4.4.3 Battery pack market price

Since the first commercially viable electric cars entered the market in the early years of 2010s the prices of electric car batteries has dropped with more than 80% according to BloombergNEF [38]. The price drop has led to more affordable electric cars for the broad market. According to the European Commission, the market share for battery electric cars in Europe increased to 12% while plug in hybrids stood for more than 30% of the market [39]. The market share for battery electric cars is expected to increase further as prices for batteries is expected to drop further. Goldman Sach expects battery prices to drop with 40% by 2025 compared to 2022 [40]. Since the higher cost of investing in a battery electric car is one of the major reasons why people hesitate buying an electric car, lower prices will pave the way for increased sales and even lower prices when production is scaled up.

4.5 Manufacturability Challenges

One significant challenge that is currently preventing mass-adoption of the LFMP battery chemistry, mentioned by [33] during the interview, is the mixing of the cathode slurry during the cell production process. When mixing a slurry for an LFMP cathode a major problem one encounters is the solid content of the solution, which is as low as 45% due to the high viscosity of the slurry. This means that large amounts of NMP solvent have to be used during the mixing process, which later proves a challenge during the drying and solvent recovery stages of the production process.

A large opportunity that could ease the manufacturing of LFMP cells is a transition to a water based slurry process, which was mentioned in the interview with [33]. This possibility of improving lithium-ion battery production is also mentioned by Daniel [41], where he discusses the advantages of eliminating NMP completely from the production process. One of the said advantages is that a water based process does not "produce flammable vapors" that later additionally have to be captured, distilled and recycled. However it is also mentioned that there are complications associated with a water based slurry. The concerns includes both the interaction between water and the active materials. As well as the current collector surface, which is to be coated with the slurry, is hydrophobic. This property prevents the solution from spreading evenly [41].

Another area with difficulties within manufacturing that was mentioned by [33] is the production of high-nickel NMC batteries. As one of the important functions of cobalt is to maintain the crystal stability, these nickel-rich batteries with relatively low cobalt content exhibit stability problems. Not only is their cyclic lifespan decreased as compared to NMC batteries with more cobalt, but they also require more careful control and monitoring during production to maintain as high crystal stability as possible. This increases the overall production cost, despite nickel itself being a cheaper resource.

4.6 Sustainability

The environmental-, economical- and social sustainability of production and use of lithium-ion batteries are studied in this section.

4.6.1 Environmental sustainability

Environmental sustainability in lithium-ion battery production and recycling is crucial for mitigating the environmental impact of electric vehicles. The life cycle assessment (LCA) discusses disparities between LFP and NMC batteries, emphasising the need to adopt efficient recycling methods. Despite challenges such as cost and technical complexity, transitioning to environmentally friendly solvents presents opportunities for reducing harm.

In the table below, we can see the composition of materials in electric vehicles battery packs. The data provides insights into the percentage of various components across different cell-chemistry's, including LFP, NMC-111, NMC-622, and NMC-811. Notably, the table outlines the proportions of active materials, carbon, copper, aluminum, electrolytes, and other key components. The BOM is based on a Pack containing 70.6 [kWh].

Table 4.5: BOM of different of different cells in battery packs, reprinted from [8].

	LFP	NMC-662	NMC-111	NMC-811
Active Material (%)	35.96	36.10	38.17	31.54
Carbon (%)	19.11	22.07	20.17	24.44
Silicon (%)	0.00	0.00	0.00	0.00
Binder (%)	1.12	1.19	1.81	2.22
Copper (%)	8.26	7.08	7.21	7.23
Wrought Aluminum (%)	17.52	17.85	17.26	18.41
Cast Aluminum (%)	0.00	0.00	0.00	0.00
$LiPF_6$ (%)	1.78	1.37	1.38	1.39
Ethylene Carbonate (%)	4.98	3.81	3.87	3.88
Dimethyl Carbonate (%)	4.98	3.81	3.87	3.88
Polypropylene (%)	0.80	0.63	0.66	0.76
Polyethylene (%)	0.21	0.18	0.18	0.22
Polyethylene Terephthalate (%)	0.20	0.19	0.19	0.20
Steel (%)	0.67	0.60	0.60	0.62
Thermal Insulation (%)	0.32	0.36	0.33	0.37
Coolant: Glycol (%)	2.70	2.95	2.61	2.97
Electronic Parts (%)	1.39	1.82	1.69	1.88

The Bill of materials from figure 4.5 indicates that LFP uses less active materials compared to NMC-111 and NMC-622 [8]. Active materials such as manganese, lithium, cobalt and nickel are not considered environmentally sustainable. In addition some active materials are classified as toxic and carcinogenic. Therefore these materials need to be recycled in accordance with the principles of circular economy, or alternatively they should be re-used [42].

In the LCA, NMC chemistries environmental impact are compared to each-other in relation to the nominal storage capacity which was 23.5 [kWh] for both cells. The total cell mass of the different battery types measured 164, 99 [kg] for the NMC battery and 203, 1 [kg] for the LFP battery. The LCA system boundary contained five main phases during the cell lifetime which were analysed, these are seen below.

- Production phase including the mining and refining of lithium and preparation of the cathode materials.
- The first use phase was based on electricity losses due to the charge-discharge efficiency and weight of the lithium-ion battery.
- Reuse phase, the parts and components was assumed to be switched but the cells were reused.
- In the secondary use phase, the use scenario of retired LFP and NMC batteries after re-purposing is the energy storage field.
- The fifth phase was the recycling phase. In the recycling phase end of life cycle (EoL) NMC batteries were recycled by hydrometallurgy and pyrometallurgy, while EoL batteries were recycled by hydrometallurgy and direct physical recycling [43].

The extensive LCA analysed the environmental impact from the battery production phase, first use phase, re-purposing phase, secondary use phase and recycling-phase combined. Different types of environmental impact were observed, for example global warming, acidification and the effect on the ozone layer [43].

The largest environmental load came from the production phase, first use phase and the secondary use phase for both cell types. In the comparison between the two cells the LFP cell had a drastically larger environmental impact. The larger impact is caused by the used electricity for the batteries as they were produced in China where the energy market is dominated by coal-fired power in combination with a longer secondary service-life of the LFP battery when compared with the NMC. Therefore the main environmental impact for both use-phases for both cell types were the electricity usage, in other words if the energy source was renewable or not [43].

The NMC cell generally has around 1000 to 2000 life cycles while LFP has around 2000 to over 6000 life cycles depending on the depth of the discharge, the temperature the battery was exposed to and other environmental factors [44]. Since the LFP cell had a greater total power consumption in the second use phase it was concluded that it had around 1.8 times the environmental impact as the NMC which depends on the longer secondary life than NMC [43].

Hydrometallurgy, pyrometallurgy and direct physical recycling are different recycling methods used to recycle the metals used in lithium-ion batteries. The LCA concluded that hydrometallurgy in comparison with direct physical recycling and pyrometallurgy has the potential to alleviate various forms of environmental impact to a greater extent [43]. Hydrometallurgy involves the use of aqueous solutions to extract metals from battery components, offering advantageous features such as high metal recovery rates and relatively lower energy consumption compared to pyrometallurgical methods.

To summarise the environmental impact of the lithium-ion batteries depends on the source of the electricity used to power the batteries in the first and second use-phase.

Another point is that recycling could reduce the environmental impact in various ways. [43] Lastly, it also stated that in the other phases not impacted as much by the coal-fired electricity production, the NMC and the LFP cells had a very similar environmental impact.

Although there are challenges with recycling processes in both economical and environmental aspects, the environmental pollution reduces when recycling lithium-ion batteries to recover materials [42].

The Sustainability aspect was additionally covered in the interview with [33] where is became clear that there are differences in the recycling process for the different battery chemistries. According to [33] the recycling process for NMC is "very easy" as compared to the one for LFP, this is due to the fact that the process for LFP is chemically more difficult. On top of that, the resources extracted from LFP recycling are less valuable than the ones obtained from NMC batteries, which makes the whole endeavour less financially appealing. Additionally this is another area where the LFMP chemistry proves to be advantageous as it is also easier to recycle than ordinary LFP batteries.

In table 2.2 it is shown that the solvent recovery process during manufacturing of lithium-ion batteries is approximately $46,84\%$ of the total energy consumption. A high energy consumption has a higher impact on the environment and its resources, especially when the energy production is powered by fossil fuels.

In recent years there has been a lot of research to transition to a more environmental and less hazardous solvent for the cathode in lithium-ion batteries [45]. This is mostly in order to cope with the safety concerns associated with traditional solvents like NMP (N-Methyl-2-Pyrrolidone) but also to reduce the manufacturing costs and the environmental impact it has. One of the better options for this is moving to water-based solvents. From a safety perspective it eliminates all risks associated with flammability as well as removing the toxicity, enhancing workplace safety and reducing regulatory compliance burdens. Due to water being readily available it also reduces the overall cost in the production. However, water-based solvents often exhibit different rheological properties, leading to difficulties in maintaining optimal slurry consistency and stability. This inconsistency can result in non-uniform coatings, affecting cathode performance and reliability.

Adhesion presents another significant challenge when transitioning to water-based solvents. Achieving strong adhesion between cathode materials and current collectors is essential for ensuring the mechanical integrity and electrical conductivity of lithium-ion battery electrodes. Traditional solvents like NMP facilitate robust adhesion through interactions with binder materials, promoting effective binding between active particles and conductive additives. Water-based solvents may struggle to replicate these adhesive properties, leading to issues such as delamination and reduced cathode performance [45]. However the energy required to induce a liquid-to-gas phase transition for water is 4 times higher than for NMP on a mass basis, but the water still evaporates 4.5 times faster than NMP and offers shorter drying times, lowering the total drying energy by a factor of 10 [46].

The stability of cathode materials is also a concern in regard to water-based processing methods. This is due to the cathode materials being extremely sensitive to moisture and pH levels, which can affect their structural integrity and electrochemical performance. Water-based solvents introduce additional moisture into the electrode formulation in comparison to the NVP based slurries, potentially leading to material degradation and decreased cycle life [45]. The experimental study [46] shows that the water-based cathodes display slightly lower performance and higher cell-to-cell variation at higher discharge rates.

Moreover, scalability poses a significant hurdle for water-based processing methods [46]. While laboratory-scale experiments may demonstrate promising results, translating these findings to large-scale production requires careful optimisation and scale-up efforts. Factors such as batch-to-batch consistency, equipment compatibility, and production throughput must be considered to ensure efficient and cost-effective manufacturing processes.

Both LFP and NMC cells have been shown to work with water-based solvents, although NMC cells have exhibited some individual compatibility issues [47]. While LFP cathodes are generally stable in water-based solvents, optimisation of processing parameters are still necessary to achieve optimal performance. Moreover, NMC cathodes, especially those with higher nickel content, have been observed to exhibit altered pH values when processed with water due to reactions occurring during dissolution, potentially leading to compatibility issues. This phenomenon can significantly impact the reliability and lifespan of battery systems, particularly in demanding applications such as electric vehicles.

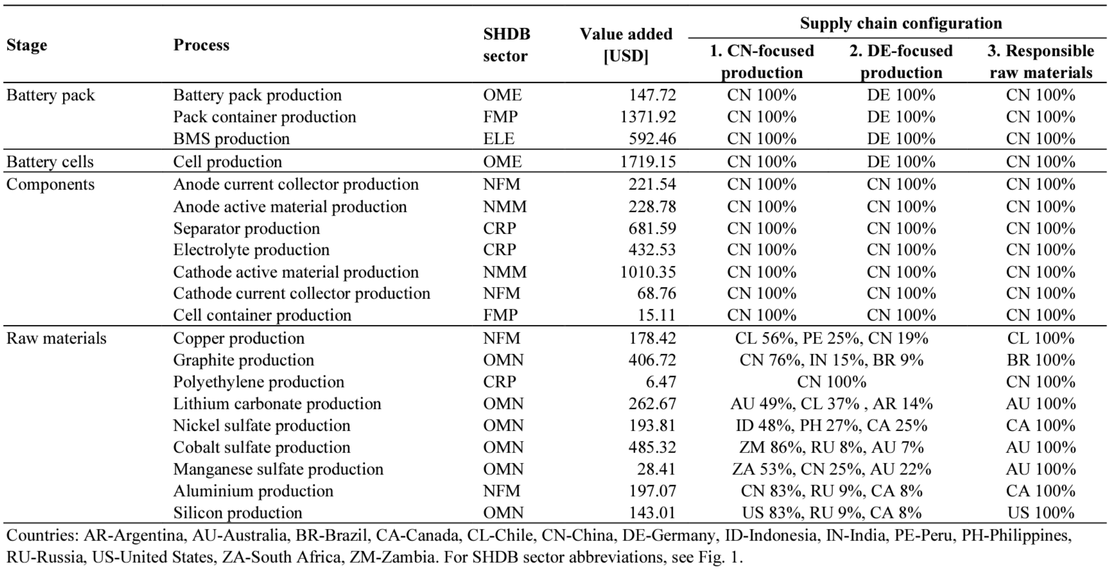
4.6.2 Social sustainability

Lithium, cobalt, manganese, nickel and graphite are all materials used in lithium-ion batteries that are often associated with environmental- and social sustainability issues within their supply chain and production.

Thies et al. [6] has conducted a Social Life Cycle Assessment (S-LCA) of the supply chain of lithium-ion batteries using data from the Social Hotspot Database regarding social risk with respect to child labor, corruption, occupational toxics and hazards, and poverty. S-LCA is a methodology similar to a regular LCA but instead of focusing on an environmental impact of a product during its life cycle, S-LCA focuses on the socio-economic interactions of the activities in the supply chain.

The production of lithium-ion batteries is heavily dependent of raw materials for the active materials of the cells. These materials are mainly mined and produced in a handful of countries. Australia is the largest producer of lithium followed by Chile and Argentina. While nickel production is fairly spread out over the globe, Indonesia is by far the largest producer in the world with 20.6% of the global total [48]. Cobalt production is heavily concentrated in DR Congo where more than 60% of the global total is produced [6]. Manganese is mainly produced in South Africa, China and Australia. The majority of graphite production is concentrated in China with some production in India and Brazil.

Table 4.6: Production activities in the supply chain of a lithium-ion battery pack with corresponding SHDB sectors and production shares of countries for three alternative configurations, reprinted from [6].



Stage	Process	SHDB sector	Value added [USD]	Supply chain configuration		
				1. CN-focused production	2. DE-focused production	3. Responsible raw materials
Battery pack	Battery pack production	OME	147.72	CN 100%	DE 100%	CN 100%
	Pack container production	FMP	1371.92	CN 100%	DE 100%	CN 100%
	BMS production	ELE	592.46	CN 100%	DE 100%	CN 100%
Battery cells	Cell production	OME	1719.15	CN 100%	DE 100%	CN 100%
Components	Anode current collector production	NFM	221.54	CN 100%	CN 100%	CN 100%
	Anode active material production	NMM	228.78	CN 100%	CN 100%	CN 100%
	Separator production	CRP	681.59	CN 100%	CN 100%	CN 100%
	Electrolyte production	CRP	432.53	CN 100%	CN 100%	CN 100%
	Cathode active material production	NMM	1010.35	CN 100%	CN 100%	CN 100%
	Cathode current collector production	NFM	68.76	CN 100%	CN 100%	CN 100%
	Cell container production	FMP	15.11	CN 100%	CN 100%	CN 100%
Raw materials	Copper production	NFM	178.42	CL 56%, PE 25%, CN 19%		CL 100%
	Graphite production	OMN	406.72	CN 76%, IN 15%, BR 9%		BR 100%
	Polyethylene production	CRP	6.47	CN 100%		CN 100%
	Lithium carbonate production	OMN	262.67	AU 49%, CL 37% , AR 14%		AU 100%
	Nickel sulfate production	OMN	193.81	ID 48%, PH 27%, CA 25%		CA 100%
	Cobalt sulfate production	OMN	485.32	ZM 86%, RU 8%, AU 7%		AU 100%
	Manganese sulfate production	OMN	28.41	ZA 53%, CN 25%, AU 22%		AU 100%
	Aluminium production	NFM	197.07	CN 83%, RU 9%, CA 8%		CA 100%
	Silicon production	OMN	143.01	US 83%, RU 9%, CA 8%		US 100%

Countries: AR-Argentina, AU-Australia, BR-Brazil, CA-Canada, CL-Chile, CN-China, DE-Germany, ID-Indonesia, IN-India, PE-Peru, PH-Philippines, RU-Russia, US-United States, ZA-South Africa, ZM-Zambia. For SHDB sector abbreviations, see Fig. 1.

In the S-LCA study conducted by Thies et al. [6], a battery pack with a capacity of 52.9 [kWh], a weight of 314.3 [kg] and with an NMC cell chemistry was considered. The scope of the study included the extraction of raw materials, the production of intermediates, the production of the cells, and the final assembly for battery packs. To limit the study, three different hypothetical supply chains were used. One where production was centered in China and raw materials came from the top three producing countries from 2017. However, DR Congo is not available in the social hotspot database so Zambia, its neighbouring country was used to approximate similar social context of cobalt production. The other two supply chain configurations were a Germany-centered production and one that was focused on responsible sourcing of raw materials which was done by sourcing 100% of the material from the top producing country that would result in the lowest risk. See table 4.6 for a full explanation of the supply chain setup.

In figure 4.4 the results from the assessment are presented in four graphs, one for each risk category and are quantified in the amount of risk hours produced. The results show that using a Germany-centered supply chain results in a low amount of risk hours in the production of the cells and the packs. However, the sourcing of raw materials and components maintain a high amount of risk hours. For the responsible sourcing of materials, it is clear that the total amount of risk hours are still quite high because of where the production for that supply chain is located. For all four graphs, it is evident that reducing the amount of risk hours for the components is not possible for any of these configurations. The results also show that the China-based supply chain results in the highest amount of risk hours for all risk categories.

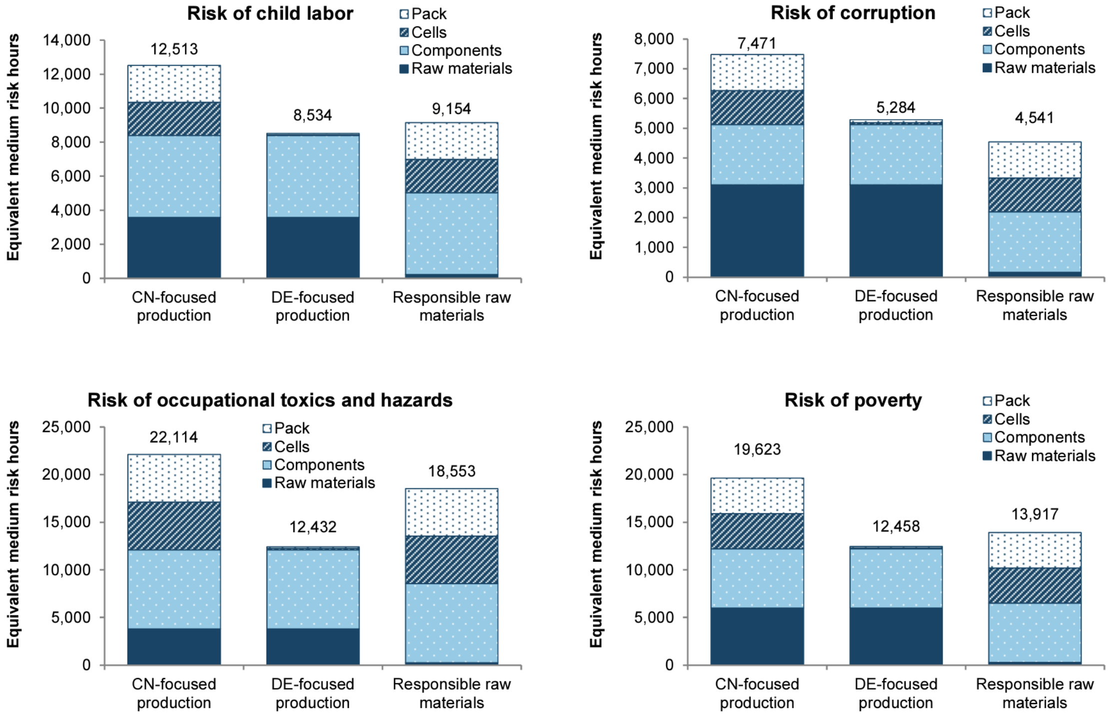


Figure 4.4: Assessment results for selected social risk of different supply chain configurations. [6]. CC BY-NC-ND

4.7 Results from laboratory produced batteries

Results from testing the laboratory produced batteries in the Landt Battery Test System are displayed below. The batteries were tested with the same tests. Showing several charge/discharge-cycles and both the current and voltage was measured as well as the efficiency and specific capacity for the battery. The batteries produced by the group gave ambiguous results and therefore values from other scientist's batteries were used.

4.7.1 LFP

Figure 4.5 displays the charge/discharge capacity the battery has over several cycles and it's efficiency. The green and blue dots shows that the battery loses capacity and efficiency with higher number of charge/discharge cycles. The first cycle deviates from the rest of the cycles and therefore it has not been taken into account. This is likely due to when a lithium-ion battery undergoes its initial charge, a solid electrolyte interface (SEI) layer forms on the anode [49]. This layer is critical for the battery's long term stability and performance but its formation consumes lithium-ions.

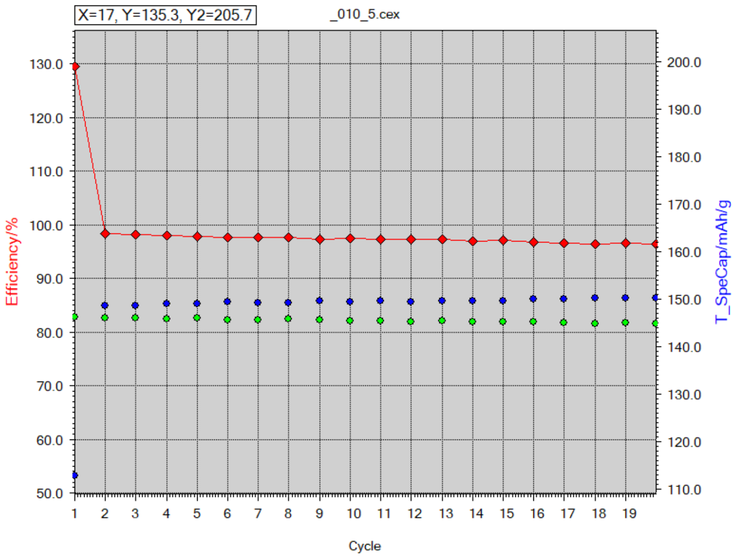


Figure 4.5: Applied charge/discharge (blue and green), the battery's capacity and the efficiency

Figure 4.6 shows the result from the battery testing of a working LFP battery. The figure shows current and voltage over time which indicates that the battery has worked over the testing time for several cycles.

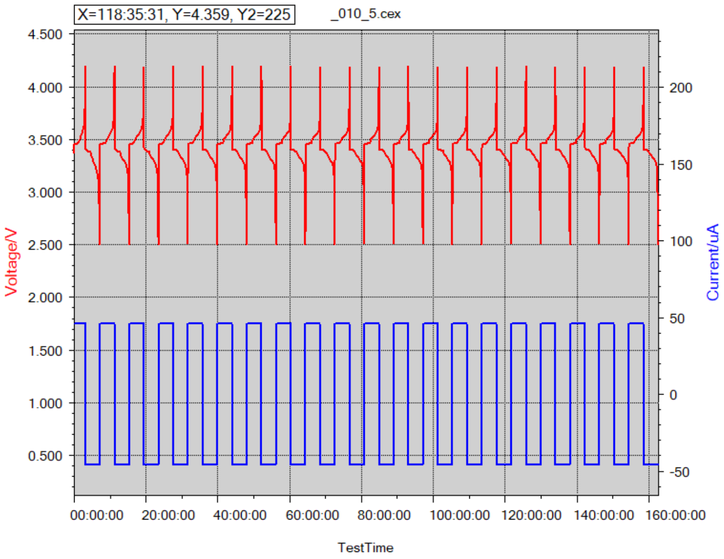


Figure 4.6: Several cycles with voltage and current over time

Figure 4.7 shows voltage as a function of capacity for all cycles. Initially the lines follows a similar pattern, but after a few cycles the lines start to deviate showing a degradation in capacity.

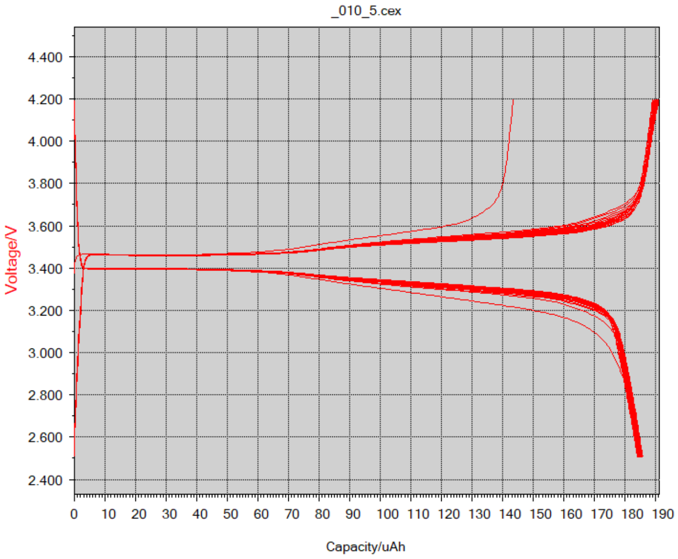


Figure 4.7: Voltage as a function of capacity for a LFP battery

4.7.2 NMC-811

Figure 4.8 displays the charge/discharge capacity the battery has over several cycles and it's efficiency. The green and blue dots shows that the battery loses capacity and efficiency with higher number of charge/discharge cycles.

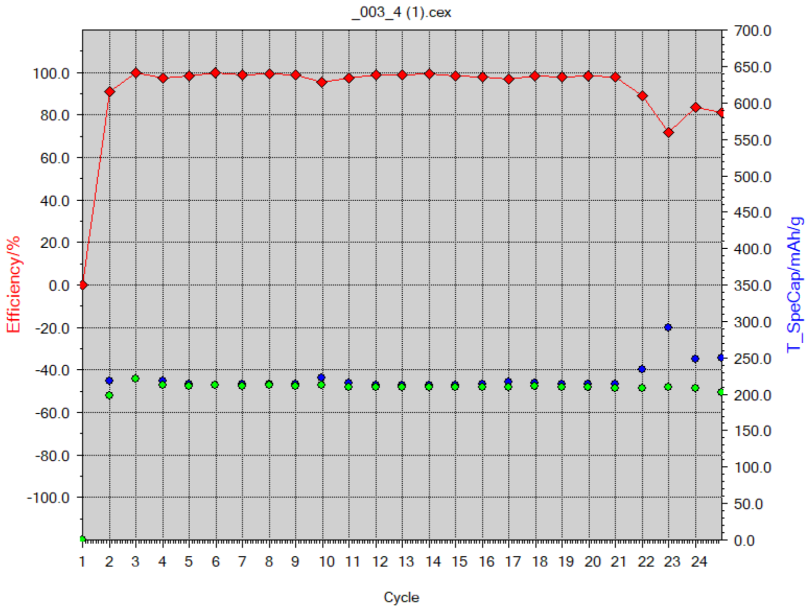


Figure 4.8: Applied charge/discharge (blue and green), the battery's capacity in blue and the efficiency

Figure 4.9 shows that the battery was functional throughout the entire test.

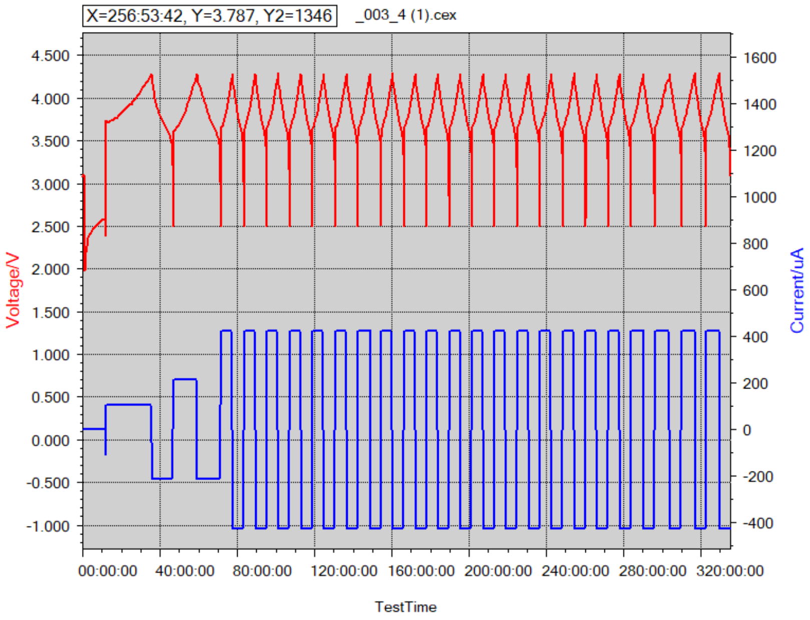


Figure 4.9: Several cycles with voltage and current over time

Figure 4.10 voltage as a function of capacity for all cycles. Initially the lines follow a similar pattern but after a few cycles the lines start to deviate showing a degradation in capacity.

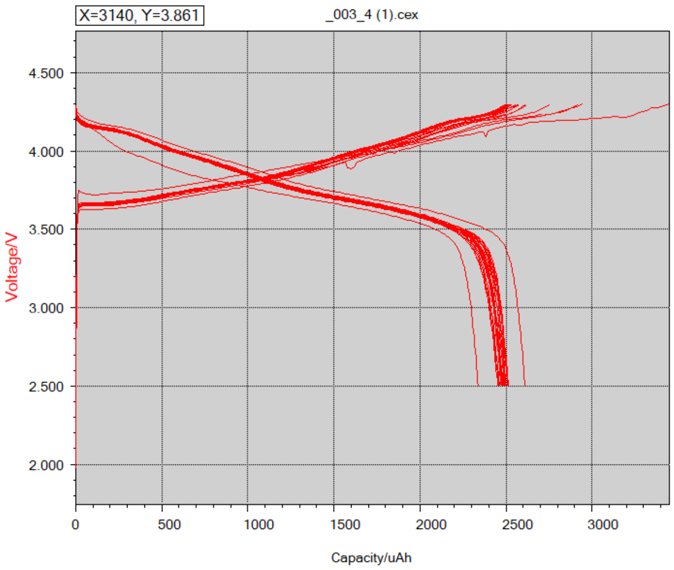


Figure 4.10: Voltage as a function of capacity for a NMC-811 battery

4.7.3 NMC-111

Figure 4.11 displays the charge/discharge capacity the battery has over several cycles and it's efficiency. The battery's performance varies significantly with compared to the other two battery types.

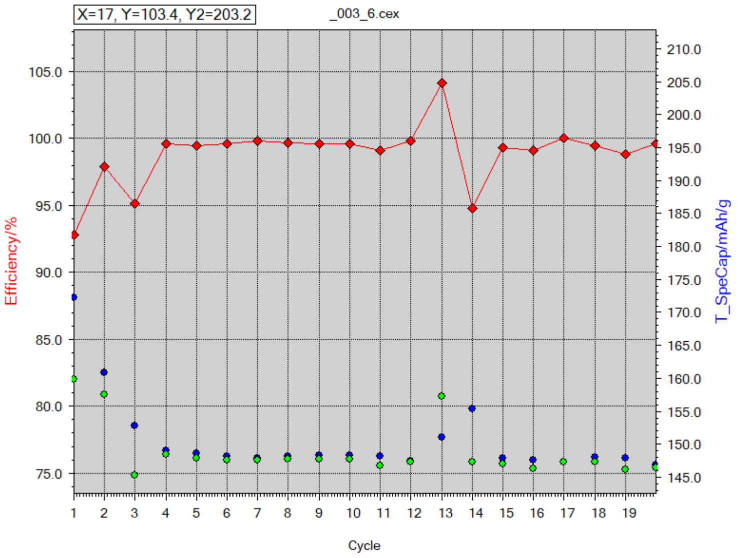


Figure 4.11: Applied charge/discharge (blue and green), the battery's capacity in blue and the efficiency

The battery was functional throughout the entire test which can be seen in figure 4.12.

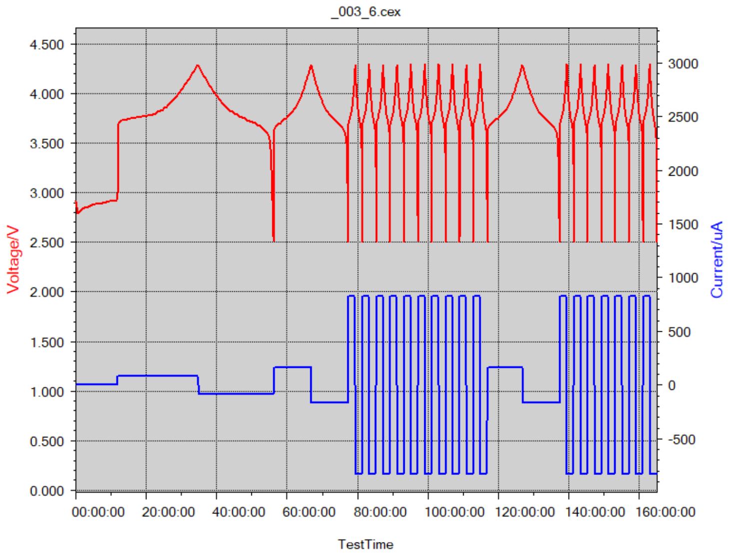


Figure 4.12: Several cycles with voltage and current over time

Similar to the other graphs showing capacity as a function of voltage, figure 4.13 shows a degradation in capacity over time.

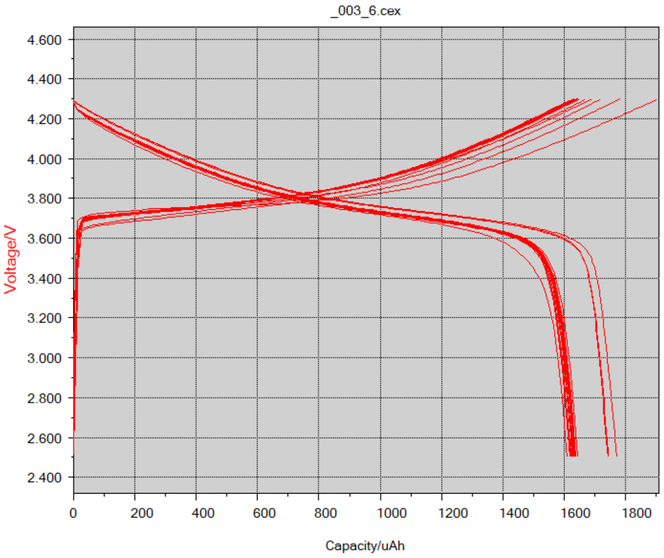


Figure 4.13: Voltage as a function of capacity for a NMC-111 battery

4.8 Future technologies reducing the use of cobalt

As the demand for electric vehicles continues to rise, researchers are exploring innovative approaches to enhance battery technology while reducing reliance on cobalt, a costly and environmentally concerning component.

4.8.1 Structural batteries

Scientist at Chalmers University has been working on introducing structural batteries to the market [50]. The goal of the structural batteries is to make the batteries contribute to the systems structural performance compared to today's battery that adds weight without contributing to any structure.

Promising results: The experimental trials uses ultrathin carbon fiber tapes with a width of 15 $[mm]$ as negative electrodes and a single-side LFP $LiFePO_4$ coated aluminum foil as a positive electrode. In between these layers a thin glass fiber layer was used as a separator.

From the trials the results have been very promising. On the electrochemical side the result has been showing a energy density of 23.6 $[Wh/kg]$ and mechanically a elasticity module of 25.4 $[GPa]$.

4.8.2 LFMP battery cells

Lithium Manganese Iron Phosphate (LMFP) batteries, derived from the foundation of lithium iron phosphate (LFP) cells, represent a notable advancement in battery technology. Trough strategically substituting a part of the cathode's iron with manganese, LMFP achieves a 15% to 20% increase in energy density, while upholding comparable cost-efficiency and safety standards [51].

The stable olivine-type crystal structure of LMFP ensures safety and durability during charging and discharging due to less deformation, outperforming traditional lithium-ion (NMC) batteries in thermal stability and cycle life. Zhao [51] also concludes that while LMFP shares similarities with LFP in theoretical capacity, its higher energy density, achieved through a 0.5V higher operating voltage, positions it as an attractive option for middle-class electric passenger cars.

5

Discussion

In lithium-ion batteries today, large quantities of cobalt are being used in NMC cell chemistries. The options to decrease cobalt in the industry today have been researched throughout this report and the comparison between them aims to show the possibilities to minimise cobalt usage in the near future. In this section the results from the laboratory work, literature review and interviews are analysed and discussed.

5.1 Potential means of decreasing cobalt reliance

There are different ways in which cobalt usage in lithium-ion batteries could be decreased in the near future. In this project several candidates for cathode materials, ones that contain lesser amounts of cobalt than what is common within the industry today, have been identified.

The first option that has been investigated in this report is to switch out NMC cells to readily available LFP cells that do not contain any cobalt.

A compliment to LFP that was also studied throughout this project is the manganese doped variant of LFP, denoted as LFMP. This chemistry is showing promising potential that indicates it could become a widely used alternative in the near future.

Another alternative that became apparent during this project is to decrease the cobalt content in NMC cells, without completely eliminating it's usage. In general this approach involves a transition to NMC-811+ chemistries, ones that can be found today in applications such as sports or luxury automobiles.

5.2 Comparison of cell performance

The comparison between the performance metrics of NMC and LFP cells comes down to deciding which trade-offs are acceptable. NMC cells offer a great advantage when it comes to specific energy, for example the NMC-811 which supplies around 250 $[Wh/kg]$ compared to a basic LFP cell can that only supply circa 170 $[Wh/kg]$. The NMC's superior energy density makes it suitable for high performance applications and long range electric cars where the possible travel distance is of considerable importance. On the other hand, it does not offer the safety advantages that the LFP cells provide. The stability and safety features of the LFP cells make for a compelling option for car manufacturers where the safety is of great concern.

The mission of mitigating the cobalt usage in NMC- and LFP batteries is strongly influenced by the interplay between technological innovation, environmental stability and social responsibility within the electric car industry.

In the urge of reducing the challenges of child labour and poor work environments the LFP cell chemistry is a promising competitor that aligns more with these challenges. But in the comparison between different cobalt levels, the NMC-811 represents a positive progress towards reducing the cobalt content while maintaining a very high energy density and performance levels. This chemistry really showcases the advancements in battery technology to contribute to a more sustainable manufacturing process. However a lot of further research is needed for them to actually compete with the LFP in the safety and safety-performance categories. Furthermore, a shift in the supply chain of lithium-ion batteries can contribute to the mitigation of the negative social effects of raw material extraction and battery production. By transitioning to a supply chain where production is heavily concentrated in, for example, Germany and sourcing all raw materials from responsible countries it is shown that the risk hours for child labour, corruption, poverty and occupational toxics and hazards could drastically decrease. However, making such a transition in today's environment with a high demand for lithium-ion batteries would be extremely difficult and would require a lot of time and resources.

The cost of a lithium-ion battery changes extremely dynamically between the different cathode chemistries used within the cell. As of today, the average NMC cathode constitutes approximately 51% of the total cost of the finished cell, which allows an LFP cell to be approximately 40% cheaper. Since the market price for the valuable metals constructing a lithium-ion battery is extremely volatile, putting an exact number on it is difficult, and it is even more difficult to make future predictions.

One of these critical metals is cobalt, and while the NMC-811 has made major achievements in the mission in reducing the cobalt usage compared to other cells like NMC-111 and NMC-622, the matter of fact is that it still contains some amounts of it. This makes it reliant on a supply chain imprinted with stability issues and economic uncertainties. In contrast to this the composition of the LFP cell makes it so that it doesn't have to rely on the cobalt industry, resulting in a potentially more straightforward and stable supply chain, thereby mitigating uncertainties and potential price fluctuations. This inherent advantage not only enhances cost-effectiveness but also renders LFP less susceptible to discrepancies in material availability and pricing.

Today manufacturers have managed to develop NMC batteries with a higher nickel content (NMC-811+) which currently negatively influences their overall cost profile. At the same time high nickel content can contribute to increased specific energy, allowing for greater specific capacity and improved performance of the lithium-ion batteries. These characteristics make the NMC-811+ batteries particularly suitable for applications where high specific energy is critical.

One of the challenges to the cost structure is the extremely volatile price of nickel. This has a lot to do with nickel being subject to price fluctuations driven by an array of factors such as spanning global supply-demand dynamics and geopolitical tensions. However since the price generally is lower then the cobalt price, which is exposed to the same demanding economical difficulties, the overall material cost for the cells is lowered with higher nickel content.

However, even though the material is cheaper the production of NMC-811+ is currently very complex. This creates the need for specialised production techniques, neat quality controls and additional monitoring. These extra complexities to manufacture the battery result in all potential cost savings being totally erased and the overall manufacturing cost being higher.

5.3 The balancing act of sustainability, manufacturing and cost factors

The LCA studied throughout this project provides crucial insights into the environmental impact of the LFP and NMC lithium-ion batteries throughout their whole life cycle. It also elucidates the most contributing factors like production, use, reuse phase, secondary usage and recycling and further explains their environmental impacts. However an important aspect to discuss is that the result from the LCA is slightly misrepresenting the CO_2 output from the actual cells. This is due to the LCA taking the usage phases into consideration, which is good because efficiency losses that occur while charging can be included. On the other hand this also means that the higher life expectancy a cell has, the larger CO_2 output is associated with the charging of the battery. This is why the LFP has a much greater impact during the two usage phases than the NMC. Additionally the LCA shows that how the electricity used for charging the batteries is being produced affects the two usage phases heavily. In other terms, the battery that can sustain more charging cycles gets penalised in the studied LCA.

The LCA also emphasises the importance of adapting different recycling methods, like hydrometallurgy, pyrometallurgy, and direct physical recycling. Since the hydrometallurgy uses aqueous solutions to extract metals from battery components it uses less energy than the pyrometallurgy where the cells has to be exposed to much greater heat which consumes large amounts of energy. It also offers a much safer environment for the people working in comparison to the physical recycling were people are physically in contact with the cells which could potentially result in physical harm if not done in a safe manner. In addition to this the hydrometallurgy can also result in a much more efficient process were the recycling can be done more precise and the processes can be tailored to recover valuable metals like cobalt, nickel, and lithium, which are essential for the production of new batteries.

Having such a precise extraction could allow manufacturers to reduce their need for new cobalt, decreasing their dependencies of complex supply chains with problems such as unethical mining. If companies are able to have a effective extraction it also means that the previous cells with a high cobalt percentage cathodes can be recycled and used to form new cells, for example high-nickel NMCs that don't require very much cobalt and thus could be produced in a larger quantity with the same amount of that resource.

However, despite all the environmental benefits it is a very costly process. It also requires a lot of technical complexity making the process difficult. The cost-effectiveness of recycling operations heavily depends on factors such as the market prices of recovered metals, the efficiency of recycling technologies, and government regulations.

The composition of materials in electric passenger vehicles battery packs, as shown in table 4.5, plays a pivotal role in both economical and environmental aspects of adoption in electric cars. Economically, material costs are a significant determinant of the overall affordability of a battery pack.

From an environmental standpoint, materials like cobalt and nickel are finite resources susceptible to depletion and environmental degradation. Furthermore, the energy-intensive processes involved in manufacturing materials like aluminum and copper contribute to carbon emissions and energy consumption. In the BOM the materials are listed, when studying the percentages it becomes apparent that an LFP battery pack needs more resources like copper and steel. However here it can also be noted that the safety features such as electronic parts, thermal insulation and coolant can be singificantly reduced in the LFP packs. This is one of the benefits that N.Boardman discussed in the interview, as the risks involved are greatly reduced due to a more stable chemistry in LFP compared to NMC. As mentioned earlier this is very beneficial in car manufacturing if the manufacturer safety is kept as one of the major priorities while also saving costs.

The decision whether to use a water-based solvent in the manufacturing-process is a very complex decision and a real balance act, taking many things in to consideration. One of the more compelling advantages is that it eliminates a lot of environmentally harmful factors since it doesn't involve any toxic chemicals. The manufacturing process then also becomes a lot more work-environmental friendly making a lot of safety equipment in consideration to solvents like NMP obsolete. Aside from the work environment benefits, water is a non-toxic substance which is readily available making the purchase-cost for material significantly lower and reducing complex supply chain issues.

However there is still a lot of significant problems that have to be resolved and addressed for it to reach a widespread adoption. One such challenge is the variability in rheological properties, which can lead to difficulties in maintaining optimal slurry consistency and stability. The inconsistencies in the coating thickness can drastically affect the performance of the actual cell which was apparent in the experimental part of this project, the result of this can be a great variation of the voltage and functionality between the cells from the same batch of slurry. This can be a great concern for large scale manufacturing because the slurry needs to be uniformly distributed over such a large surface area. This is an area of the process were the NMP clearly excels the solvent with water. Due to the viscosity of it, the slurry behaves completely differently resulting in a much easier process to ensure an even layer of coating.

Another great concern for the widespread usage of the water-based solvent is the sensitivity of the cathode material in the NMC cell to water exposure. Interaction with water results in a non-desirable PH-level which by itself drastically lowers the life expectancy and reliability of the cell. It is also asserted that this is especially harmful for batteries in demanding applications like the electric car industry. The changed PH levels make adaptation and potential benefits of water-based solvents not being fully realisable in practice making the adaption of water-based NMC-manufacturing almost impossible.

If the manufacturers were to transition to water-based processing only for the LFP cells where it has been shown to work decently, only with some adaptations in how the slurry is being processed and applied, it is still not certain it would save the manufacturers money regardless. This is due to the process being very different from traditional NMP-based processes. To accommodate the difference an entirely new manufacturing facility is required just to make a specific type of cell, in this case the LFP. This necessity is additionally caused by the risk of cross-contamination with cell types that are sensitive to water exposure.

If the process of applying and drying the solvent is approximately 15% of the total cost of the cathode, and the cathode is responsible for around 50% of the cost for the finished cell, thus the application and drying would be around 7.5% of the finished cell-cost. This has to be taken into consideration when looking at the necessary equipment needed, for example the company would need a new mixing-, application- and drying equipment for this process. It is unclear if the large upfront investment cost could be offset by the fact that the water-based solution would dry around 10 times quicker. This would also imply that instead of having a versatile and flexible production as companies have today, where they can alter between the different types of cathode chemistries, a completely separate plant would be needed in order to manufacture the water-based LFP cells, resulting in an extremely expensive endeavourment.

If the companies decide to take on this venture however, say for example in combination with production of LFMP cells, it could present strong economical opportunities. This is in large due to the LFMP cathode providing a potent alternative capable of storing energy levels comparable with for example NMC-111. The LFMP cathode is not only completely free of cobalt, has a fairly high specific energy but in combination with the water-based processing it would also reduce the risk of work environmental risks and attain a potentially low cell cost. It offers a stable chemistry that is a perfect alternative for the passenger car industry as a cost effective and safe solution that would still be able to output relatively- high performance or long range.

5.4 Laboratory experiment

The manufacturing process in this project has yielded multiple valuable insights into the field of battery manufacture. Notably the obtained results underscore the impact that the charge and discharge cycles can have on the batteries capacity with different cathode chemistries, and how it also affects the overall efficiency off the cell.

Furthermore the lab experiment also elucidates the importance of using compatible materials within the entire manufacturing process and preventing contamination. Unintentionally the slurry mixing process was firstly carried out with plastic mixing containers. This led to an unforeseen complication. The NMP which was used as solvent reacted with the containers and created a grainy slurry, this grainy slurry was applied to the current collector in accordance with industry standard practice but the result was really undesirable. The cathode layer had really poor rheological properties that resulted in an uneven and grainy cathode unsuitable for any type of further manufacturing.

These insights also highlighted the sensitivity of the manufacturing process, indicating that large changes, such as a transition to water-based processing, will entail many variables that need addressing before the process generates desirable results.

5.5 Future Outlook

LFP battery cells can initially appear very appealing along a wide range of considered metrics, for instance their ability to last up to 9000 charging cycles until reaching 80% of their original capacity, as compared to 2500 cycles for the same effect on high-nickel NMC cells, can be considered highly advantageous. But the LFP cells come with one major drawback, namely their relatively low energy density. In contrast to NMC chemistries that can reach up to 300 [Wh/kg] the LFP is only able to deliver around 170 [Wh/kg] in specific energy, which is barely more than half that of the NMCs. This severely impacts the ability for LFP batteries to be used in the electric automobile industry, where range is considered one of the most important metrics when creating a vehicle that is attractive to customers.

Another attractive feature of LFP cells are its safety characteristics. A battery fire releases a lot of different emissions, heavy metals and harmful organic compounds into the air. With LFP cells being less susceptible to battery fires, they are considered much safer both for the user and the environment.

Additionally, because of LFP cells being less volatile, less air gaps in the battery pack are also needed for cylindrical LFP cells as compared with NMC ones. Although not increasing the specific energy, the smaller air gaps make it possible to insert more cells in a given volume, thus increasing the energy density. This is especially useful since the battery pack often has the same volume for a given vehicle, regardless of used cell type. As this is done to ease manufacturing of the car it makes volume a crucial restricting factor. Although the battery pack will gain weight, the increase in energy density in the battery pack helps to slightly mitigate the difference in specific energy between LFP and NMC cells.

Despite the range limitations of LFP battery powered vehicles there still exists a likely possibility of them having a significant market share in the near future, as their ability to withstand frequent charging cycles makes them ideal for short range applications, such as taxis that drive within cities or low-end vehicles where the customer is willing to compromise on range in favor of a lower purchase cost. Manufacturers may also be willing to transition to LFP due to supply-chain related concerns, further increasing the potential market share of this battery chemistry.

As previously mentioned a further complement to the LFP chemistry is the manganese doped variant, known as LFMP. This very recently developed battery chemistry attempts to address the core disadvantage associated with LFP cells, which is as previously stated their comparatively low energy density. As the manganese content increases the voltage stability of the cells their nominal voltage also increases, which means the batteries can now be charged to higher voltages without failing. This in turn increases their energy density to as high as 220 [Wh/kg], making it far more competitive with NMC chemistries.

Currently large-scale LFMP production still faces some hurdles to overcome, which are mostly related to the large amounts of NMP solvent that have to be used during the production process. As discussed in this report, this is a problem that could potentially be solved through water based processing in the near future. If this was to happen the LFMP battery could potentially take a very large portion of the electric car battery market, as it retains the life-cycle and supply-chain advantages of LFP cells with a significantly improved long-range capability.

In the premium electric car market high range remains possibly the most important feature of the vehicle, placing very strict demands on what batteries are chosen for the application. This in practice means that this market segment is dominated by NMC-811+ chemistries, or in other terms high-nickel NMCs that currently offer the highest specific energy among commercialised cells. At the moment there does not appear to be a clear competitor to these battery cells, which points towards the conclusion that they will continue to dominate this part of the market in the near future. Due to their high nickel content these high capacity NMC cells also play an important role in reducing the overall cobalt consumption, even though they still retain a certain amount of that critical resource.

However, the high-nickel NMCs do not come without some production related issues, which are explicitly caused by their low cobalt content. As the role of the cobalt is in large to stabilise the cell it becomes increasingly difficult to create stable crystals as the percentage of cobalt is lowered, resulting in a more difficult and thus expensive manufacturing process. Additionally, the cyclic life of the cells is also negatively impacted by the low cobalt content, meaning that high-nickel NMC cells degrade considerably faster than for instance NMC-111 or NMC-622 counterparts. These factors indicate a high likeliness that NMC-811+ cells will only be used in the most range demanding applications, as the disadvantages associated with them makes them unsuitable for most other use cases.

5.6 Ethical aspects

It is necessary to respect intellectual property, all from using pictures to patents. When discussing and presenting innovations and technology in the thesis it is important to have a transparent workflow, respect intellectual property rights and be aware of patents property ownership.

Industry collaboration through interviews and visits may create a biased result. Research integrity is necessary to avoid skewed data which can lead to unethical results and the report could for example misrepresent information about different battery technologies. Industry bias can be a problem when working with the institute and industries working on battery development. This can take form in a multitude of ways, for example people's and companies' personal interests can be seen as facts.

The problem with skewed data and industry bias was handled through a transparent treatment of information and through crosschecking facts using several different sources.

6

Conclusion

Decreasing cobalt usage in lithium-ion batteries is a matter of high importance. The mining of the cobalt is plagued by dangerous and poor working conditions. Additionally, there are geopolitical and strategical problems related to the supply chain of cobalt, where cobalt is a very expensive material. All these factors create an incentive to decrease cobalt usage in lithium-ion batteries. In the industry today, a lot of cobalt rich NMC batteries are common, the solution to decrease the cobalt usage in the cathode material comes in various ways.

LFP batteries do not use cobalt at all. They are not able to achieve as high specific energy as the used NMC batteries, however they are much cheaper to produce. This is making LFP batteries a great choice for low-end electric cars where low cost is a priority and the range is allowed to be less.

In the near future, LFMP batteries which are manganese doped LFP cells, are likely to be produced industrially. LFMP cells have a higher specific energy than LFP cells and will thus be a great choice for mid-end electric cars that need a slightly higher range.

For the high-end electric cars where long range and power are the most important factors, it is a better choice to minimise the cobalt in the NMC battery than switching to an entirely different cell chemistry. Decreasing the cobalt and thus increasing the nickel is actually increasing the specific energy in the battery. This makes low-cobalt cell chemistries such as NMC-811+ a great choice for high-end electric cars.

The research shows that there are possibilities to minimise cobalt usage in commercialised lithium-ion batteries within the electric car industry. Using lithium-ion cells that are currently on the market or are likely to be introduced in the near future, it is possible to decrease cobalt usage for all electric car lithium-ion batteries.

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A

Appendix 1

Appendix 1 contains transcipts for the interviews. The first interview with Nils Boardman is shown on the following page, note that the entire interview was done in swedish. The transciption with the materials engineer begins the page after the interview with Nils Boardman is finished.

Möte-20240318_120600-Mötesinspelning

18 mars 2024, 11:06fm

36m 29s

Marcin Kryger 0:39

De första frågorna syftar om säkerhet med avseende av batterier. Vi har nämligen hört att det ska en vara skillnad på vilken säkerhetsutrustning som man behöver ha i batteripacket för NMC gentemot LFP celler. Vi har då blivit lite fundersamma vad det är för säkerhetsutrustning som finns i ett NMC pack som man kan spara ner på i en LFP.

niels 1:00

Ja först vad det är för kemi såklart och men sen paketeringen också. Om du har en cylindrisk cell eller om du har en till prismatiskcell eller om du har en pouchcell. Dom i sig kommer också påverka vilken utrustning som krävs ganska mycket. Sen är det ju också beroende på applikation, är det ett batteri som är på väg eller är det statiskt batteri. Ytterligare sen när man säger väg, är det transport eller en personbil. Allt detta kommer påverka resultatet i vilken utrustning som krävs. Vi försöker vi göra ett exempel, säg att vi utgår från en NMC kemi. Det är en kemi som är mycket energipackat. De är ganska säkra egentligen, men i batterivärlden osäkra eller mer volatila. Om du har en NMC cell med ett cylindrisk format, ofta så har du någon typ av design guidelines, om du har en cell så måste du ha en viss air gap till nästa cell. Det här airgapet gör då att om den cellen brinner fullt ut så ska den cellens brand inte skapa en kedjereaktion i batteripacket så att nästa cell börjar brinna. Har du designat din cellmatris så att alla celler ligger på rätt utrymme så ska en cell inte propagera utåt. Då behöver du inte ha släckning, eftersom det bara är en cell som brinner upp. Det är fortfarande allvarlig och det kan ha allvarliga konsekvenser. Har du en liten cell i en batterilåda, du behöver fortfarande gasventiler så att du inte skapar en bomb. Så länge branden inte sprider sig från den här cellen till en massa olika celler så borde allt kunna förhålla sig ganska bra inom batteripacket. För att det är en metallförpackning och det är mycket värme som skapas i en cell som brinner men det är en väldigt liten cell gentemot massan i hela systemet. Då kanske du inte behöver ha alternativa släckmetoder utan det räcker med en bra design.

Kollar man istället på prismatiska celler, de kan vara riktigt stora. De kanske är 10x20 och 2-3 centimeter breda för att få en bra uppfattning. Jämför du den volymen med en cylindrisk cell så är den 4 gånger mer. Då är det 4 gånger mer brandfarligt material som, om en tar eld så brinner den 4 gånger mer. Sen finns det prismatiska celler som är bilbreda. Den är lika bred som jag beskrev, men den är utdragen till lika bred som en bil. Det är ganska många celler då i samma paket och tänder den eld så kommer det hända mer. En annan sak med prismatiska celler är att de ofta ligger face to face stackade så de har inget air gap. För paketeringen så är det så gött med en fyrkantig cell att man kan lägga dem kloss an och det gör man. Har du en större cell, mer termisk massa och mer kemisk massa som kan antändas som kan brinna längre och kraftfullare, och kan skapa den här kedjeeffekten då. Där kanske du behöver ha en släckningsmetod då, eller ha en kedjereaktions prevention. Det är det man egentligen letar efter, att en cell brinner upp kan det bibehållas innanför batteripacket. Börjar många celler ta eld så börjar hela bilen stå i lågor.

Släckningsmetoden kan vara att pumpa in skum eller kylmedel för att ta ner temperaturen så mycket som möjligt, branden kommer fortsätta men det motverkar att alla andra ställen kommer att börja brinna också. Termisk ledning eller kylning som att dumpa någon typ av vätska, skum eller liknande. Du kan också använda gas, en cell brinner självmant och det finns gaser som motverkar effektiviteten av branden. Därför kan du pumpa gas in i systemet för att släcka eller åtminstone mitigera hur bra det brinner. De två är ganska ovanliga och du kanske har de på lastbilar med en massa prismatiska celler.

Men du har ju nästan alltid termo barriärer, alltså icke brännbart material och olika material som inte brinner som leder bort värme förmågan och som också kan motverka att vi får en kortslutning. En mekanisk barriär för kortslutningen och en termisk barriär för catastrofic event. Alla batterier har så att man försöker mitigera den termiska rusningen och spridningen i facket så gott man kan. Sen så har det ju kylsystemet då som är som är i batteriet sen innan. Har du ett termiskt event så sätter man på max kylning, bara för då skiter man fullständigt i allting annat.

Marcin Kryger 9:31
Ja, rimligt ändå

niels 9:43
Det finns också ett visst material som heter vad heter vermikulit som är vanligt för brandsläckning i litium jon sammanhang. Det är en mineral som inte brinner och den släpper iväg den här gasen som mitigerar hur bra det brinner. Det är ofta material av vermikulit eller att man använder vermakulit spån som man kan släppa ner. Det gör man inte i bilar, för det är för jobbigt.

Marcin Kryger 10:40
Om man skulle ha 2 batteripack som har jämför och säger att vi valde exakt samma cell format. Enda skillnaden är att jag har ett som har LFP, kemi och ett som har NMC kemi. Så kör jag med till exempel airgaps som preventions metod. Skulle man kunna ha mindre air gaps i LFP batteriet än i NMC batteriet skulle du säga?

niels 11:12

Ja, det är ju så att LFP är en mycket mer stabil kemi, den är inte liksom volatil. Det är också mindre energi i en cell och en katastrof event på en LFP kommer inte skapa alls lika mycket värme som i en NMC cell. Punkterar du en NMC cell, så kommer du se ganska stora lågor och det kommer fräsa rätt gött kan man väl säga, men på en LFP cell så kanske det pyser lite rök och det bubblar lite. Det är inte alls den här typen av pyrotekniska showen. Det är en väldigt mycket mer stabil kemi och det är ofta därför man använder den. För att den är så himla mycket säkrare.

Återigen att en cell börjar brinna är ju jättedåligt, men det kanske inte resulterar i att hela bilen brinner upp, men risken med NMC celler är att om en cell går sönder så kan det sprida sig. Dom här jättelånga jag snackade om, de här superlånga breda prismatiska celler som är liksom car length wide. Jag tror inte jag har sett det med NMC utan det är just LFP bara för att man vågar inte göra det med NMC. Det är så mycket energi som kommer börja brinna så det går inte att hantera på ett bra sätt. På LFP, drar du en spik igenom så kommer bilen inte fungera längre men bilen kommer inte brinna upp heller.

Marcin Kryger 13:17
När ni designar ett batteripack så är det hela tiden en våggång mellan energidensitet till riskerna om en cell skulle börja brinna?

niels 13:28
Ja och man ju kolla så här, om man skulle göra en batterilagring, alltså statisk batterilagring, typ ett hus. Ja då hade jag inte rekommenderat en NMC bara för att även om även det ser godare ut på specen, har du plats för ett batterilager och allt det som är inkluderat så har du ofta plats för 50% mer. Tar det upp en kvadratmeter på väggen eller 2 kvadratmeter på väggen så spelar det inte så stor roll, men om ditt hus brinner ner kommer det spela en väldigt stor roll.

Det ju massor som kör NMC på powerwalls och så, men jag hade inte gjort det. Performance mot risk är kanske inte riktigt värt det. Kollar vi istället på typ en high performance car, alltså en sportbil eller en snabbare elbil. LFP är för tungt, den har för dålig energidensitet och den är också mer värme beroende. Den möter inte performance kraven i det läget. Då måste vi köra NMC eller någon annan. Inte järnfosfat i alla fall.

Marcin Kryger 14:55
När vi inne på bilar och fordon, du varit med och utvecklat en del batteripaket i fordonsbranschen, vad kollar ni på för krav? Vad är relevant när ni bestämmer?
Just i batteri prestanda, vad är det ni tittar på? Kollar ni mycket på energidensitet eller kollar ni mer på säkerhet och sånt?

niels 15:23
Man kollar ju på allt är väl det jobbiga svaret på frågan. Nej, men ofta så får man ju någon typ av kravbild, om det är någon ”performance owner” eller någon system person eller om det är mer sälj som bestämmer. Men någon kommer ju säga så här mycket kräm behöver vi får ut, och då har vi den här ytan eller den här kostnaden. Man har lite olika boundary conditions med hårda krav. Sedan har man mjuka krav, lifecycles är ett bra sånt. Mer är alltid bra, för lite är för lite, men något där emellan är bra. Oftast kanske man säger att det inte får vara större än så här och vi måste kunna ta ut 100kW minst. Sedan får man göra en värdig matris på det här.

Kollar man på väldigt stora OEM’er, de har möjligheten att designa celler. Alltså de kommer ändra kemierna i cellerna och kommer göra en batterilina. De har full kontroll exakt vad som går in och hur de möter deras specar. De flesta har inte den lyxen, utan då sätter man upp sina ”boundary conditions” både mjuka och hårda, ta in en massa olika specar och göra en ´så bra jämförelsematris som möjligt. Låt säga att vi håller säkerhet högt, och vi måste hålla en viss power och energy density. Då faller de här bort, men de här är olika bra. Det kommer aldrig finnas en perfekt cell om du inte är med och designar den. Även när man får vara med och designa cellen så finns även de fysikaliska begränsningarna. Det är en vågskål där allting påverkar de andra, generellt sätt ligger energidensitet motsatta vågskål mot säkerhet. Ju mer energi du har på en mindre yta, vilket är vad du vill ha för det är energy density. Det som du kräver från cellen och den kemi som krävs kommer vara mer volatil, du kommer närmare och närmare dynamit på något sätt.

Det blir en bättre och bättre bomb för varje inkrement man kör.

Det kanske man inte vill ha, och då får man dra tillbaka spektrumet lite grann. Sen för termiska egenskaper så har vi power och life expectancy som är samma sak. Hur mycket kräm vill du ta in och ut ur batteriet i en viss tidspunkt. Ju mer du tar ut desto er värme kommer genereras. Ju mer värme som genereras desto snabbare blir åldringen, så det kommer påverka dina lifecycles och din totala tid som du förväntar dig från cellen. Det är en massa olika som är på varsin sida, och alla har sina egna idéer och tankar för vad som är bra eller inte beroende på din application. Det är en riktig soppa.

Marcin Kryger
Det är rätt mycket att tänka på bara för att få ihop ett pack.

niels 20:11
Ja, jag alltså cellvalet är ju det mest kritiska. Sen vilken formfaktor är ju också så väl

kritiskt, men grundkemin kommer att påverka termiska, säkerhet, performance. Allt det här kommer utifrån den cellkemi du har valt. Utöver det så er det också kostnad.
Det finns även andra faktorer som är med i den här matrisen, såsom supply chain. Hur säkert är det att köpa den här cellen långsiktigt från den här leverantören, kvaliten från den här leverantören är bra, är det en betrodd leverantör. Är det en dålig leverantör så kommer risken öka avsevärt. Även, vart får dem sina material från, hur ser deras supply chain ut bakom kulisserna. Det påverkar också säkerheten och långsiktigheten för produkten. Om man bara bortser de rena performance attributen så är det väldigt mycket mer kring business, och kostnad då såklart. Vad man är villig att betala och LFP är ju väldigt bra just för att det är väldigt mycket billigare material, det finns andra källor av råmaterial. Det är fortfarande litium så det är fortfarande en begränsning, men det är ingen eller mindre kobolt. Ja, det bygger ju mer på järnfosfat vilket är en mer naturlig källa.

Marcin Kryger 22:18
Nu när vi har kollat mycket på batteritillverkare och så, det verkar vara väldigt många som på sina low range bilar och sånt går över väldigt mycket på just LFP.

niels 22:19
Ja precis ja, så är det ju. Batteriet är lika stort och lika tungt, men det är bara med en annan annan kemi, så det har antagligen använt samma formfaktor på celler och liknande för att det ska passa i samma chassi och vara så enkelt att tillverka som möjligt. Det är bara en annan kemi och en annan energidensitet och lite andra parametrar, liksom för kylning och power och så vidare. Från utsidan så kan de se exakt likadana ut

Marcin Kryger 23:04
Även utsidan på batteripacket är nästan likadant mellan dem. Man behöver inte anpassa bilen så mycket mellan high range och low range modellerna?

niels 23:33
Precis, det ska bara vara en mjukvara grej egentligen. LFP celler och NMC celler har olika spänningar. Konfigurationerna internt i batteripacket kommer se väldigt annorlunda ut men egentligen så jobbar man mot att det utifrån ska vara samma produkt och sedan vet batteriet vad som finns inuti. Då vet bilen att det här är ett NMC pack och då har jag de här performance profilerna, de här kylprofilerna mm. Sen så sköter det sig självt nästan.

Marcin Kryger 24:01
Så rent hårdvarumässigt så standardiserar man efter liksom det tuffast kraven och sen kan man bara byta om man vill ha LFP till t.ex en Low Range?

niels 24:08
Låt säga att vi har NMC, så kanske du har den stora pumpen som ska klara 10 liter per minut i kylning. För LFP så kanske du då bara har kravet 6 liter per minut och då antingen så har man en annan pump som är billigare, eller så kör man på den stora pumpen bara för att det är enklare. Det är väldigt projekt beroende. Från utsidan av batteriet så försöker man standardisera interfacen och de adapterade komponenterna. Man har batteriytan och det är vad man håller sig inom, men insidan ser ofta väldigt annorlunda ut.

Ja, det är klart att det underlättar en massproduktion väldigt också om de är så lika som möjligt.

Ja, men säg då att vi behöver bygga 2 olika chassin för det, alltså bilchassin är en av de mest investeringstunga bitarna i en fordons uppbyggnad. För det är så mycket pressning och svetsning och det är en väldig maskin och investeringstung bit. Kan du undvika att ha 2 olika chassin så vill ju ha det till allt du möjligen kan.
Men för vissa saker typ pumparna, det är bara en liten komponent. Köper vi en miljon eller 2 miljoner så spelar det ingen roll för att vi har redan det bästa priset för det vi köper redan så många. Sparar vi 3 kronor på att köpa den lite billigare så gör vi det. Alla interface och slangar kommer vara exakt samma för att ha möjligheten att byta.

Marcin Kryger 26:23
När du kikar på olika typer av fordon som long range och mid range, då gör du väl den här balansen som vi har pratat om av faktorer. Skulle du säga att man kan specificera ut de viktigaste faktorerna för olika biltyper?

niels 26:53
Över lag så skulle jag säga att de grejerna som alla pratar är samma sak som står på pappret när du kollar på fordonen och det är ju range och power. Det är på något sätt viktigast i alla applikationer. De är också lite på vardera sida vågskålen, du kommer aldrig kunna ha ett high range pack med hög energidensitet och som också har high power.

Marcin Kryger 27:31
Ja precis, för du tar ut så mycket effekt hela tiden.

niels 27:34
Ja så då, så om du kollar på om du kollar på ett high performance pack som har mycket power output så kommer den alltid ha sämre energidensitet. Det kommer inte fungera med energidensitet med det här packet, på grund av kemin.

Bara för att ge en väldigt översiktlig, man har stora korn och små korn. Inte i kemin utan mer hur granulär ens kristaller är. Har du en stor kristall så har du väldigt många ställen du kan placera elektroner på. Den är väldigt enkel för elektroner att hitta ställen att fasta på och du kan spara mycket energi på lite material, du har en väldigt fin sfär att hoppa på. Har du minuspolen här och pluspolen där, det är en stor omväg att komma runt hela den här stora klumpen för att komma dit vi ska. Det är mycket energi som kan sparas men det är långa vägar, sedan finns det kanske en annan kristall som gör vägen ännu längre. Varje millimeter skapar värme, och värme är dåligt. Vi har mycket energi, många ställen att placera elektroner, men jobbiga komplexa vägar. Gentemot om du har en hög power cell där du har en massa små kristaller i stället. Det finns mycket färre ställen för elektroner att hitta, men det finns alltid korta vägar, och det är alltid effektivt för elektronerna att hitta sin väg till det andra mediet. Vi kan inte ha båda, antingen så har vi stora kristaller eller små kristaller. Vi kan inte blanda små och stora kristaller och tro att det löser problemet. Antingen har vi stora, små eller någonting mitt emellan. Det är för att det är en kemisk ”boundary” bara, det går inte.

Marcin Kryger 30:39
Hur mycket kollar ni på cellresistans när ni utvecklar ett paket, för det blir väldigt mycket värmeutveckling om man har massa små celler. För det är väl en av fördelarna med de här stora cellerna, just att det blir mindre cellresistans.

niels 30:57
Ja, det kan det kan vara positivt. Det är med hur man bygger cellerna i produktion så att när du har cylindriska celler så har du två ark och sen i ena änden längst ner i hörnet så har du en pluspol och i andra ändan på hörnet så har du en minuspol. Du tar du den här och rullar ihop den och lägger dem på varandra. Om vi rullar ut den här igen, lite grann som med i kristallerna, för att elektronerna ska komma härifrån hela vägen bort hit så är det en längre väg då alla ska flytta sig upp och ner. Vissa vägar kommer behöva gå väldigt långt för att komma till easiest path of resistance. Det finns några cylindriska celler som kallas Full tab, en ny teknologi som Tesla kom med för några år sen. Där har du istället för att ha dessa två end tabbarna så har du en massa olika tabbar som rullas ihop och så svetsar man ihop punkterna, som ger bättre performance då. Det traditionella sättet är att ha två tabbs och rulla ihop den. På prismatiska celler så har du ofta mer liknande full tabb lösningen då. Du har kanske vikt den en gång eller två, men du har mycket mer tabbs och kortare vägar som ger dig mycket mindre termisk uppbyggnad inuti cellen. Inuti cellen är det bättre strömbanor än i busbars. Ska du koppla cellen till någonting så behöver du en svetspunkt som har en viss resistans. Det är skönt att ha allt i samma grej för då har du bara en strömbana och en definierad väg, då blir det mindre total termiska effekter.

Lastbilar gillar prismatiska, för att det är fyrkantigt, gött att bygga med och mycket mindre värme och få mer performance. På lastbilar så kan du ha väldigt stora prismatiska celler för att du har väldigt mycket mer plats i lastbilen. I bilar så kanske du inte kan ha de stora, utan du får ha de mindre prismatiska cellerna. Då är din pro’s and con’s list, dina pro’s från bättre termisk performance gör inte så stor skillnad längre gentemot en lastbil. Där blir det ganska stor skillnad. Det är en oändlig effektiviserings och optimerings problematik. Du mycket data och hårda siffror, men så kommer någon från inköp och säger ”Vi litar inte på dem, det går inte”. Det kostar 1 krona för mycket, det går inte.

Företag och världen ändras ju varje dag också, så eftersom du har den kaotiska biten som inflikning så är det oändligt. Det kommer nya kemier, nya fabriker och nya spelare. Saker händer varje dag, men varje halvår har det en större implikation. Designar du detta halvåret eller nästa halvår så hade du inte valt samma cellkemi.

Transcript

00:00:01 Marcin

Alright, yeah, yeah, seems to work. So, what were you working with? You work at the (Major battery manufacturer) right?

00:00:12 Materials Engineer

Yeah, yeah.

00:00:14 Marcin

What was your role there? Like, what do you work with?

00:00:18 Materials Engineer

I'm a mechanical engineer in innovation team, so we are actually working on like new technologies, but that can be applied very quickly like it should be related to mass scale production like so we're working on those materials and try to find the solution in like current production processes, yeah.

00:00:40 Marcin

OK. So you're very much on the production side, OK. And do you work with batteries specifically like you? Cell manufacture, yeah? Because we had a lot of yeah, cell chemistry related questions. So I guess you'll answer as much as you can and no, so one thing we were wondering is about cobalt in the battery cells. Can you describe in any like simple way like why there is cobalt used in these batteries? What is its like chemical role in the battery cell?

00:01:22 Materials Engineer

Yeah. So basically Cobalt helps. I mean, cobalt purpose is to improve the electronic conductivity inside the NMC structure. So it improves the crystal structure stability as well. So that's why like people are mostly focusing on some cobalt.

00:01:35 Marcin

OK.

00:01:42 Materials Engineer

It should not be like Cobalt free, but maybe 0.01% or something like that. Even that is enough.

00:01:48 Marcin

Ohh OK.

00:01:49 Materials Engineer

For the batteries like, so there are some manufacturers, they are saying it's cobalt free but actually it has some cobalt as impurity you can say or something like that.

00:02:02 Daniel

To still have this conductivity, yeah?

00:02:05 Materials Engineer

Of course, like some other elements like aluminium, tungsten, they can also help. But not like as cobalt. So that's why if you see like the papers like on cobalt free NMCS especially, they don't mix like one type of dopant they add 2, 3, 4 like combination to match it. But still it's not possible.

00:02:26 Marcin

Yeah. OK. So I read a paper on the cobalt free NMC just today.

00:02:36 Materials Engineer

There is a famous paper actually from Jeff Tan Group, it's a question: Is cobalt necessary?

00:02:43 Marcin

OK so literally the question that we asked. Kind of yeah. OK, maybe we can query that later and see if we can find that study.

00:02:48 Materials Engineer

Yeah, yeah.

00:02:52 Marcin

Yeah, but so kind of like the manganese level. Yeah, we notice it often follows the amount of cobalt that you have. It seems to be similar proportions.

00:03:04 Materials Engineer

No, actually it's not necessary because the manganese is like if you say manganese is the main purpose of manganese is like to increase the voltage stability. So you can go like at higher voltages with the manganese so. You know, like there is a chemistry called LFMP.

00:03:28 Marcin

Oh LFMP, we haven't looked into. LFP is the one we're kind of comparing against.

00:03:32 Materials Engineer

That's the easiest way to see the role of manganese, because LFP and LFMP the M is manganese, basically. So if you see with LFP, you can go around up to 3.4 Volt, 3.5 higher voltage. With LFMP you can go up to 4.1 or 4.2 Volt. So basically it increases the Voltage and if you can go at higher voltage it means you can extract the capacity more.

00:03:56 Marcin

OK. So an LFMP is like a high capacity LFP or, yeah? OK.

00:04:02 Materials Engineer

Yeah, you can say that. Yeah. Or people call it like, you know, sometimes people write LFP and in the bracket "M", like, do not say it's exactly.

00:04:09 Marcin

Yeah. OK. Does it have some significant disadvantages cause or why? Why isn't it like broadly used? Or is it broadly used?

00:04:22 Materials Engineer

Now CATL will start to use LFMP. LFMP is advanced materials so it's very hard, like basically to use it as a cathode material because particles are very small, so like nano size. So when we mix when we mix slurries, there are a lot of issues. But if you solve this issue, LFMP is like best. In like the batteries because, I know, like people did some nail penetration tests and if you take NMC an LFMP like comparison and you pass the nail like...

00:05:02 Marcin

Ohh you puncture it.

00:05:03 Materials Engineer

Yeah, NMC will blast but LFMP, nothing will happen. That was safety, so.

00:05:07 Marcin

OK. They're much more like stable when punctured? OK.

00:05:15 Materials Engineer

And actually manganese doesn't have any function manganese is to maintain the electrochemical neutrality. So has plus +2 + 4 charge like it has different charges +3, + 4.

00:05:23 Marcin

OK.

00:05:34 Materials Engineer

Oxidation state of manganese is plus 3 plus 4. So when you mix with NMC so you know nickel has a charge of plus 3. So when you mix like a manganese plus 3, it will oxidize, it will lose its one charge, so it will be plus 4 and nickel will lose this plus 3 form 2 plus 2. So it's like a neutrality, charge neutrality.

00:06:01 Marcin

OK, so they become less charged. The other ions and so they're less prone to, like interacting with each other.

00:06:08 Materials Engineer

Because manganese is neutral, it doesn't take part in chemical reactions.

00:06:15 Marcin

So it's mostly for like stability reasons that it's used?

00:06:17 Materials Engineer

Voltage stability.

00:06:21 Daniel

OK, but uh, let let's say then if you compare, I don't know 111 and an 811 NMC batteries. Then in the 811 you have decreased the amount of both cobalt and manganese.

00:06:37 Materials Engineer

Yeah.

00:06:37 Daniel

Is there any reason why you would not still have a high amount of manganese to have this voltage stability?

00:06:45 Materials Engineer

You mean instead of one? It should be 2 or 3 something like that?

00:06:50 Daniel

Yeah, why? Why don't you only decrease the cobalt? Why do you decrease both the (elements)?

00:06:58 Materials Engineer
Because we want more nickel.
00:06:59 Daniel
OK, because it's cheaper.
00:07:03 Materials Engineer
Yeah, of course it's cheaper, but there there is a thing like you know as you increase the nickel, the inter lattice place in the cathode material will increase. As the amount is increased, if you put less nickel it will be like this (small). If you put more nickel the space will be higher so lithium can easily transfer. So that's why with high nickel capacity is higher. So if you consider the capacity of NMC 811 is around 200, NMC 111 is around 150 / 160. So that's that is the difference.
00:07:43 Marcin
Yeah, that that does make sense though, so yeah.
00:07:44 Jakob
Yeah, interesting.
00:07:49 Marcin
We getting very good answers here.
00:07:55 Materials Engineer
An NMC one, one, one it doesn't mean it has 10% of Nickel
00:08:00 Marcin
Which NMC?
00:08:01 Materials Engineer
I mean 111, it's actually it's very confusing. So when people said it's 111. So from that how much nickel we have?
00:08:10 Jakob
It's 30%.
00:08:11 Materials Engineer
Yeah.
00:08:12 Materials Engineer
So it's actually we call it like one by 3, 1 by 3, 1 by 3, very easy like.
00:08:15 Marcin
Ohh yeah OK.
00:08:20 Jakob
But does 111 have any advantages over 811 in terms of...?
00:08:25 Materials Engineer
So if you consider the cycle life point of view like a long cycle life, if you want to see like how much cycles it can pass and then 811 will have less cycle as compared to 111. Yeah because there is a reason like it has more cobalt, stability is more so that's why cycle (life is longer).
00:08:48 Materials Engineer

That is the reason why you know there was one cathode before, - lithium cobalt oxide. It's a famous LCO material, mostly in mobile phones, so it has very high cycle like because it has highest amount of cobalt.

00:09:05 Marcin

Oh, OK.

00:09:06 Materials Engineer

Yeah, but capacity is on 120 or something like that. So that's why you can use it in mobile phones but not in cars.

00:09:13 Marcin

OK. And they are quite unstable too, right? Like if you puncture them, the the phones go flames up, right?

00:09:16 Materials Engineer

Yeah, yeah.

00:09:21 Materials Engineer

But I mean that's more related to electrolyte also.

00:09:26 Marcin

Not that much the cathode material itself? OK. If we change subject here a bit look more at like vehicle applications. We're kind of wondering if you have any like a picture of what characteristics are kind of important for different types of battery packs like say I wanted to make a low or mid range battery pack, what kind of characteristics would I want from the cells then as opposed to if I made one for a performance car? What kind of can you have? Do you have any like picture of what if? If there's any clear outstanding features for any of these categories.

00:10:13 Materials Engineer

I mean it's completely depends like how much the range you expect from that specific car. Like if you say like you want just 300 kilometer(s) or something, I will go with NMC 111 or something like that and. If you want something with high, like 500 kilometer, 1000 kilometer then you need to go like 90% nickel or something like that.

00:10:36 Marcin

OK.

00:10:38 Materials Engineer

It's totally like depends like what customers want. Basically if they want fast charging, then you need to have a silicon anode.

To something like that, because if you add a silicon then there is a reason actually why we add silicon in the anode side because for. Like a graphite like for 6 carbon, there is one lithium, right? In silicon, if you have a silicon for one silicon, there are 4.4 lithium atoms, so it can give it can access like 4.4 lithium. So that's why capacity is higher.

00:11:17 Marcin

OK. Is that why fast charging is easier with this too as well, because they have more exchange?

00:11:23 Materials Engineer

Yeah, lithium can easily go, and the principle is also different because in graphite chemistry you have intercallation.

00:11:31 Jakob

Yeah.

00:11:31 Materials Engineer

In silicon you have alloy, so alloying.

00:11:36 Marcin

Ohh, that's yeah. We just looked at intercallation so far, OK.

00:11:39 Materials Engineer

Yeah. So it's just so there are 3 different things like if you have like you know there are people like who are developing lithium metal batteries. So in which your anode is lithium metal, high energy density application like for flights. So their principle is plating and stripping so lithium plates.

00:12:01 Marcin

Ah, so it's like, yeah. More like electrochemical. OK.

00:12:05 Materials Engineer

Yeah, yeah.

00:12:06 Materials Engineer

In graphite its intercallation, in silicon its alloying.

00:12:10 Marcin

So that's interesting, but if I wanted to use an LFP battery, what type of application would you think that's most suitable for?

00:12:21 Materials Engineer

For LFP, I would say like you can use it for like you know, taxis or something, those application it will be great.

00:12:26 Marcin

OK. Is it because it has a long cycle life like you can say?

00:12:31 Materials Engineer

Yeah, it has long cycle life and you can charge it. Like, for a lot of times. So and you just need to, you know, go in cities, right. So it's not you need to go like 500 kilometers every day. So for that I think LFP is best.

00:12:47 Marcin

And it's also cheaper so that. Yeah, OK. Yeah. So for a big fleet, that's really nice.

00:12:52 Materials Engineer

For premium vehicles, like if you say like Audi or Porsche, so for them, -NMC. Because if there is a premium vehicle you expect it should have like very high range or something like that, right?

00:12:59 Marcin

(yes).

00:13:07 Materials Engineer

Yeah. So like 500 kilometer at least this will be the condition, so. You have to go beyond NMC 811 for that.

00:13:15 Daniel

You mentioned before about that with increased range you want to increase the nickel is there... why do you want to use the 111 on the lower range? Is it cheaper? Or is it because of the increased life cycles?

00:13:35 Materials Engineer

Yeah. For the cycle life, basically, either you can use LFP or you can use NMC 111 basically or people do combination with NMC 111 and LFP.

00:13:45 Marcin

Ok. But if we like look into the near future, do you think the LFP is gonna eat away on the NMC 111 market share? Can like it's gonna, it's already doing that. So that's kind of where it's replacing if anywhere?

00:13:54 Materials Engineer

Already. Yeah, but now LFP will be replaced by LFMP.

00:14:02 Marcin

Ohh OK, so that's the new one coming in. OK, alright.

00:14:06 Materials Engineer

But it's very hard to beat NMC 811 or 9, -90%

00:14:11 Marcin

Yeah, yeah. OK. But do you think that the like premium market segment that they're going to keep on going with NMCs in the near future?

00:14:11 Materials Engineer

(Yes) -90% Nickel.

00:14:21 Daniel

And that is simply because of the specific capacity and the range?

00:14:25 Materials Engineer

So basically it's mostly dependent on the energy density. So if you see like LFP, you can get energy density of around 170 Wh per KG. For LFMP it is 210 to 220. So there is a slight increase in energy density right.

00:14:37 Marcin

Yeah.

00:14:45 Materials Engineer

With NMC 811 or plus you get around 300 watt hour(s) per KG.

00:14:51 Marcin

Yeah, that's a lot more.

00:14:52 Materials Engineer

Right.

00:14:52 Marcin

So and you would say that energy density is like the most crucial metric for range. Like those are very closely tied together, right? OK, yeah.

00:15:00 Materials Engineer
This yeah. Yes.
00:15:03 Materials Engineer
It's related to weight also. Like if you have more energy density you can reduce the weight of batteries so the battery pack weight will be also decrease.
00:15:05 Marcin
Yeah.
00:15:11 Materials Engineer
And then after that cathode. OK. Now you reach up to 300. Now you want more energy density. Put silicon. You can increase up to 320. You can put lithium metal. You can go to 340. So these are like the designs (you can use).
00:15:29 Marcin
But do you know what they put in sports cars? Is that also NMC territory or like what is it?
00:15:33 Materials Engineer
No, no, no. It would be like, it should be MMC +811 plus for sure. Yeah.
00:15:42 Jakob
So things like the Porsche Taycan is probably 811?
00:15:43 Materials Engineer
Yeah, 811 plus, yeah.
00:15:47 Marcin
Why? Why do they go with 811?
00:15:49 Materials Engineer
Because you get more range like right for the...
00:15:51 Marcin
...It's for the range. It, OK, it's. It's still there.
00:15:55 Marcin
Yeah. So if you want the smaller battery. Because LFP, do they have a higher discharge rate? Like you can pull more current current from them or they they do have that right. But that doesn't outweigh the the weight problem that they bring? OK.
00:15:57 Materials Engineer
Yeah, yeah.
00:16:14 Materials Engineer
And then there is a separate application like there is one like people focus on energy, there is just another application power. So for power like, it's like it's not like a very hard to do that because mostly for power requirement it's expensive as compared to the energy stuff because there is a reason, for power we want like exactly same energy density, but we need to increase the power. So for that what we need to do is like your electrode should be thin.
00:16:50 Marcin
OK. So that's more like the packaging or like or?
00:16:52 Materials Engineer

Yeah. So in energy dense electrode, your electrodes are thick like thickness of electrode is very high both side cathode and anode side.

00:17:00 Marcin

And that's so you can fit many ions in there(?)

00:17:02 Materials Engineer

Yeah. Yeah. So you have more lithium or more NMC, so more capacity, but in power application you can't put like a thick electrode you need to put thin, otherwise it will be very hard to...

00:17:13 Marcin

Yeah, because you want the short path and you want them (ions) to jump quickly?

00:17:15 Materials Engineer

Yeah, yeah, short.

00:17:17 Materials Engineer

Yes. So it means you need to put more electrode as compared to the energy dense batteries, right? So it means more cost also. Yeah. So that's why the power requirement is like for example Scania or Volvo trucks. So that's like more like a power requirement, yeah.

00:17:40 Marcin

Oh, that's a power one. So that the power is the limiting problem in, but the range is also difficult right in the in the truck like it's...

00:17:49 Materials Engineer

No, I mean, that's what I'm saying. So for power, we try to maintain same energy if we increase the power, so energy won't be an issue, it just.

00:17:56 Marcin

It's just a more expensive pack because you (have a more complex geometry)?
(Materials Engineer confirms.)

00:18:00 Daniel

But with this LFMP battery cell, because that would create a better voltage stability and increased voltage right? That would increase the power I assume.

00:18:14 Materials Engineer

Yeah, I mean it can if you have a like a thin electrode then it will because for energy dense application it will be slightly harder now because for example, might if you get a target like around 200 Wh per KG then you need around like electrode thickness will be around 30 milligram per centimeter square around something like that. But it's very hard to make 30 milligram per centimeter square, it will crack if you...

00:18:42 Marcin

It's too thin or...?

00:18:44 Materials Engineer

No, it's very thick.

00:18:45 Marcin

Oh, it's too thick, OK.

00:18:46 Materials Engineer
Yeah, but for same 200 NMC thickness is around 17, so it's almost half it will not crack so these are the challenges like in the production processes.
00:18:59 Marcin
And the like power that you can extract which is coupled to the electrode thickness is that coupled to like internal resistance, is that the measure of like how easily the charge can kind of travel in the battery?
00:19:08 Materials Engineer
Yeah, yeah, of course. Yeah. So we have a criteria of DCR direct current internal resistance. We check there are specific format like customer has a different things like we will ask like at 1C for one second, some ISO conditions and all. Maybe you can check it on website, what are these criteria. And some customer asked like after 10 second at 2C what is the internal resistance of the cells.
00:19:40 Marcin
OK.
00:19:41 Materials Engineer
So each company has its different way to measure the internal resistance, but there is also like an international standard as well.
00:19:49 Marcin
Yeah, I was thinking, because we're gonna build some cells in the lab. And so if we try to measure their internal resistance, will that tell us something about how much power can be extracted with these cells?
00:20:00 Materials Engineer
Yeah, I mean power you can easily calculate it's simple like you just need the specific capacity of the cell. Then you need a... You need a nominal voltage.
00:20:03 Marcin
Yeah.
00:20:12 Materials Engineer
And you need the current like what you applied and you can calculate the specific power. It just we need to know the nominal voltage right?
00:20:23 Marcin
And the nominal voltage is. Some average value, right? It's not?
00:20:27 Materials Engineer
No, it's not actually the average value, it's different. Average voltage is different, nominal voltage is different.
00:20:31 Marcin
OK. Well, how is the nominal voltage defined? I still haven't understood that.
00:20:35 Materials Engineer
It's it's totally depend on the chemistry, like for example if it is a LFP, the nominal voltage is around 3.4 Volt. If it is NMC, then it is around 3.8 Volt or something. So it depends on

how much energy density, how much energy it's you can extract from it. So there is a calculation based on the energy not... yeah.

00:20:49 Marcin

Yeah, Ok.

00:21:05 Daniel

Alright, I have a question about the the internal resistance because cobalt increased conductivity, right?

00:21:15 Materials Engineer

Yeah.

00:21:15 Daniel

Would decreasing the cobalt is it directly impacting the the internal resistance?

00:21:23 Materials Engineer

Yeah, it will affect the internal resistance of the cell, but you can, like you know. You can counter it by some kind of surface coating or some doping technology to reduce the internal resistance of the cell. So you can make some ion conductive surface coating so lithium ion can easily transfer so internal distance will decrease.

00:21:47 Marcin

So it can be countered. OK.

00:21:49 Materials Engineer

But internal resistance is not just on the cathode. It also depends on what kind of conductive additives or what kind of binder you use, because binder is mostly insulating material, so it will increase the resistance.

00:22:04 Marcin

So it yeah, it's related to the whole production of the entire cell.

00:22:07 Materials Engineer

Yes, internal resistance is not like a... It depends on like: What kind of chemistry you have? Cathode, anode, electrolyte.

00:22:18 Marcin

How you put it together? Yeah. OK. Yeah, we we were kind of wondering about the production process as well. Are there any significant differences when producing an LFP or an NMC chemistry? It's very similar, even at like large scale?

00:22:19 Materials Engineer

Yes.

00:22:35 Jakob

Even in scale, like large scale.

00:22:39 Marcin

But is there some (difference)? What's the then like major cost driver that makes the cost difference between an LFP and an NMC cell? It's not in the production process, is it the purchase cost of the material?

00:22:52 Materials Engineer

It's the cathode material. Yeah, because the cathode itself, I mean cathode I think cost around... 40 to 50% of the battery. Cathode itself.

00:23:07 Marcin

OK. Oh, that's a lot, actually. Yeah. So that, that's what makes the difference. Like, it's not, like much more difficult to produce one of them.

00:23:17 Materials Engineer

So LFP is cheaper than NMC, so you know the cost will reduce for LFP.

00:23:22 Jakob

Yeah, because last time we talked to you, you talked a lot about like safety equipment for an NMC that you don't need for an LFP, but that doesn't hinder any production?

00:23:32 Materials Engineer

Yeah, that is it's. Then it comes to the battery system part. So it's their job, how they can reduce the cost. If they can't, then they will tell it's not possible with the NMC. We need to do something. Then we will say it's not possible for LFMP for us. Just an example we can do NMC plus LFMP mix.

00:23:36 Jakob

Yeah. So it doesn't matter.

00:23:53 Materials Engineer

And then you can try.

00:23:56 Marcin

How do you make a mix like? Do you have different cells or?

00:23:59 Materials Engineer

No, no, no. We blend the cathode.

00:24:00 Marcin

Ohh, it's literally and it works like that. You can actually do that. Hmm.
That's interesting. That kind of adds another dimension.

00:24:10 Materials Engineer

Yeah, because you add properties of NMC and LFMP together, right, so you can get higher energy density.

00:24:19 Marcin

Comparison just got way more difficult.

00:24:21 Jakob

That sounds kind of overpowered than compared to just having one of them.

00:24:25 Materials Engineer

Yeah. No, I mean people will not mostly do one of them because only one like for example LFMP as I mentioned is very tricky to making production process and...

00:24:38 Materials Engineer

That's why CATL still didn't announce LFMP production yet. But if you mix NMC, it's become much easier with LFMP.

00:24:48 Marcin

Ah so we take a bit LFMP and mix with NMC and you get some...

00:24:51 Materials Engineer
For example, I take 90% of NMC and 10% LFMP, I blend it and it will still pass that test.

00:24:55 Marcin
OK. You get like a cheaper NMC that still has good properties, OK.

00:25:01 Materials Engineer
Yeah.

00:25:04 Daniel
Since it will be more complex to manufacture the LFMP would that create the higher manufacturing costs compared to the others?

00:25:16 Materials Engineer
Yes. Otherwise, you invent some new binder or something that will make it possible something like that.

00:25:22 Marcin
Do you think this is gonna be something happening pretty soon, like, uh, big progress in in the LFMP?

00:25:25 Materials Engineer
Yeah, yeah. LFMP is very promising technology so I mean, at least it will have some higher energy density as compared to sodium ion batteries.

00:25:41 Daniel
If we just continue on the on the price a bit more, is there any difference if you compare different NMC batteries? Like if you if we have as you said 111 and 911.

00:25:56 Materials Engineer
Yeah, so cost.

00:25:56 Daniel
Is there any difference in the manufacturing cost?

00:25:58 Materials Engineer
Yeah, yeah, 911 is just harder, so it will be expensive.

00:26:03 Marcin
OK, why is 911 harder? Is it? What? What makes it hard?

00:26:08 Jakob
Labor intensive?

00:26:09 Materials Engineer
No, I mean so basically you need to make it properly, right? We need to make sure it will give proper results and all. So you need to make sure the crystal stability is good and all. So for that the manufacturing cost will increase.

00:26:25 Marcin
OK, because it is less stable, right? Yeah. OK.

00:26:27 Materials Engineer
It is less stable.

00:26:30 Daniel
But the material cost should decrease.

00:26:33 Materials Engineer
Uh, yeah. As compared to if you are using less cobalt then yes, the cost will cost will reduce. But the I mean the manufacturing cost will increase because as I mentioned stability you know so it's like there will be some increase and some decrease.
00:26:49 Daniel
Yeah, OK. Does the overall cost increase? Yes. OK.
00:26:53 Materials Engineer
Yeah, overall cost.
00:26:57 Marcin
Do you think there are any like other chemistries that will push cobalt out of the battery industry in the near future like? If the producer wants to decrease the amount of cobalt, do you think they have any options to turn to?
00:27:15 Materials Engineer
Yeah. I mean the best option is to switch to sodium. Basically to do that, but it's sodium is quite tricky actually. I mean, even if like you see a lot of manufacturers are starting to make sodium ion batteries.
00:27:18 Marcin
OK.
00:27:29 Materials Engineer
But I think sodium ion batteries will be basically for energy storage applications like you know, like you have big storage units and then you can use it for your home or like anything like that. But.
00:27:42 Marcin
Because they had that low energy density, right? Yes. OK.
00:27:45 Materials Engineer
So it has around 160 Wh per KG, so slightly lower than LFP, yeah.
00:27:53 Marcin
So and the Cobalt free NMC chemistries, they don't seem very promising or?
00:27:58 Materials Engineer
They are promising, but like you know, it's still not past the all the requirements that we get with Cobalt.
00:28:07 Marcin
Yeah. OK.
00:28:07 Daniel
It's mostly the life cycle. The cycle, yes?
00:28:09 Materials Engineer
Yeah, mostly lifecycle, yeah.
00:28:11 Marcin
Because I read about some NMA, I think that's nickel manganese aluminium, right?
00:28:18 Materials Engineer
Yeah, yeah.

00:28:19 Marcin
But I think they had problems with their battery destroying itself after some cycles.

00:28:26 Materials Engineer
So yeah, Tesla chemistry. I think they're using NCA. They are not using manganese. OK. Yeah. So it's a different chemistry, but now they're switching to LFP again. So yeah.

00:28:41 Jakob
Yeah, because in the short range versions they have the LFP, right? (Materials Engineer confirms)

00:28:49 Marcin
I mean honestly I think we covered all the questions (we had).

00:28:55 Jakob
I have a question about the production. So the ones you make in (Major battery manufacturer) right now are in the (Undisclosed) factory or do you have production in (Undisclosed)?

00:29:07 Materials Engineer
I think not now in (Undisclosed), it will take a lot of time, maybe 2027 or 2028.

00:29:10 Jakob
Yeah. OK. But are there any difference in like lead time between NMC chemistries and LFP? Like how long it takes to create a battery? Or is it pretty much the same?

00:29:23 Materials Engineer
What do you mean by lead time?

00:29:24 Jakob
Uhm, just like from unfinished product to finished product is the time, pretty much the same for all different chemistries?

00:29:34 Materials Engineer
Yeah. Yeah, it's almost similar, yeah.

00:29:37 Jakob
Because you mentioned the 911 is harder to make, but it's or 811, it's hard to make, but it's the..., time is the same?

00:29:44 Materials Engineer
Yeah. I mean the thing is that like if we produce those NMC material, then yes, then it will take time. But for example if you are... if someone supplies you then it's much easier, right? You just take a material from some company and then you can produce the batteries right? So mostly company do that. So there's a source of material from some other industry and. So it's like a homework for them to synthesize these better batteries.

00:30:11 Jakob
Yeah. Ok.

00:30:14 Marcin
Are there like availability problems that you have encountered like... There's some resource that's very hard to get your hands on? For example like say cobalt. Is that easy to to buy right now?

00:30:30 Materials Engineer
No no. It's not easy, that much easy due to restriction also now, so...

00:30:34 Marcin
OK, the... which restrictions?

00:30:36 Materials Engineer
Restriction I mean, I mean, if you consider Sweden so. Yeah. So you want everything sustainable, right?

00:30:41 Marcin
Yeah. So that's a problem in the process, OK, because LFP is much easier to get get all the ingredients for, right.

00:30:49 Materials Engineer
Yes, but with LFP there is an issue. Like recyclability.

00:30:55 Marcin
Yeah, or yeah, that was the question. What's the difference in recycling?

00:30:59 Materials Engineer
NMC is very easy to recycle as compared with LFP.

00:31:02 Marcin
So is it because the components are more desirable in an NMC or is it because it's chemically easier? It is chemically easier. OK.

00:31:10 Materials Engineer
Chemically, yeah. Separation process for LFP is quite hard as compared to NMC. And I mean we if we compare the carbon footprint with LFP or NMC, then with the NMC is lesser so.

00:31:27 Marcin
And that's because of the recycling process, OK.

00:31:29 Materials Engineer
Yes, recycling. Mostly recycling.

00:31:33 Marcin
So and the for the LFP, it's also gonna be a problem that it's cheaper, right? It's it's not as valuable.

00:31:39 Materials Engineer
Actually recycling process of LFP is expensive as compared to...

00:31:43 Marcin
Yeah, but they... what you get out is cheaper, so it's not as worth to do, right?

00:31:47 Materials Engineer
Yes. Yeah.

00:31:49 Marcin
So it's even less likely to be happening.

00:31:51 Materials Engineer
Yeah, but if we improve the recycling process for the LFP yeah, then it's possible.

00:32:00 Marcin

,

Do you think that if they get the recycling process, like improve it and get it online. The LFP is gonna increase in like it's presence on the market?

00:32:10 Materials Engineer

Yeah, yeah. Yeah, especially LFMP because LFMP it's easier to recycle and.

00:32:15 Marcin

Yeah. Oh, it is so it... It's another advantage of the LFMP.

00:32:17 Materials Engineer

As compared to LFP.

00:32:22 Marcin

So the LFMP 's problem is really that it's harder to synthesise.

00:32:25 Materials Engineer

No, harder to process it.

00:32:28 Marcin

Harder to process, which part of the (process)?

00:32:30 Materials Engineer

So basically you have a synthesis process that will manufacture batteries like you make slurry. Then you make electrodes. That is the hardest part for LFMP.

00:32:39 Marcin

OK. Where where does it go wrong? Like or where? Where is it problematic?

00:32:45 Materials Engineer

Because it's very hard to make a slurry also because it's very thick.

00:32:53 Materials Engineer

And mostly, if you see the papers, they will mention also like the solid content, basically solid content. How much solid is like and how much liquid part is in the slurry so.

00:33:04 Marcin

Yeah.

00:33:06 Materials Engineer

For NMC, solid content is like around 75% for LFP is around 60%, for LFMP is around 45%. So yeah. So you have more NMP.

00:33:16 Marcin

It's less solid and more liquid.

00:33:21 Materials Engineer

Yes, like a solvent.

00:33:22 Marcin

Ah, OK.

00:33:22 Materials Engineer

So so basically, if you have more NMP then when you do the electrode fabrication, you need a recovery for NMP, right, because NMP is toxic.

00:33:32 Marcin

You don't want it in the battery later?

00:33:35 Materials Engineer

Yeah, and so basically LFMP is very energy intensive, so the during the drying you need to recover more NMP as compared to NMC and LFP. So that is very tricky part.

00:33:49 Marcin

OK, OK. So that one is actually in the manufacturing part where it's (problematic)? Ok.

00:33:55 Materials Engineer

But of course, like if someone come up with dry coating dry electrodes application or something so you don't need to care about NMP or anything. Or water based process. Then it doesn't matter.

00:34:08 Marcin

OK, OK. But you believe this is coming pretty soon?

00:34:11 Materials Engineer

Yeah. Yeah, because LFMP is processable with water also. So it's just it's not as much as as like mature as like with NMP.

00:34:20 Marcin

Yeah. Yeah, OK.

00:34:21 Materials Engineer

Yeah. So you can go to lab and make an LFMP slurry very quickly that's that is OK, but when you're doing production, it's very hard.

00:34:29 Marcin

It's very hard because you want to recover all the solvent? Yeah. OK. (Materials Engineer confirms).

00:34:36 Jakob

Yeah, I don't have any more questions I think we've got some really.

00:34:37 Marcin

No. Yeah, yeah, actually, I'm very happy with the answers. At least I think it cleared up a lot because we were wondering about these things kind of hard to get like a condensed answer like you gave us here because the papers are, well... kind of advanced for my level. Like I tried to read them, understand and I just see all these numbers and I...

00:35:02 Marcin

But well, thank you very much. Thank you. Thank you. I think this is. Yeah, this is all I can pause the transcription.

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