

Master Thesis

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Abstract

Electric vehicles powered by batteries are slowly but surely displacing internal combustion-fuelled automobiles. So far, research in the development of higher performance batteries is advancing pretty slowly. The most important factors include long range, extended battery life, fast charging, safety, and low cost. However present lithium-ion battery technologies have so far succeeded to deliver acceptable performance but at a high cost with average battery longevity. So far, EV manufacturers have had tough task of choosing the best LI-ion chemistry to balance off between performance, lifespan, and cost.

This paper takes an overview of the main batteries that are being currently used in EV's in which cobalt is an important part of the electrode along other materials and comparing them to other batteries, but specifically lithium iron phosphate batteries by using SWOT analyses. An MCDM based technique was then utilised into 2 scenarios / perspectives to categorize even further, and finally indicating the different rankings of each battery. This strategy could be useful for anyone who is looking into acquiring an EV to make sure they obtain the right battery chemistry for their needs.

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I Table of Contents

I Table of Contents	v
II List of Symbols and Abbreviations	viii
III List of Figures	ix
IV List of Tables	x
1 Introduction	1
2 State of the Art	2
2.1 Battery Cell Parameters and Specifications	2
2.2 Lithium-ion Battery Composition	4
2.2.1 Cathode	5
2.2.2 Anode	7
2.2.3 Electrolyte.....	9
2.2.4 Separator.....	10
2.3 Lithium-ion cell manufacturing process	11
2.3.1 Manufacturing of electrodes.....	11
2.3.2 Assembly of cells	12
2.3.3 Formatting and testing	14
2.4 Most Common Lithium-Ion Batteries found in EV`s	15
2.4.1 Li-ion batteries that do not contain cobalt.....	16
2.4.2 Li-ion batteries that contain Cobalt.....	18
2.5 Lithium battery cells in different shapes used in EV's	20
2.5.1 Cylindrical shaped cell	20
2.5.2 Prismatic shaped cell	22
2.5.3 Pouch shaped cell	22
2.6 Li-ion battery capacity degradation mechanisms.....	23
2.6.1 Solid Electrolyte Interphase (SEI)	23
2.6.2 Electrolyte Oxidation	23
2.6.3 Lithium Plating	23

2.7	Recycling Methods.....	24
2.7.1	Mechanical recovery	24
2.7.2	Pyrometallurgical recovery.....	24
2.7.3	Hydrometallurgical recovery.....	25
2.7.4	Direct recycling	25
2.8	Lithium batteries for EV's for the future	26
2.8.1	Lithium Silicon.....	26
2.8.2	Solid State	27
2.8.3	Lithium Sulphur.....	28
2.8.4	Lithium Air.....	29
3	Motivation and Objectives	30
3.1	Thesis Motivation.....	30
3.1.1	Personal Motivation	31
3.2	Thesis Objectives.....	32
4	Methodology	33
4.1	SWOT Analysis.....	33
4.1.1	Strengths and Weaknesses	34
4.1.2	Opportunities and Threats.....	34
4.2	Multi Criteria Decision Analysis, Weighted Sum Model	35
4.2.1	Weighted Sum Method Steps	36
4.2.2	Analytical Hierarchy Process (AHP).....	36
5	Results.....	40
5.1	Swot Analysis for LFP, (Lithium Iron Phosphate)	41
5.2	Swot Analysis for cobalt-based cells (NCA, NMC)	41
5.3	Swot Analysis Comparisons LFP vs NCA NMC	42
5.3.1	Cycle Life vs Cost differences between LFP, NMC, NCA.....	42
5.3.2	Prismatic vs Cylindrical vs Pouch Cells.....	44
5.3.3	Main cathode materials found in NCM, NCA, LFP, the good and the bad	48
5.3.4	Safety	51

5.3.5	Specific Power Comparison	53
5.3.6	Operating in winter temperatures comparison LFP vs NCA, NMC	53
5.3.7	Degradation Comparison (LFP vs cobalt-based Li ion)	54
5.3.8	Opportunities for LFP, NCA, NMC	60
5.3.9	Threats for LFP, NCA, NMC	67
5.4	Multi Criteria Decision Analysis WSM	69
5.4.1	Analytic Hierarchy Process (AHP).....	72
5.4.1.1	AHP Scenario 1: Compact EV (non-cobalt battery).....	73
5.4.1.2	AHP Scenario 2: Higher Performance EV (cobalt battery).....	79
6	Summary and Outlook.....	86
6.1	Summary	86
6.2	Outlook	88
7	Publication bibliography	Error! Bookmark not defined.
8	Appendix	103
8.1	Battery Pack Project (48 volt, 11600 mah).....	103

II List of Symbols and Abbreviations

Ah -- Ampere-hour

Wh – Watt hour

kWh -- Kilo watt hour

GWh/y -- Giga-watt hours per year

Kg – Kilogram

W – Watt

Wh/kg -- Watt hour per kilogram

°C -- Degree Celsius

V – Volt

L – Litter

AC – Alternating current

Al-air – Aluminium air

BMS – Battery management system

DC – Direct Current

DOD – Depth of discharge

EV -- Electric vehicle

HEV -- Hybrid electric vehicle

Li-air -- Lithium air

LIB – Lithium-Ion Battery

Li-ion -- Lithium ion

Li-po -- Lithium polymer

Li-s -- Lithium sulfur

LMO -- Lithium manganese oxide

LTO -- Lithium titanate

NCA -- Lithium Nickel cobalt aluminum oxide

Ni-Cd -- Nickel cadmium

Ni-Mh -- Nickel metal hydride

NMC -- Lithium nickel manganese cobalt oxide

SEI -- Solid electrolyte interface

SOC -- State of charge

SOH -- State of Health

Zn-air -- Zinc air

III List of Figures

Figure 1: Li ion battery composition (Accelerating Microscopy 2019)	4
Figure 2: Separator (Costa 2019).....	10
Figure 3: Influence of Electrode Density (Smekens et al. 2016)	11
Figure 4: LTO Battery (35AH LTO Lithium Titanate Battery 2021).....	18
Figure 5: Different cell shapes (Lidbeck and K. Syed 2021)	20
Figure 6: New smelting reduction process.jpg (GGC 2020).....	24
Figure 7: Silicon based lithium-ion battery anodes.jpg (Zuo et al. 2017).....	27
Figure 8: The Future of All Solid (Kartini and Theresa Genardy 2020)	28
Figure 9: Li-air (Badwal et al. 2014)	29
Figure 10: Swot Analysis (Designedge 2017).....	33
Figure 11: Ranking of entities with Multi-Criteria (Uppal 2020).....	35
Figure 12: AHP Diagram (Taherdoost 2017, p. 244)	37
Figure 13: AHP Importance scale (Taherdoost 2017, p. 245).....	38
Figure 14: AHP matrix table example (Accelerating Microscopy 2019).....	38
Figure 15: Eigenvector formula (Jalaliyoon 2012, p. 6).....	38
Figure 16: Eigenvector corroborated formula (Jalaliyoon 2012, p. 6).....	39
Figure 17: Positive, inverted formula (Jalaliyoon 2012, p. 6)	39
Figure 18: Formula $w = (w_1, w_2, w_3, \dots, w_n)$ (Taherdoost 2017, p. 245).....	39
Figure 19: CI formula (Taherdoost 2017, p. 245).....	40
Figure 20: Value of RI (Taherdoost 2017, p. 245)	40
Figure 21: No. of cycles vs DOD (Power Tech 2021)	43

Figure 22: Cylindrical cells (Arar 2020b).....	46
Figure 23: Pouch Cells (Accelerating Microscopy 2019)	47
Figure 24: Prismatic Cells (Arar 2020b).....	47
Figure 25: The Next-Generation Battery Pack Design (BatteryBits 2020).....	48
Figure 26: NCA,NMC LFP Thermal Runaway (linda 2020).....	52
Figure 27: Li ion Temperature Effects (Lixia Liao 2021, p. 271)	54
Figure 28: Li ion DOD (Xiong 2019b, p. 37)	57
Figure 29: LFP Cycle Capacity (Liu Qi et al. 2018).....	57
Figure 30: Li ion Over voltage (Xiong 2019b, p. 39)	58
Figure 31: Degradation of Commercial Lithium-Ion Cells (Preger Yuliya et al. 2020).....	59
Figure 32: LMFP Testing (Lithium Australia 2021)	61
Figure 33: Second-life-EV-batteries (Engel et al. 2019, 3).....	64
Figure 34: Duesenfeld Recycling (Duesenfeld 2021).....	66
Figure 35: AHP Diagram 2	73
Figure 36: Random consistency index (Punthutaecha 2018).....	78
Figure 37: Lithium ion battery value chain (Lebedeva 2017, p. 25).....	89

IV List of Tables

Table 1: SWOT Analysis LFP.....	41
Table 2: SWOT Analysis NCA NMC.....	41
Table 3: MCDA Linguistic Terms.....	69
Table 4: MCDA 5 Point Scale.....	69
Table 5: MCDA Decision Matrix	71
Table 6: MCDA Normalized Decision Matrix	71
Table 7: MCDA Normalized and Weighted Decision Matrix (equal weights).....	72
Table 8: MCDA Overall Score and Ranking (equal weights)	72

Table 9: AHP Weight Calculating Attributes (no cobalt).....	74
Table 10: AHP Sum of values (no cobalt).....	76
Table 11: Normalized Pairwise Comparison Matrix (no cobalt)	77
Table 12: Criterion Weights Calculation (no cobalt).....	77
Table 13: AHP Calculating Consistency (no cobalt)	77
Table 14: AHP Calculating consistency, Calculate ratio (wsm / cw) (no cobalt).....	78
Table 15: MCDA Normalized and Weighted decision Matrix (no cobalt).....	79
Table 16: MCDA Overall Performance Score and Ranking (no cobalt).....	79
Table 17: AHP Weight Calculating Attributes. (cobalt).....	80
Table 18: AHP Sum of values (cobalt)	83
Table 19: AHP Normalized Pairwise Comparison Matrix (cobalt)	83
Table 20: AHP Criterion Weight Calculation (cobalt)	84
Table 21: AHP Calculating Consistency (cobalt)	84
Table 22: AHP Calculating consistency, Calculate ratio (wsm / cw) (cobalt).....	85
Table 23: MCDA Normalized and Weighted decision Matrix (cobalt).....	85
Table 24: MCDA Overall Performance Score and Ranking (cobalt)	86

1 Introduction

The Lithium-ion battery has gained a broad global utilisation in personal electronic devices and in the last decade this applies to electrified transport as well. All after Sony's debut for their digital video recorders in 1991. (Masias et al. 2021)

Lithium Batteries that can be recharged have been very popular for customers in early years to power up their electronic devices. and lately the market is booming for the segment of electronic vehicles. Since the 1990's the market for the rechargeable batteries has been very strong with such electric, mobile devices such as: cell phones, toothbrushes, digital cameras, portable radios, etc. Nickle-metal hydride cells however have been substituted with lithium batteries quickly. Form the start of the twenty first century, large lithium sized batteries are turning into the main power plants in mobile, rechargeable devices as well for the electric mobility sector. But still to now, these lithium batteries have not been taken advantage of fully for accumulating renewable energy and for grid balancing (Kerchner 2021)

In the year 1828, the first electric vehicle had emerged, then the first production one was made in 1884. The silent motor type had an advantage over steam and fossil fuelled vehicles at the time that were loud because they did not have a muffler. These combustion engine vehicles also were hard to start and so they needed so called "chauffeurs" that were people that mainly specialized in keeping those cars to a certain operating temperature.

Later on, the mufflers for these combustion engine cars were invented in 1897. In 1911 the electric start followed, and so the demand for bigger and faster combustion engine vehicles grew. That left the EVs in the shadows.

In the last years, there has been an aim to lower carbon emissions and also the decline of unfavourable consequences these engine combustion vehicles can cause. And so this has led to the new resurfacing of electric vehicles, and the research of new technologies in batteries. (Miao et al. 2019)

Are gas stations going to be replaced with quick charging ones for EV's? Does the future world seem to be powered by electric vehicles? Well over the last few years, there has been an increasing enthusiasm about this type of transportation and governments are backing the installation of these charging stations. In addition, for interest in the electric sector, governments from France and the United Kingdom have agreed to not sell any kind of petrol fuelled vehicles from the year 2040. The automotive corporations that once did not believe in the future of electric vehicles are now investing billions of dollars towards their

manufacturing. Only in the United States, there will be ready to buy 127 different automobiles that will be fully battery operated by 2022. (Lee 2018)

According to Carlier, 2021 sales of EV's went up to 8.3 percent from 4.2 percent back in 2020, however this scenario is going up rapidly and by the year 2050, it is anticipated that eight out of ten vehicles sold globally will be electric. (Carlier 2022)

The main purpose of this thesis is to analyse the most popular batteries in the market at the moment (NMC, NCA) which contain cobalt as one of the main ingredients in their mixture and compare them against LFP which has a totally different mix and does not include any. These types of batteries were distinguished based on their main strengths and weaknesses, then they were both evaluated with the main criteria that characterizes them in two scenarios with two different kinds of customers in their own perspective, each opting for one of the chemistries. This paper can help answer the following question: Are the most popular batteries in present day in fact a better solution for each customer or manufacturer that produces them?

2 State of the Art

2.1 Battery Cell Parameters and Specifications

Parameters

Capacity or Nominal Capacity (Ah for a specific C-rate) – The total Amp-hours available when the battery is drained from 100 percent SOA to the cut-off voltage at a specific discharge current given as a C-rate. The capacity of a device is determined by multiplying the discharge current in Amps by the discharge duration (in hours), and it diminishes as the C-rate increases.

C- and E- rates – Discharge current is frequently represented as a C-rate in battery descriptions to normalize against battery capacity, which varies greatly amongst batteries. A C-rate is a measurement of how quickly a battery is depleted in comparison to its maximum capacity. A 1C rate indicates that the discharge current will completely drain the battery in one hour. This amounts to a discharge current of 100 Amps for a battery having a capacity of 100 Amp-hours. This battery would have a 5C rate of 500 amps and a C/2 rate of 50 amps. Likewise, the discharge power is expressed by an E-rate. A 1E rate is the discharge power required to completely drain a battery in one hour.

Charge Current (Recommended) – The optimal current at which the battery is charged under a continuous charging strategy until around 70% SOC before switching to a constant voltage charging system.

Cycle Life (number for a specific DOD) – The maximum number of discharge-charge cycles a battery may go through before failing to achieve certain performance requirements. For given charge and discharge circumstances, cycle life is estimated. The pace and depth of cycles, as well as other factors like temperature and humidity, determine the battery's actual operational life. The cycle life decreases as the DOD increases.

Depth of Discharge (DOD) (%) – As a percentage of maximum capacity, the proportion of battery capacity that has been discharged. A deep discharge is defined as a discharge that exceeds 80 percent DOD.

Discharge Current, Maximum Continuous – The maximum current at which the battery can be discharged continuously. This limit is usually defined by the battery manufacturer in order to prevent excessive discharge rates that would damage the battery or reduce its capacity. Along with the maximum continuous power of the motor, this defines the top sustainable speed and acceleration of the vehicle.

Energy or Nominal Energy (Wh (for a specific C-rate)) – The total Watt-hours available when the battery is drained at a specific discharge current (defined as a C-rate) from 100 percent state-of-charge to the cut-off voltage is referred to as the battery's "energy capacity." The discharge power (in Watts) is multiplied by the discharge time to compute energy (in hours). Energy, as well as capacity, diminishes when the C-rate rises.

Internal Resistance – The resistance within the battery, which is normally variable for charging and discharging, is also affected by the state of charge of the battery. The battery effectiveness falls as internal resistance rises, and thermal stability suffers as more of the charging energy is transferred to heat.

State of Charge (SOC, %) – The current battery capacity expressed as a percentage of highest capacity. To estimate the change in battery capacity over time, SOC is usually determined using current integration.

Voltage, Charge – When a battery is fully charged, it is charged to this voltage. Charging systems often include constant current charging until the battery voltage reaches the charge voltage, followed by constant voltage charging, enabling the charge current to reduce until it is extremely minimal.

Voltage, Cut-off – The lowest voltage that can be used. The "empty" state of the battery is commonly defined by this voltage.

Voltage, Nominal – The battery's reference or describing voltage, sometimes referred to as the "normal" voltage of the battery.

Voltage, Terminal – With a load applied, the voltage connecting the battery terminals. SOC and discharge/charge current influence terminal voltage.

Other Parameters

Energy Density (Wh/L) – The “normal” energy density of a battery per unit volume, often known as the volumetric energy density. The specific energy of a battery is determined by its chemistry and manufacturing. It determines the battery size necessary to accomplish a specific electric range, together with the vehicle's energy utilization.

Power Density (W/L) – The highest amount of electricity available per unit of volume. The specific power of a battery is determined by its chemistry mix and production procedure. It calculates the battery size needed to meet a specific performance goal.

Specific Energy (Wh/kg) – Also known as the gravimetric energy density, it is the nominal energy density of a battery per element mass. The specific energy of a battery is determined by its chemistry and packing. It calculates the battery weight necessary to accomplish a specific electric range, as well as the vehicle's energy usage.

Specific Power (W/kg) – The highest amount of power available per unit of mass. The specific power of a battery is determined by its chemistry and manufacturing. It calculates the battery weight necessary to meet a specific performance goal.

(MIT Electric Vehicle Team 2008)

2.2 Lithium-ion Battery Composition

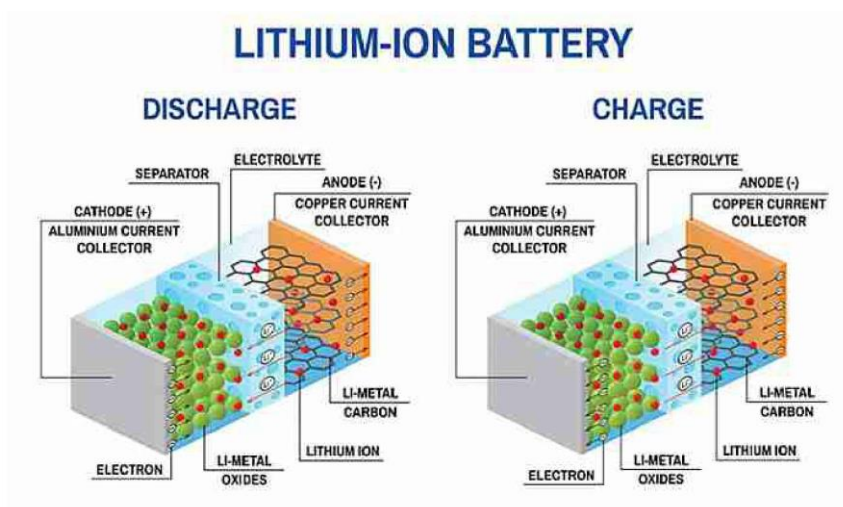


Figure 1: Li ion battery composition (Accelerating Microscopy 2019)

Lithium-ion battery history began in 1962. The first battery that was invented was called a primary battery; this could not be recharged once it was discharged the first time. Different materials were used such as manganese dioxide for the positive electrode and lithium for the negative. In the year 1972 Sanyo introduced this battery to the market. In 1985 a company called Moli Energy manufactured and introduced the secondary battery which was the first battery that could be rechargeable. This battery was composed of molybdenum sulphide as the positive electrode and lithium as the negative one. Due to the lithium being the negative electrode, this design was not really safe. (Korthauer 2018, pp. v–vi)

In order to go further into the lithium-ion battery design, the following step was to utilize elements for the two electrodes to facilitate an intercalation and deintercalation of lithium and to provide high voltage. In 1991, Sony produced the first lithium-ion battery that could be recharged. Carbon was the active material in the negative electrode and as the positive electrode, lithium cobalt oxide took place. Subsequently, lithium-ion batteries were manufactured in countries such as South Korea and Japan in different applications (Korthauer 2018, pp. v–vi)

2.2.1 Cathode

The positive electrode in a LIB is also referred to as cathode, in which the electrochemical cell is reduced. Therefore, there is a better possibility for the electrode to be positive as opposed to the anode. However, LIB cathodes generally operate by keeping guest ions, Li⁺ ions for instance, which reciprocally propel from the cathode to the anode. They do so by using one of two techniques: they either are composed a material that consists of a structure that grants detachment and insertion of ions, or a reversible redox reaction is undertaken by the cathode itself. LIB's include two-way intercalation systems where the cathode and the anode are constructed in a way that they can enable lithium cations to be inserted or extracted. Formerly, cobalt was used as the primary material in cathodes, today many different syntheses of cathode materials have been researched and improved. (Saskia and Kartini 2019)

2.2.1.1 Cathode Materials

Up to date cathode materials consist of lithium-metal including LiCoO₂, LiMn₂O₄, and Li(NixMnyCoz)O₂, vanadium oxides, olivines like LiFePO₄, and lithium oxides that can be recharged. The most widely researched materials for lithium-ion batteries are layered cobalt and nickel oxides. They are very stable when it comes to high voltage, but cobalt is not very accessible and its dangerous, this is a great disadvantage for producing in a big scale. Manganese provides a lesser cost, high thermal substitution and great rate capabilities but in-sufficient cycle performance. Cobalt, nickel and manganese blends the top properties and

decrease disadvantages. Vanadium has magnificent kinetics and contain broad capacity. Nonetheless, the material is usually shapeless thanks to the addition and extraction of lithium, which leads to cycle performance limitations. (Claus 2008)

Olivines are not toxic, and their capacity does not fade in high percentage, but the conductivity is poor. Coating methods were introduced to compensate for bad conductivity, however they generate a certain amount of manufacturing costs to the cell. (Claus 2008)

2.2.1.1.1 Lithium Manganese Spinels

One of the oldest compounds that have been studied that date back decades ago and is still employed extensively is the use of Li Manganese oxide (Li-Mn-O). The depolarizer was its initial use. It is easy to get access too, not costly and contains the proper electromechanical characteristics. Lithium manganese is the material that is used the most, when compared to the lithium cobalt based one, which is toxic and expensive, or also to the lithium-nickel based one which is difficult to produce. It is perfect for tiny helium and lithium ions intercalation because of its different shapes. The lambda shape with its spinel ($Mn_2 O_4$) lets the Li-ion to be intercalated. Some of the benefits of Li-Mn spinels include a great thermal threshold, great rates and very low effect on health and the environment. For Li-ion in this compound, the diffusion rate is $10^{-6} - 10^{-10}$ sq. cm/s. Decreased capacity issues emerge when cycling frequently. This is because the electrochemically active Mn^{3+} ion is instable when it goes over 55 C. In these cases the enhancement of acid-resistant material on $LiMn_2O_4$ can be accomplished by doping certain metal ions (Mekonnen and Sundararajan 2016, p. 4)

2.2.1.1.2 Lithium Metal Oxides

The most extensively researched cathode materials for li-ion batteries are the lithiated nickel and cobalt oxides. They are both distinguished by their great structural stability. A short supply in resources can be an issue to produce, which makes them more expensive and harder to combine. Solid solutions for these layered compounds have been developed to resolve this problem. The most popular solid solution compounds are $Li Ni_{0.5} Mn_{0.5} O_2$ and $Li_{1.2} Cr_{0.4} Mn_{0.4} O_2$. Studies made have shown that a combination of low-valent metal transition ions and low stress in the activated state is crucial to high-rate capability cathodes. Layered metal oxides are ideal for fast loading and discharge applications. These materials seem to perform well when exposed to temperatures beyond 300 degrees C (Mekonnen and Sundararajan 2016, p. 4)

2.2.1.1.3 Olivines

$LiFePO_4$ (Li-iron phosphate) is the name of the compound used in olivines. They have a flat discharging level of 150-160mah/g and a reasonable capacity. They are non-toxic and display a small decrease in battery life over time. Compared to other cathode materials,

these blends are distinguished for their lower volume charges and charge/discharge heat exchange. Their safety superiority compared to li-cobalt based cathode makes them preferable for higher grade applications. The iron metal transition (Fe) is cheap, readily available and eco-friendly. Conductivity for these materials however is not that good and voltage is lower than 4V. This challenge has been improved by two methods. One is to reduce cathodic particles; the other is to utilize LiFePo₄ nano composites with conductive carbon matrix. This opened the way for progress in the synthesis of olivines with other metals. Though olivines with transitional metals can be difficult to synthesise and have limited capacity, they have high discharge capacity and high energy output. (Shukla and Prem 2008, p. 320)

2.2.2 Anode

In both the mechanism and location in the Li-ion battery, the anodes are mentioned to be nearly the total opposite to the cathode, while the cathode is reduced during discharge, anode becomes oxidated, the anode is also known as the electrode that is negative. Anode materials need to have plentiful pores, have high conductivity, last long, be light in weight, have a low cost and appropriate voltage in combination with the cathode for present Li-ion batteries. Therefore, carbon-based anodes are used for most common cathodes. Most of the time graphite are used, which are then baked into copper anodes and meet the demands of the cathodes. Nonetheless, the graphite no longer meets these requirements because of safety, cost and environmental matters of batteries of the future. Elevated demand is also a factor in how the materials in future anodes will alter. (Saskia and Kartini 2019)

2.2.2.1 Anode Materials

Lithium, graphite, lithium-alloy, inter-metallics and silicon are included in the anode material section. Lithium appears to be the most common material, but it creates cycling issues and dendritic development, in effect this generates short circuits. Because of their low price, and accessibility, carbon anodes are the most used anodic material. In contrast to the load density of lithium 3862 mah/g however, the assumed capacity is only 372 mah/g. Few attempts with novel graphite and carbon nano tubes have been aimed at augmenting the capacity, but this leads to a higher manufacturing cost. Alloy anodes and inter-metallic blends have high capacities, but they demonstrate an impressive size change, which ends up in having a bad cycle performance. Researchers have tried to master the size change by testing nano crystalline materials and by including the alloy phase with aluminium, bismuth, magnesium, antimony, tin, zinc among others in a non-alloy balance matrix with cobalt, copper, iron or nickel. Silicon contains an impressive capacity of 4199 mah/g, according to a

blend of Si₅Li₂₂. Nevertheless, the cycling performance is not good and the vanishing of the capacity overtime needs to be further researched. (Claus 2008)

2.2.2.1.1 Carbon-based Anodes

Graphite is one of the main carbon materials used as an anode. They are composed of layers packed in either hexagonal or rhombohedral patterns. When the lithium ion is introduced, these graphene layers reposition themselves on top of each other in a AA pattern and the "staging" happens. The lowest cost, availability and favourable electromagnetic properties are the advantages and carbon is the main anode material in Li-ion batteries. But the lithium intercalation capacity is low compared to Li-ion alloys. In the manufacturing of commercial lithium-ion cells, especially portable equipment, graphitic carbons are employed as an anode material. The crystalline carbon has increased its importance because of its flexibility to temperature control thanks to its organic structure and its excellent cycling capability, its more compatible with lithium. By developing structural and surface modifications, carbon-based anodes have been known to have on-going advances in their charge-discharge efficiency and discharge capacity. There are new developments in which Hitachi has designed artificial graphite by changing the structure of pores and particles. (Shukla and Prem 2008, 315,316)

2.2.2.1.2 Novel graphite and non-graphitic anodes

Notable progress is made with modified natural graphite and other graphite carbon such as "kish" graphite. Recent research shows that the electrochemical properties are enhanced on altered graphite as an outcome of the oxidation of the natural graphite in the air. Artificial graphite anode production needs heat treatment at temperatures from 3000C which requires more energy and may end up in the development of gasses. Kish graphite can have Lithium intercalation above 372mah/g, which is the set theoretical value. Furthermore, Kish graphite manufacturing is not costly and can be carried out at a lower temperature of 1500 C.

Non-graphitic carbons contain graphite domains but do not show the structure that graphite is known to have. They can also be called "disordered carbons". Even though their capacity is not reversible, and it is not to be compared with natural graphite, these materials have less risk to have a disruption in the solid electrolyte combination. That makes them the ideal match for Li-Manganese oxide, which challenges metal dissolution. (Mekonnen and Sundararajan 2016, p. 3)

2.2.2.1.3 Lithium Alloy Anodes

Lithium Aluminium is one of the first Li-alloy anodes to be created as the Li-ion battery anode. Cycling challenges can be enhanced by changing up the surface film by adding substances such as Di-lithium Phthalocyanine. The change in volume while lithiation and delithiation processes happen is another issue for this material. But the utilisation of dimensionally stable anodes can resolve this challenge. This can be made through the use of a submicron alloy particle alloy that is surrounded by a stabilizing matrix and an intermetallic host where one metal alloy mixes with the lithium, but the others don't. Metals that mix with Lithium can be aluminium (Al), cadmium (Cd), magnesium (Mg), bismuth (Bi), tin (Sn), and antimony (Sb). On the other hand, the metals that do not blend with lithium are copper (Cu), cobalt (Co), iron (Fe) and nickel (Ni). Al₃Ni, Fe-Sn, Sn-Sb and Sn-Cu are some of those intermetallic elements, with successful results as anode materials (Mekonnen and Sundararajan 2016, p. 3)

Another material labelled as a substitute to carbon anode is lithium titanium oxide. The cycle of this material is fine since the cycle of this material is good since, as opposed to most other intercalation electrodes, there are no volumetric changes during Li insertions and extractions. Their use is restricted to applications with a high operating voltage that does not require a high energy density. This material is recommended for nano structuring because of its low conductivity. (Mekonnen and Sundararajan 2016, p. 4)

2.2.3 Electrolyte

One of the most significant and costly components of the lithium-ion batteries is the electrolyte. The Li-ion motion is modulated by electrolyte aspects while charging and discharging takes place (salt detachment capacity, density, and liquid range). In order to elude "death weight", the totality of electrolyte inside the cell must be cautiously applied, which can decrease the gravimetric density. Liquid aquatic electrolytes, used in other batteries, like lead-acid, are extremely safe and non-flammable but contain a limited operative potential (~1.2 V), this would be insufficient to develop high energy densities. As a result, it was in the 1950's those non-aqueous electrolytes were created for Li-ion batteries. The perfect electrolyte for a Li-ion battery must contain a vast electrochemical stability window to evade the ongoing decay against redox reactions and proper ionic transportation properties. In the event of any short circuits or chemically and electrochemically dormant towards other battery (e.g., outer shell), it must allow an electronic division of electrodes. The standard lithium-ion battery electrolyte contains a blend of organic, aprotic solutions that are used to separate a conducting salt. Other materials (salts, organic blends or solvents) are inserted in minimal numbers (commonly below 5wt%) in the electrolyte in order to

increase the properties of the electrolyte (e.g., blend of the developed SEI or flame retardancy). Dendrites are the outcome of mixing lithium metal with liquid electrolyte, however, these can be lowered by utilizing solid polymer electrolytes that contain a great molecular weight polymer matrix, where lithium salt is separated. (Varvara 2017)

2.2.4 Separator

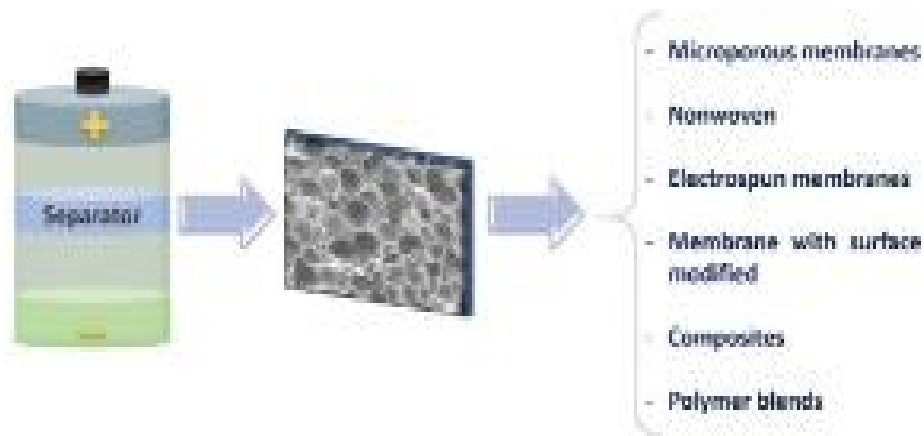


Figure 2: Separator (Costa 2019)

The separating material is located in the middle of the electrode that is negative and the one that is positive to impede them from physically reach each other, while allowing free ion travel and electronic course isolation. Its is a very small porous layer containing a polymer membrane (Polyethylene – PE or Polypropylene –PP), textured mat that is not woven (constructed of natural cellulose or polymer such as PVDF or PVF) or a blend that is not organic (Al_2O_3/SiO_2). In the company of electrolytes and electrodes, it has to be chemically and electro chemically stable, it also needs to be mechanically firm to resist the high tension when the battery is being put together. For strong ionic conductivity, this separator must contain enough pores to intake the liquid electrolyte. The battery performance, in addition to energy density, cycle life, power density and security, the choice of the right separator is consequently essential.(Surace 2015, p. 30)

2.3 Lithium-ion cell manufacturing process

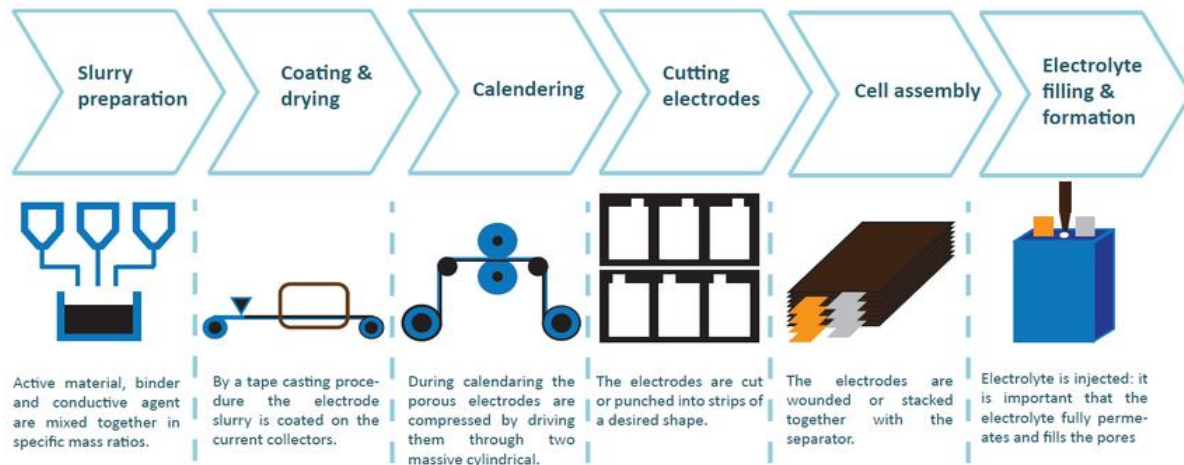


Figure 3: Influence of Electrode Density (Smekens et al. 2016)

2.3.1 Manufacturing of electrodes

2.3.1.1 Mixing (pouch, cylindrical, prismatic)

A spinning tool is used to mix at least 2 different raw materials to produce a slurry, which necessitates conductive additives, solvents and binders on top of active materials. There is a contrast between (dry) mixing and dispersing (wet mixing). Furthermore, the procedure might be carried out under vacuum in order to keep away from gas inclusions. The mixing and dispersion procedure must be tailored to the electrode design that will be generated. (Locke Marc et al. 2018)

2.3.1.2 Coating (pouch, cylindrical, prismatic)

Employing an application tool, the slurry is transferred on the foil. The foil is coated either sporadically or frequently. Typically, the bottom, top and sides are sooner or later coated. The foil that is coated is then passed to the dryer regularly. After the initial drying phase the foil that is coated on one side, it is manually taken back to the coating system, then the second side is coated. (Locke Marc et al. 2018)

2.3.1.3 Drying (pouch, cylindrical, prismatic)

In a continuous process, the active ingredient is dried regularly it has been coated. Heating removes the solvent from the substance. • The cathode coating contains a highly combustible solvent that may be recycled. Rolling systems or floating air streams are used to move the foil. It is necessary to use a floating dryer in order to cover both sides simultaneously. There are multiple temperature zones in the dryer so that each person has their own temperature profile. In most cases, a chamber system is used to do this. In either case, the foil is rewound (traditional) or coated on the second side once it has been cooled down to room temperature. (Locke Marc et al. 2018)

2.3.1.4 Calendaring (pouch, cylindrical, prismatic)

The electrodes are compacted by two enormous rolls that are cylindrical during the calendaring phase. The thickness of the electrode is reduced to a restrained value by implementing high pressure ((300–2000 kg·cm²–). Approximately 40 percent in size in the pores is decreased. This increases the density, and also enhances electrode material adhesion. After this step, the electrodes may be dried up for a second time to get rid of water contamination. The following step of the process takes place in a dry room. (Smekens et al. 2016)

2.3.1.5 Slitting, cutting (pouch, cylindrical, prismatic)

In this step, the electrodes are either cut or slit into wanted strips. To avoid a raised edge that may cause a short circuit in the cell, a clean cut is a must. Negative electrodes are in the end a bit bigger than positive electrodes to dodge the forming of dendrite and lithium deposits on the edge of the negative electrodes. When the negative electron is overgrown it will have a loss of energy density in the whole cell. The electrode is secured contacting tabs. (Smekens et al. 2016)

2.3.1.6 Vacuum drying (pouch, cylindrical, prismatic)

A special goods carrier is used to drive the coated daughter rolls. After that, the coils are placed in a vacuum oven. The drying time ranges from 12 to 30 hours. Residual moisture and solvents are separated from the coils during the drying process. Evaporation at low temperatures as a result of a low total pressure is used to reduce residual moisture. The coils are either moved directly to the dry room or dry packed under vacuum after they have been vacuum dried. (Locke Marc et al. 2018)

2.3.2 Assembly of cells

2.3.2.1 Separation (pouch)

Separation is made for the manufacturing of the pouch cell and defines the separation of the anode, cathode and separator sheets from the daughter rolls. The daughter roll that has been dried are uncoiled and put into the separation tool. The slitting step is often made with a punching tool in a steady procedure. The sheets then are separated and placed in a magazine or sent straight to the next step.

The left over edge of the sheets are then utilized as the welding portion area for the cell tabs. (Locke Marc et al. 2018)

2.3.2.2 Stacking (pouch)

While in the stacking step, the electrode sheets that have been sorted, are stacked in an anode, separator, cathode, separator, anode, etc. sequence. A There are quiet a few

different stacking technologies that have been patented by different manufacturers. The anode and cathode sheets are introduced from left to right to a folded separator that is shaped like a Z. This separator is employed as a never-ending form of tape, and it is slitted off when the stacking process is done. Sheets are often placed and shipped by vacuum grippers. According to cell specs, a cell stack can be made up of 120 layers. (Locke Marc et al. 2018)

2.3.2.3 Packaging (pouch)

In order to package the pouch cell, the current connector foils (anode and cathode, aluminium) are first attached with cell tabs by applying a laser or an ultrasonic welding process. The cell stack is then placed in the pouch foil (the pouch foil is deep drawn in previous step). After this, the pouch is often sealed on three sides. One edge of the cell (bottom one normally) will not be sealed so it can be filled up with electrolyte in the following steps of the process. (Locke Marc et al. 2018)

2.3.2.4 Electrolyte filling (pouch)

The electrolytes are filled in after the packaging step. During this step, the sub-processes "filling" and "wetting" have to be differentiated. With the aid of a dosing needle, the electrolyte is filled into the cell under vacuum (filling). By pressurizing the cell, the capillary effect in the cell is started (wetting). Expulsion and partial filling are done over and over multiple times according to the cell category and manufacturer. The pouch then is finally completely sealed under vacuum. (Locke Marc et al. 2018)

2.3.2.5 Winding (cylindrical, prismatic)

After vacuum drying of the daughter rolls, winding is needed for the manufacturing of cylindrical and prismatic cells. The electrode foils and two separator foils are wound around in the centre pin for the cylindrical cell or a winding rod for a prismatic cell. This foil order is alike the stacking process for the pouch cell. The wounded-up result is called jelly roll. An adhesive strip is utilized to fix the positioning of the single foils of the jelly roll. The stacked process time is remarkably slower than the one for the winding process. (Locke Marc et al. 2018)

2.3.2.6 Packaging (cylindrical, prismatic)

The jelly roll is introduced into a sturdy, metal housing just like the cell stack used in the pouch cell. The borders of the jelly roll in the prismatic cells are compressed, secured and ultrasonically welded to the terminals of the lid of the cell. Jelly roll is protected while being introduced into the prismatic casing with the use of insulation foil. The primary step in a cylindrical process involves inserting the bottom insulator and jelly roll into the cylindrical

casing. • After that, the anode collector is generally welded to the bottom of the casing and the existing cathode collector is welded onto the lid. (Locke Marc et al. 2018)

2.3.2.7 Electrolyte filling (cylindrical, prismatic)

After the jelly roll has been set in the casing, the electrolyte filling occurs. Later on, a division must be made between the "filling" and "wetting" subprocesses during electrolyte filling. A high precision needle is used to fill up the cell with the electrolyte. By pressurizing the cell, the capillary effect in the cell is started (wetting). Expulsion and partial filling are done over and over multiple times according to the cell category and manufacturer. Later on, the cells are sealed up with the use of crimping, beading or welding. (Locke Marc et al. 2018)

2.3.3 Formatting and testing

2.3.3.1 Roll pressing (pouch)

This process for the pouch where it will undergo an optional roll pressing operation after the electrolyte has been filled. With the assistance of a gripper, the lithium-ion pouch cell is clamped in a special made good carrier. Roll pressing guarantees optimal dispersion and absorption of the electrolyte under given pressure and this is done with a servo motor that guides the cell through the rollers, the rollers are then also cleaned simultaneously by cleaning rollers. This process step promotes as preparation for the following formation since the areas that are electrochemically inactive are prevented by applying this pressure. Roll pressing ensures that the maximum capacity of the cells is achieved and the rejection rate is reduced. (Locke Marc et al. 2018)

2.3.3.2 Formation (pouch, cylindrical, prismatic)

The formation defines the processes when the battery first charges and discharges. The cells are introduced into special good carriers in racks connected by spring-loaded contact pins. After that the cells are charged and discharged depending on the exact current and voltage curves. Lithium-ions are fixed in the crystal structure of the graphite on the side of the anode during the formation. The solid electrolyte interface (SEI) is made at this point, that forms an interface layer among the electrode and the electrolyte. The guidelines while in formation all depend on the producer and have a big effect on the cell performance. Cells here portray the vast knowledge of the company that manufactures them. (Locke Marc et al. 2018)

2.3.3.3 Degassing (pouch)

There is an intense gas accumulation through the first charging process, for the most part with most pouch cells and even more with the bigger kind. Pressured good carriers force gas into available space called a gas bag. The gas bag is pierced into a vacuum compartment

while degassing, and the escape gasses are absorbed. Finally, the cell is vacuum-proofed. The gas bag is then detached and discarded as hazardous waste. Finishing folding and adhesive of the seal edges, as necessary, is an alternative to decrease the external size of the pouch cell.

The gases that have been taken out have to be processed also before they go into the exhaust. (Locke Marc et al. 2018)

2.3.3.4 Aging (pouch, cylindrical, prismatic)

Aging means that it is the last step in the process, and it is done to ensure the quality of the cells. In this process, it takes an average of three weeks to monitor the cell performance and characteristics by evaluating the open circuit of the cell often. Normally the cells go through high temperature aging and then normal temperature aging. Cells are kept into aging shelves or towers. The cell is then sold to the customer. If there is not a considerable change in the cell's properties in this time they have been stored. Just like in the formation phase, the pouch cells are not pressurized in this step. The time it takes for the aging process is up to the technology and the chemistry that the manufacturer is applying. (Locke Marc et al. 2018)

2.3.3.5 EOL testing (pouch, cylindrical, prismatic)

In this last step, the cells have to be tested before they leave the facility in an EOL testing rig. Cells are taken out of the good carriers in the aging racks and are put into the test station where they are discharged so they can be shipped. A cell producer can then make different types of tests such as: leak tests, OCV tests, pulse tests, Internal resistance measurements, and visual inspections. When the testing is finally done, the manufacturer can categorize the cells depending on the performance data. After the cell has passed the different tests done, they can be packed and shipped, cells usually have a plastic cover and are put into cardboard boxes. Cells usually have a plastic cover and are put into cardboard boxes. (Locke Marc et al. 2018)

2.4 Most Common Lithium-Ion Batteries found in EV's

NMC have actually the highest energy density just behind NCA and are presently employed in various electric powertrains, electric tools and recreational vehicles such as e-scooters and e-bikes. Since the introduction of mass production of electric vehicles, most research and development operations were focused on NMC. (Accardo et al. 2021, p. 2)

Another of the most popular chemistries in li-ion today is NCA which Tesla started using in the form of cylindrical 18650 cells, while in the meantime every other company was using either prismatic or pouch shaped cells. Later on, Tesla found a way to increase the capacity of the cell and that was by implementing a separator that was thinner in size and also making the container of the battery bigger from 18650 to a 21700 cell with their model 3 in the US. (Johnson 2020)

However, Tesla introduced their Tesla model 3 with LFP battery in China in 2020 and they were satisfied with the outcome. Now, recently, they reported that all of their model 3 and model y will be standardized with this type of batteries worldwide. (Hanley 2021)

2.4.1 Li-ion batteries that do not contain cobalt

2.4.1.1 Lithium iron phosphate (LFP)

As a cathode substitute, Lithium Iron Phosphate was created by JB Goodenough et al. in 1996 to substitute the lithium cobalt oxide which structure was unstable when overcharging. LFP has been very popular since then due to the high thermal stability, long cycle life and great tolerance. If the LFP is kept at high voltage for long stretches of time, it is tolerated to full charge conditions and less stressed compared to other lithium-ion cells, which makes LFP very particular. On the other hand, the conductivity of this material is not as high in comparison with lithium metal oxides. However, there are two efficient solutions that are available to improve structural conductivity and surface conductivity, metal doping and conducting material coating on LFP electrodes that promote a noticeable increase in the obtainable capacity at a reasonable charge and discharge current density. Moreover, nanoscale components can make transportation lengths brief. To date, many battery manufacturers have marketed carbon-coated nano-LFP materials with success. Until recently a high number of electric vehicles such as BYD, Chevrolet Spark and BMW Active Hybrid 3 and 5 series have been using the LFP technology. (Ding et al. 2019, p. 8)

The BYD Group uses LFP technology mainly for its Electric vehicles such as electric forklifts, buses and cars to power their drivetrains.

LFP lessens its nominal voltage by 3.3v on each cell under the ones that are based off of cobalt. Colder temperatures decrease the performance with most batteries and life cycle is shortened when storing in high temperatures and this also includes the LFP cells. The self-discharge for LFP is higher than other Li-ion batteries, which can lead to problems of balance. The use of high-quality cells and/or sophisticated electronics control can reduce this but at the same time rising manufacturing costs. (Ding et al. 2019, p. 10)

Even with these solutions, the LFP tech still encounters a limited energy density of approximately ($\sim 120 \text{ Wh kg}^{-1}$) compared to the max of ($\sim 170 \text{ Wh kg}^{-1}$). This number is significantly less than the energy density demanded for the newer EV generation of ($>250 \text{ Wh kg}^{-1}$) by the year 2025. Moreover, LFP technology is more relevant for heavy-duty applications such as trucks and buses compared to mobile electronic devices that have lower volumetric density. As a result of this flaw, NMC, MCA and the combinations of NMC/NCA and LMO/NMC will be most likely to be preferred by the OEMs due to their greater specific energy. In addition to the automobile possibilities and because of its low costs and long life cycle, LFP still has a major potential to market in the power supply sector. (Ding et al. 2019, p. 10)

2.4.1.2 Li-Manganese Oxide (LMO)

M. Thackeray and his colleagues first announced the spinel Lithium-Ion Manganese oxide or LMO in 1983. Moli Energy marketed the lithium-ion battery cathodes in 1996. LMO contains a three-dimensional Li^+ diffusion, along with a firmer spinel construction, costs less and is not toxic in relation to LCO. Notably, Li^+ ions can fill $[\text{Mn}_{204}]$ polyhedral frameworks to allow better rating abilities opposed to materials that contain two-dimensional frameworks for Li^+ diffusion (Ding et al. 2019, p. 10)

LMO's low capacity (148 mah g^{-1}) is an important disadvantage. Furthermore, because of un-steadiness of the electrolyte, it has a weak performance, which leads to a Mn decay (uneven response of Mn^{3+} ions to Mn^{2+} and Mn^{4+}) and loss of capacity. LMO has mild safety and relatively poor specific energy among the four major Li-ion chemicals. (Cho et al. 2001, pp. 1074–1705)

Even with these disadvantages, LMO still has an advantage of being the least expensive compared to many electrode materials, this is very important for ev's to be introduced to the market. The majority of LMO batteries are mixed with NMC to refine the specific energy and elongate the lifespan of the Electric vehicle utilization. This blend offers the prime for each system, and most EV, including the Nissan Leaf, Chevy Volt, BMW I3 and so on, all use LMO/NMC blends. LMO, which usually represents thirty percent in the LMO / NMC combination, boosts speed by a high current level, whereas the rest of the NMC part constitutes a longer range. In the near future, the need for LMO will therefore be mainly driven by the mixture of LMO / NMC in electric vehicles. This kind of blend of cathodes could be substituted for electric cars and electric buses for LFP in China. (Ding et al. 2019, p. 10)

2.4.1.3 Lithium Titanate (LTO)



Advantage of Lithium Titanate Battery:

1. faster charging: 10mins fully charged
2. high discharge rate: as much as 10C-15C
3. wide working temperature range: -50°C ~ 65°C
4. super long cycle life: over 25,000 times

Figure 4: LTO battery (35AH LTO Lithium Titanate Battery 2021)

Since the 1800's, batteries containing lithium titanate negative electrodes have existed. The graphite is included in the negative electrode instead of the graphite in a Li-titanate cell, and this material takes the shape of a spinel structure. The opposite electrode could be lithium manganese cobalt oxide. Spinel lithium titanate has been considered to be a very advantageous electrode material all due to the non-change in size while in lithiation, this contributes to an amazing life cycle of the electrode, joined with an enhanced safety due to an exceptionally flat discharge plateau of approximately 1,55 V vs Li / Li+. The low conductivity of this material and the Li+ diffusion coefficient can follow a deficient performance in high power levels. But this could be corrected by the decrease of the li-ion transport path lengths by using the right nanostructure, and by making the electronic conductivity better by applying doping, surface coating and mixing composites with improved electronic conductors, for example: carbon materials. Because of their great safety level, these batteries are employed in medical applications that are mobile. (Miao et al. 2019)

2.4.2 Li-ion batteries that contain Cobalt

2.4.2.1 Li Cobalt Oxide (LCO)

Lithium cobalt oxide is abbreviated LCO and its one of the most used LI-ions, it has these chemical symbols LiCoO_2

Li-cobalt is a common option for applications like pc's, mobile phones, and digital cameras due to its high specific energy. A cobalt oxide cathode and a graphite carbon anode compose the battery. Lithium ions pass from the anode to the cathode during discharge due to the cathode's layered structure. On charging, the flow reverses.

Similar to other lithium-ion batteries that contain cobalt, they too have a graphite anode which sets a low cycle life by a changing electrolyte interface. To increase longer life, loading capabilities, and cost, newer applications include nickel, manganese, and/or aluminium. Because of the high cost of cobalt and improved performance by mixing it with other active cathode components, Li-cobalt is losing popularity to Li-manganese, but mostly to Lithium Nickel Manganese Cobalt and Li-Nickel Cobalt Aluminium Oxide. Disadvantages of Li-cobalt include its short life cycle and poor thermal stability. (Battery University 2021)

2.4.2.2 Li Nickel Cobalt Aluminium Oxide (NCA)

Since 1999, cobalt aluminium oxide has existed for specific applications. It contains a high energy and specific power (rate of energy supply from the cell) and a long-lasting life; these characteristics are also included in the NMC battery and therefore makes the two very similar. NCA is not very safe though as the other lithium batteries, this means that specific safety control measures are to be used in electric vehicles. It is also more expensive to produce, and this restricts its usability for other applications. Tesla is to date known to be the only EV producer that has NCA chemicals, claiming it contains even less cobalt in its NCA battery production than NMC811 (Nickel 80%, Manganese 10%, cobalt 10%). (Miao et al. 2019)

2.4.2.3 Li Nickel Manganese Cobalt (NMC)

NMC batteries contain superior capacity, mixed with top power and high cycling rate, causes them to be perfect for the use in the new generation of electric vehicles. Besides these factors, the NMC has the lowest self-heating rate when compared to the other kinds of lithium-ion batteries that are available at the moment. (Cobalt Institute 2021)

The lithium-nickel-manganese-cobalt oxide (NMC) battery includes a cathode that has about 10 to 20 percent cobalt. While the NMC battery contains a reduced capacity when compared to the Lithium cobalt oxide, the long-life and the specific superior power is ideal for the use of e-scooters, electric tools, and electric vehicles (Cobalt Institute 2021)

Whilst NMC material can be sorted into different mixtures, the blueprint normally contains 3 parts, 33% manganese, 33% cobalt and 33% nickel. This mixture sometimes called the 1-1-1 is a common option for mass manufacturing of battery cells that compose applications that need numerous amount of cycles. This is possible because of the lesser use of cobalt, following a lower cost in materials. (Targray 2020)

2.5 Lithium battery cells in different shapes used in EV's

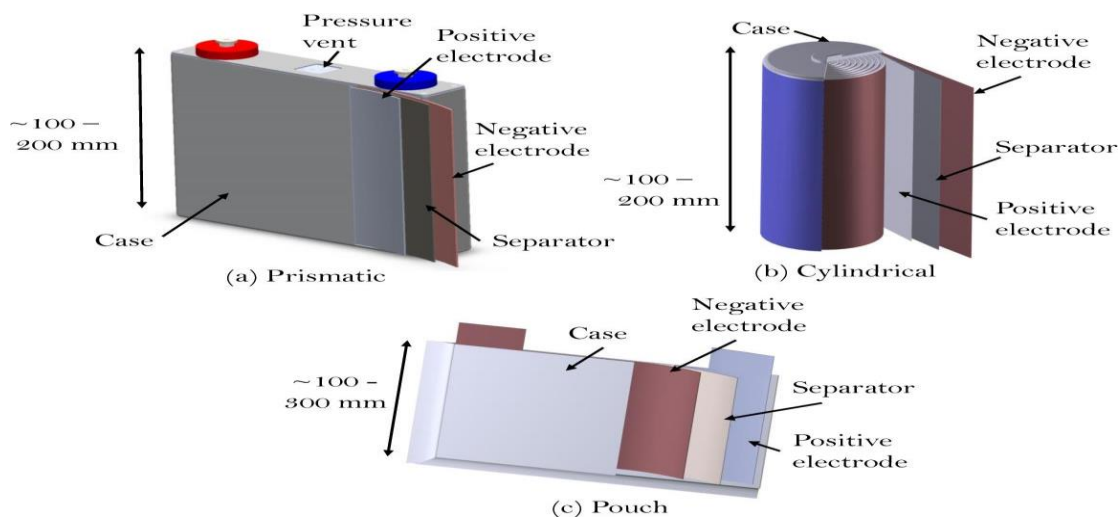


Figure 5: Different cell shapes (Lidbeck and K. Syed 2021)

Lithium batteries come in different sizes and shapes according to the specific use they are needed for. Classic lithium-ion battery cells are made in three different shapes which include cylindrical prismatic and pouch shape cells, but the materials used on these do not change. The most popular one is the cylindrical one used to this day; the outer shell is made up of stainless steel. This shape cell is the easiest to produce and because of the outside package that is completely closed, it is able to handle large inner pressures. The cylindrical cell also comes equipped with a vent that can open up in case of excessive pressure. Most of the devices that use this type of cell are the ones that are not very small in size, and these include power banks, power tools and communication applications. The cylindrical battery that is mostly used is the 18650 cell which measures 18 mm wide and 65 mm in length. But now with the rise in popularity of mobile and pocket sized devices, the demand for the prismatic cells has also increased. (Yuan et al. 2011, p. 21)

2.5.1 Cylindrical shaped cell

As the name implies, cylindrical lithium batteries contain electrodes that are enclosed in a cylindrical shaped cell which is made very compact inside a special metal case. This single characteristic allows to lower the risk that the electrode compound will fall apart, even if utilized under heavy circumstances. (Beck 2019)

Problems such as mechanical vibrations, mechanical enlargement of current conductors, and thermal cycling from charging and discharging could influence on how long the battery

can last. And so to help reduce these issues to the maximum, the design of the cylindrical application is very important. (Beck 2019)

A series of cells are combined and function in parallel within a battery pack. This helps increase the voltage and the battery pack combined capacity. (Beck 2019)

2.5.1.1 18650 Cell

Li-ion batteries possess a voltage and capacity rating, just like all other batteries. For all lithium cells, the nominal voltage is 3.6 volts, so if a certain voltage wants to be achieved, more cells can be connected in series to get the higher voltage desired. In general, all lithium ion cells contain the nominal voltage of just 3.6 volts. This voltage can change though, when the battery is fully charged, it can reach up to 4.2 volts, and when it is discharged, up to 3.2 volts. Very important to remember is that going above 4.2 or below 3.2V could permanently harm the battery and also could ignite a flame. (Aswinth Raj 2019)

The cell dimensions, weight and form are critical physical characteristics. Li-ion batteries that are sold come in several shapes and proportions. The easiest to be found Li-ion battery application is called the 18650, which has a cylinder form with a length of 65 mm and a diameter of 18 mm. This was planned at first to be used in laptops, the outcome 18650-scale economies led to the embracing of many power tools, electric bikes and even Tesla electric vehicles. (Muenzel et al. 2015)

2.5.1.2 21700 Cell

At first, 21700 type lithium-ion batteries were analysed and created for the use in electric vehicles, and so this means that the capacity of one single 21700 cell can reach about 3 - 4.8 Ah, which is 35% higher than a 18650 cell. This is ideal to be able to adapt to the demand of electric vehicles for longer travels and also to enhance the rate of vehicle battery space. The energy density of the 21700 battery has also improved significantly when comparing it to the 18650. The energy density of the early 18650 batteries were about 250Wh/kg, and for the new battery technology of the 21700 battery it is around 300Wh/kg, which is almost 20% more. (Greenway battery)

Tesla Motors created the most recent, standard, cylindrical lithium-ion battery called the 21700 in the United States and Panasonic in Japan. The 21700 is the typical battery that comes in a cylindrical shape, but it's a bit bigger, measuring 21mm in diameter and 70mm in length, the 0 is for the cylindrical shape. (Greenway battery)

The 21700 is predicted to be 10% lighter. Even though the total mass of the 21700 battery is larger than the 18650, the single battery energy density is higher following the enhancing in capacity. The same energy needed to produce the single battery can reduce the problem of

system management by about one third and lower the number of metal structure and electric fittings of the battery package. Samsung SDI discovered that these 21700 cells are 10% lighter than the previous battery when they made the change. (Greenway battery)

2.5.2 Prismatic shaped cell

The Lithium-ion prismatic cells are composed by broad sheets, stacked on top of each other, coiled up and packed into a metal cube or solid plastic case. Rather than jelly rolling, the electrodes can as well be put together by stacking them in layers.

In a prismatic cell, portions of separator sheets and the electrode that can be found near the corners could experiment more stress than the rest of the cell. The electrode coatings could be damaged, and the electrolyte could be distributed unevenly.

The cell box shape allows ideal use of the space that is used when combining them into packs. Nevertheless, this important space is accomplished at the price of more challenging thermal management. This is due to the fact that there is no room left over among the cells, unlike the cylindrical cells when they are packed.

Prismatic cells are produced with a capacity that goes from a few ampere hours that are intended for cellular phones and personal computers to hundreds of ampere-hours purposed for electric vehicles. The production of prismatic cells can be more costly and also they could be enlarged with time while using. While they are less likely to expand than pouch cells, cylindrical cells operate better in this matter.

(Arar 2020a)

2.5.3 Pouch shaped cell

The pouch cell was introduced to the world in 1995 with a completely new design. Instead of utilizing a cylindrical shape metal and a glass-to-metal supply-through for insulation, foil tabs were welded to the electrode and fixed to the pouch take the negative and positive terminals towards the outside of the cell. The pouch cell utilizes available room the most efficiently and accomplishes the highest packaging efficiency among battery packs with 90 to 95 percent.

The removal of the metal casing decreases weight, but the cell requires another form of battery support. A plain, flexible, lightweight battery design solution is available throughout the pouch cell. However, it's life expectancy can be reduced due to exposure to high temperatures and humidity. These type shaped batteries can be seen in applications for military, consumer and electronic automotive enterprises. The pouch batteries do not have a regular size pattern; therefore, each manufacturer build their own specific designs for their specific needs. Pouch packs are commonly li-polymer, most of the time the durability and

specific energy are less compared to a cylindrical shaped cell. (Epec Engineered Technologies 2020)

2.6 Li-ion battery capacity degradation mechanisms

2.6.1 Solid Electrolyte Interphase (SEI)

The lithium ions are transported into the anode while Li-ion charges and the voltage of the battery goes up. Because of the electrochemical decomposing of the electrolyte in the anode, a solid electrolyte interphase (SEI) is created on the surface of the anode. SEI is made up of lithium oxide and lithium carbonate. This reaction is made on the first cycles, it uses the lithium ions that are recyclable.

Not all lithium ions revert to the cathode during discharge phase due to forming of the SEI layer and the battery capacity is reduced. Following the initial cycles the SEI layer continues to gain volume through cycle, which ultimately blocks graphite-electrolyte interactivity and could cause the failure of the battery. (Xiong 2019b, p. 31)

2.6.2 Electrolyte Oxidation

Electrolyte oxidation happens electrochemically at the surface of both the active material and the conductive carbon particles, which is comparable to the growth of the SEI layer.

Evidence suggests that the initiation of faradaic oxidation processes occurs only at electrode potentials larger than 4.8 volts on Li/Li⁺, which is higher than what is predicted in typical lithium-ion cell operation. As the battery holds this high charge, it will degrade quicker over time. This oxidation reaction could harm the battery life even more than cycling effects.

Cathode electrolyte oxidation also causes partial auto-discharge of the battery. (Rinkel et al. 2020, 3,4)

2.6.3 Lithium Plating

Lithium plating is the development, during charging, of lithium metal around the Li-ion battery anode, where lithium ions from the cathode are introduced into compounds in the anode with layered structures (intercalation). The lithium ions build up and form metallic lithium when the speed of moving lithium ions is greater than the speed of intercalation. This is mainly due to the over-charge above 4.2V of Li-ion batteries, low temperatures (under 15°C) and high-current loadings. Dendrite production is also enabled by the deposition of metallic Li. When the local anode potential falls below 0 V versus Li/Li⁺, this event happens. Li plating can also be caused by a poorly constructed cell or the use of ineffective charging techniques.

(Janakiraman et al. 2020)

2.7 Recycling Methods

2.7.1 Mechanical recovery

Mechanical treatment is when the material is shredded and the different elements are separated, this takes to the extraction of the black mass. This black mass usually is the main reason to recycle Li-ion batteries, to extract the valuable raw materials such as cobalt, nickel, manganese, lithium, etcetera. (Lebedeva 2017)

2.7.2 Pyrometallurgical recovery

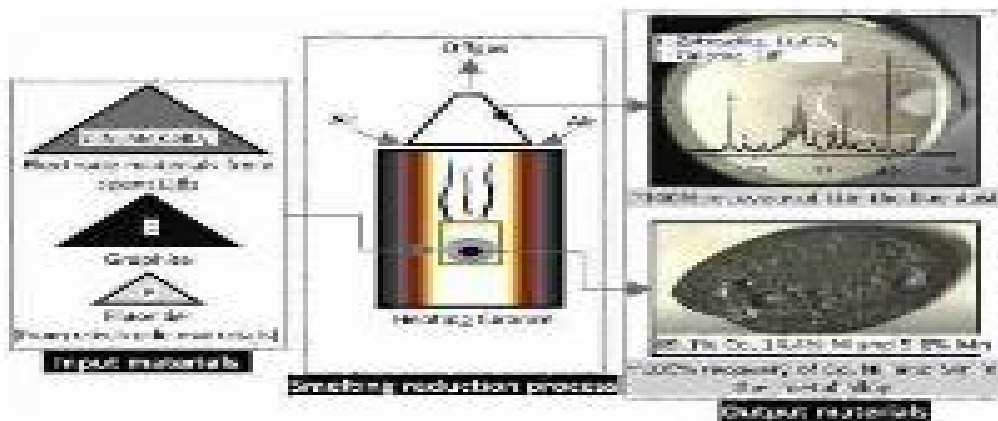


Figure 6: New smelting reduction process.jpg (GGC 2020)

Researchers have suggested that a new method combining pyrometallurgy and hydrometallurgy recycle precious metals from used LIB's could reduce Li loss during the recovery process.

While pyrometallurgy is an easy way to recycle valuable metals from spent LIB's, it is not eco friendly because it has high energy and secondary emissions. Furthermore, Lithium loss during the recycle process is a serious issue that must be addressed. (Zheng et al. 2018)

For industrial recovery of Co, pyrometallurgy is commonly used. The common use of worn-out LIB's is similar to the smelting of ore. The standard LIB's are first split up into different cells before the smelting process and then put into a heating furnace. The temperature in the pre-heating zone should be less than 300°C to make sure that the electrolyte is fully evaporated without explosive activity. The temperature of the furnace should be above 700°C for in the pyrolysis zone. The objective of this process is mainly to separate the plastic from the battery. The material is smelted into alloys of Cu, Co, Ni, and Fe, Li, Al, Si, Ca, and some Fe slag in the smelting reduction zone. Usually only Cu, Co, Ni and small quantities of Fe are recovered with this approach. Since Co plays an irreplaceable function in LIB commercial applications and the efficiency of thermal metallurgy in recovering Co instead of Li is strong, the economy of this recuperation method depends in large part on the

amount of Co in worn-out LIB's and the variation in the cobalt market sector. Nevertheless, as battery producers may already acknowledged, the high cost of Co and the environmental effect it has had in the last few years, LiMn₂O₄ and LiFePO₄ are being produced which do not have any electrode materials that contain Co. This conventional approach has little prospect of growth, given the limitation of lithium resources. (Zhou et al. 2020)

To be able to extract lithium from worn-out batteries it is possible to transform any electrode content in Co alloys and Li concentrates by the selective pyrolysis process of an arc furnace. After this, Li is hydro metallurgically removed and subsequently transported and deposited in the form of Li₂CO₃. Other materials can also be extracted. This approach can be used not only in electrode recycling materials but also in electrolytes to recycle Li and Fe etc., which significantly increase the recovery efficiency. (Zhou et al. 2020)

2.7.3 Hydrometallurgical recovery

There are normally three macro-processes that conclude the hydrometallurgical process steps such as accumulation, purifying and recuperation of metal alloys. Different organic and inorganic acids were examined as solvents. In addition, there is research available on leaching methods for the chemical conversion of metals by employing bio-organisms. In order for the hydrometallurgical process to take place, first the materials need to be prepared and this has to be done by separating the batteries, pulling them apart manually and then pulverize or shred them. By pulling the batteries apart by hand to an electrode form results in highly cleansed starting materials and the needed particle sizes to promote the following hydrometallurgical process. However, due to economic and safety concerns, for the industrial production, manual removal of precious cathodic matter does not seem to be expedient. At certain times, when electrode coatings are mechanically removed, the particles containing copper and aluminium could still not get separated and they could end up into the coating fraction along other impurities, which include residues of the solvents. Strong organic acids and expensive additives are generally needed for the hydrometallurgical processes. Significant amounts of liquid waste are also generated. But other than that, the cathode coating metals can be extracted selectively and energy effectively. (Recovery 2019)

2.7.4 Direct recycling

Direct recycling prevents the crystal structure of lithium-ion cathodes from collapsing. The advantage of keeping the value of what transforms raw materials into the cathode, and it can be quite substantial. Direct recycle has also another advantage that helps other costly elements such as electrolyte salts, anode graphite, and copper and aluminium foils to be extracted. In direct recycling, the battery pack is shredded, and a black mass (mixture of

anode and cathode powders) is accumulated, which then are coated in polymers (adhesive that fixes them to the metal foils). Those powders must then be cleaned carefully without harming the active powder surface, for example, by removing adhesive with a solvent or by heat depolymerizing. (Hughes 2020)

But not all batteries are being shredded. Some companies such as Relib which is based in the UK, take the battery pack and divide it open into the anode, cathode, and separator so that the materials end up in a far purer fashion. This gets rid of risks of technicians conducting manual dismounting and avoid getting electrocuted, by developing an automatic disassembly system. The only thing to do is to remove metal foils from the active surface of the material. The ReLiB team has therefore developed an ultrasound delamination method that can separate cathodes from metal current collectors 100x faster than acids.

In principle, recyclers need to consider why the battery needs recycling while direct recycling recovers the highest value product. The active cathode material has often degraded – it must be revitalized with new lithium to be useful again. Spectroscopy allows you to estimate roughly how much lithium is missing, and new lithium can be supplemented by a lithium hydroxide cathode mixture and heating to 220°C. And a rapidly changing market means that manufacturers always shift to better chemical solution. It may be necessary to upgrade cathodes retrieved in this way. For example, older nickel cobalt batteries contained much less nickel than new iterations. It is necessary to increase the nickel content of the recovered material in order to recover something that the market wants to acquire. (Hughes 2020)

2.8 Lithium batteries for EV's for the future

2.8.1 Lithium Silicon

Silicon (Si) is one of the most up-and-coming candidates to substitute graphite among all possible lithium-ion anodes for these reasons: Si contains the biggest gravimetric capacity of 4200mAh g⁻¹ and lithiated to Li_{4.4}Si, also has volume capacity of 9786mah cm⁻³, that is calculated with primary volume of S₁, instead of lithium metal. Si displays a discharge mean voltage of approximately 0.4 volts, which is good for keeping reasonably open circuit voltage and elude unwanted lithium plating process, Si is also available in big amounts, it has a low cost and its environment friendly (non-toxic). Along with the process of lithiation and delithiation of the S₁, come the dramatic increase in volume (about 360% for Li_{4.4}Si) and the enormous reproduction of stress is followed, which also leads to serious consequences. (Zuo et al. 2017)

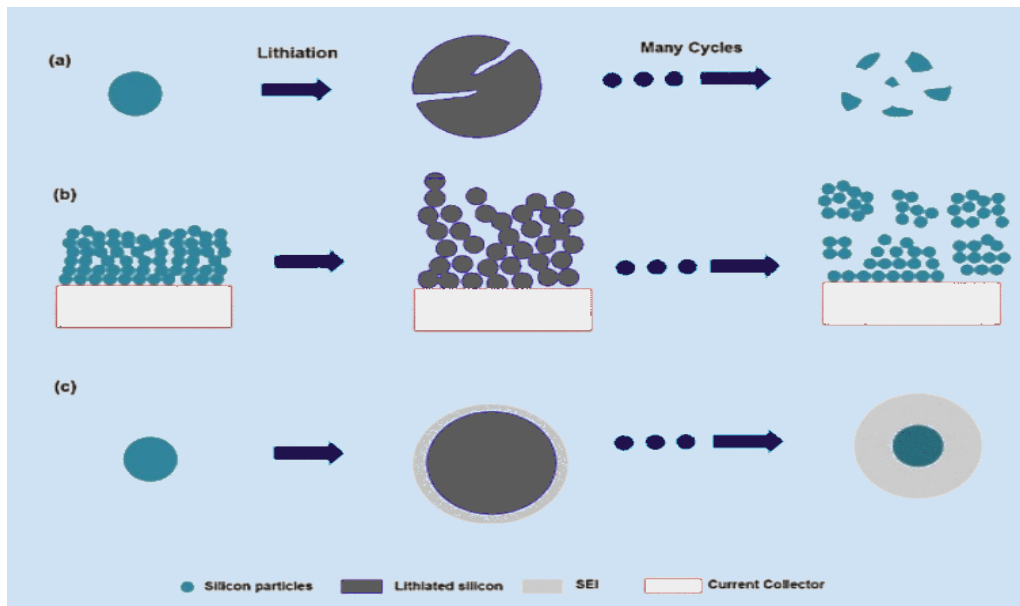


Figure 7: Silicon based lithium-ion battery anodes.jpg (Zuo et al. 2017)

- a) The integrity of the electrode structure degrades as a result of a progressive pulverization during repetitive discharge/charging.
- b) The interfacial stress-induced disconnection between the electrode and the current collector.
- (c) Endless consumption of lithium ions happens in the course of constant formation-breaking-reformation process of the SEI layer.

All of these processes speed up the collapse of the electrode and the capacity to decline in a synergistic way. The critical volume expansion problem also contributes to the dull electrochemical cinematics due to Si's low electron conductivity. (Zuo et al. 2017)

2.8.2 Solid State

Several problems faced by the current lithium-ion batteries are due to their liquid electrolyte. Indeed, with the flammability of chemical substances, safety concerns arise. The solvent and conductive salt side reactions conduct to capacity degradation and aging. On the other hand, all solid-state batteries are safer because they don't contain flammable organic materials, and also, they could offer a great development of energy density. ASSB's have a solid electrolyte, that acts as an electrical insulator and ionic conductor at the same time, rather than a porous separator that is saturated with liquid electrolyte. The usage of a compact electrolyte as a physical barrier for lithium dendrites also makes it possible to use lithium metal in place of the anode material. (Kartini and Theresa Genardy 2020)

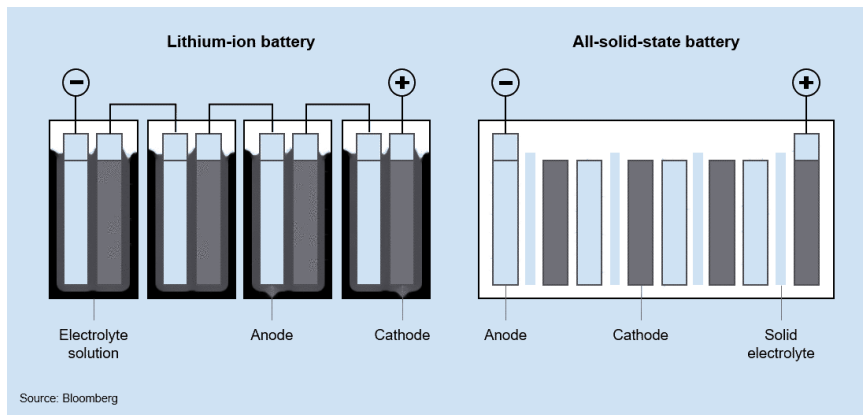


Figure 8: The Future of All Solid (Kartini and Theresa Genardy 2020)

Research on solid electrolytes is increasing because of safety. The current commercial lithium-ion battery, which is based on liquid electrolyte, will be replaced in the near future by the solid-state battery, all solid-state batteries will be very safe and efficient. This is due to the solid electrolyte having a high melting point and also because of its high ionic conductivity. When a solid-state battery is employed in an electric vehicle, the cooling components will no longer have to be present, which will make the battery pack less heavy, and this will have a good effect since the electric vehicle will have a better range and will also occupy less room for the battery. The technology is not yet available on the market, but it promises to replace the current lithium-ion batteries. (Kartini and Theresa Genardy 2020)

2.8.3 Lithium Sulphur

Researchers are working on how to build up a lithium-sulphur battery's charging cycles it can do before it stops working to make it compete to the actual lithium-ion design.

The next generation power cells we could be able to utilize in EV's and portable devices could be lithium-sulphur batteries, which are less heavy, and cost less than battery cells made today. It would all depend if researches can figure out how to make them last for longer periods of time. (Merrifield 2019)

The most appealing thing here about sulphur batteries is that they actually can reserve more energy than a cell that has the modern li-ion tech. This implies that in a single charge, it can last significantly longer. Another advantage of Li sulphur batteries is that they can be produced in factories where Li-ion are manufactured, making production relatively easy. (Merrifield 2019)

Sulphur, which is a low-cost raw material, is used as an oil industry by-product instead of using cobalt which is very expensive and also is liable to fragile world supply chains. And using sulphur can offer significant savings per unit of power. (Merrifield 2019)

The key issue is that today's batteries made of lithium-sulphur can't be recharged sufficiently long before they can become commercially feasible. All of this lies in the chemistry within: every time a Li-sulphur battery is charged; chemical deposits increase and that deteriorates the cell and it reduces its lifespan. These deposits develop dendrites which are thin, tree-like structures that start building up within the battery from the lithium anode, the electrode that is negative. These deposits deteriorate the anode and the electrolyte, which is the instrument for the transmission of lithium ions to come and go. That lessens the energy of the battery and can also lead to a short circuit, likely creating an electrolyte to ignite. This issue has been reported and can affect li-ion batteries, and that's the reason airline safety has a need to ask customers to have their battery packs for their cell phones or laptops in their carry on luggage, where they could observe better if any smoke or fire ever happened. (Merrifield 2019)

2.8.4 Lithium Air

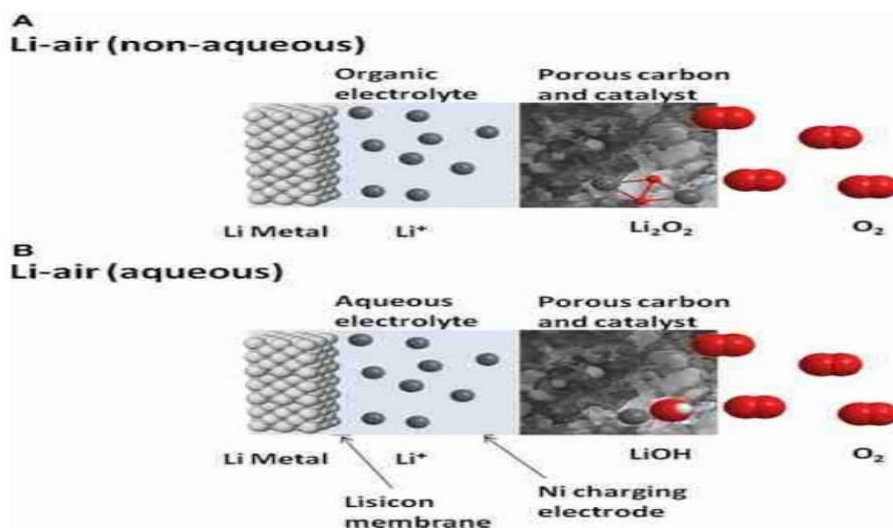


Figure 9: Li-air (Badwal et al. 2014)

The lithium-air cell combines in its elementary form a reversible lithium metal electrode with an oxygen electrode created by a stable species of oxide. There are two types of Li-air technology: a non-aqueous form and an aqueous one, which offer at least 10 times the energy storage capacity from today's regular lithium-ion batteries. The cathode is a pore-conductive carbon that works as the oxygen reduction substance, while metallic lithium is the anode. (Badwal et al. 2014, p. 11)

The reduction of oxygen in the non-aqueous system ends up with peroxide formation. This equation shows the general reaction: $2\text{Li}(s) + \text{O}_2(g) = \text{Li}_2\text{O}_2(s)$

A cell that has this reaction contains an open circuit voltage of 2.96 V and works at certain energy values that go from 3460 and 11680 Wh kg⁻¹. While discharging takes place, the cell pulls oxygen and at the same time grows in mass, at the same time it reduces its volume while charging, so that particular energy can achieve the limit when it is charged fully.

The Lithium-air cell that is in the aqueous form, water is implicated in the oxygen decrease, in the meantime, the lithium electrode has secured from any contact with water normally by the use of LISICON (Lithium-ion conducting solid electrolyte). Usually the electrolyte solution is a saturated one of LiCl and LiOH and the final product is a hydrated lithium hydroxide like the following equation: $4\text{Li(s)} + 6\text{H}_2\text{O(l)} + \text{O}_2\text{(g)} = 4(\text{LiOH}\cdot\text{H}_2\text{O})(\text{s})$ (Badwal et al. 2014, p. 11)

When the reaction contains water, it complicates the cell functioning and reduces the specific energy, which is approximately 2000 Wh kg⁻¹ and differs over 100 Wh kg⁻¹ with charging state. The main issue with the aqueous form of the lithium-air is the difficulty in maintaining lithium metal separation from the aqueous medium, although this is still an imposing efficiency level. To date, most of the Li⁺ conducting solids have not been sufficiently stable over aqueous solutions for the longer term. They also contribute substantially to cell impedance, which decreases the thickness of this protecting layer, but is limited by the inferior mechanical strength of very thin layers. For these motives, most research work is focused on the non-aqueous form in lithium-air batteries. (Badwal et al. 2014, p. 12)

3 Motivation and Objectives

3.1 Thesis Motivation

Why is this research necessary, what is the problem?

Cobalt is one of the most popular elements that is used for manufacturing lithium-ion batteries, that power electric vehicles. The Democratic Republic of Congo supplies fifty to sixty percent of the worldwide supply and records indicate of poor human rights that include mining involving children, as well as high cost of this material. (Goldman 2017)

This is where other possibilities may come into place, there are other batteries that do not contain cobalt and, in this case, the LFP would be a good candidate. With lower cost, new tech that assures to make the energy density higher than before (but will be very hard to be higher than mixtures that contain cobalt), and lastly, safer. However, cell packs that include cobalt, such as ones built with NCM cells are still preferred in Europe. (Ribeiro and Tang 2020)

This evaluation is necessary in order to help customers make a demand of the best chemistry they can get when they purchase an EV or even any kind of vehicle that is electric and is powered by batteries. This study would also help manufacturers of any kind of electric vehicles make the right choice when deciding for a certain chemistry to produce their vehicles.

What is this research about?

This research was conducted to evaluate battery systems that contain cobalt in their electrodes, and which seem to be very popular in today's EV market and compare them to mixes which do not contain cobalt, then the purpose is to determine what battery chemistry would be the best in the long run.

How it will the evaluation be done?

This study will be conducted including SWOT analyses at first to evaluate each set of batteries to determine their main strengths and weaknesses. One for LFP and another for NMC and NCA which are very similar when it comes to their characteristics, and both contain cobalt in their chemical mixture.

With the results from the SWOT Analysis, a multi criteria decision analysis was utilised to rank the batteries, this was made by setting the 8 most important criteria, an average weight to accommodate each rate of importance to each of the criteria was used for this step.

Lastly, an analytic hierarchy process was implemented to determine each weight of importance for all eight criteria. This was done in two separate scenarios with different point of views to see what battery in the end was the overall better in the ranking.

3.1.1 Personal Motivation

As a consumer, I have had e-scooters and e-bikes for a while, and I always wondered how these li-ion packs worked as a whole and how they were built using many single 18650 or 21700 cells just in case one of mine was ever faulty. I have seen that most of the times the battery pack was the most expensive part of a bike or scooter if they ever needed to be replaced.

After researching further, I know that these recreational vehicle battery packs are built very similar to EV packs, just at a smaller scale. While doing this work, one of my batteries' capacities started to fade away slowly and after doing further investigation on the topic, I started ordering tools and parts needed to try and build a new pack. Took some time to get everything together, but following the various steps very careful, I successfully built my own

48v 11.6 ah battery pack that can install on my e-bike. After this, I am confident that I can also build bigger, more powerful packs or even a small power wall in the future.

3.2 Thesis Objectives

A literature review was carried out to offer context for the thesis motivation and objectives. Section 2.1 gives an overview and a brief description on the major parameters and specifications on LIB's.

Section 2.2 covers and explains the major components of the Li-ion batteries such as:

- Cathodes and the different types of materials they consist of and their advantages and disadvantages.
- Anodes and the main materials that can either be carbon or non-carbon based.
- Electrolytes and its main role inside the LIB.
- Separators and what it takes for this component to be effective.

Section 2.3 helps the reader know the steps it involves when manufacturing either pouch, cylindrical or prismatic cells. Most steps are basically the same on all three when it comes to electrode manufacturing. They start to take different procedures once it is time for assembly and the final step which involves formatting and testing, but that only includes the pouch type, the cylindrical and prismatic steps stay pretty much the same. And so, this aids the reader understand that it wouldn't be different steps to manufacture either the cylindrical or prismatic and therefore the main effect would be in the materials applied in the battery system.

Section 2.4 narrates the most popular types of cell technology used in today's EV's including some of their advantages and disadvantages. This segment is divided into two sub sections. The first is the kind of cells that do not involve cobalt in their material mix and that includes battery technology such as LFP and LMO. The second portion mentions the type that has cobalt in their mix of materials, and this includes technologies such as LCO, NCA, and NMC.

Section 2.5 describes the three main different shapes of battery cells used in EV's and mentions how they are composed and also why some manufacturers may use one shape as opposed to the other two.

Section 2.6 introduces and explains the main causes of degradation mechanisms that affect Li-ion batteries and how in most cases these can be prevented to make them last a bit longer and keep them safe.

Section 2.7 brings up four different methods of recycling LIB's at the end of their life which consist of mainly extracting and separating these valuable materials so they can be mixed again into new lithium-ion battery cells. These procedures include mechanical, pyrometallurgical, and hydrometallurgical recoveries, along with direct recycling.

Section 2.8 talks about some of the weaknesses current LIB's face as of today, also mentions compositions of different new technologies that could take their place in the near future such as: lithium silicon, solid state, lithium sulphur, and lithium air batteries.

4 Methodology

4.1 SWOT Analysis

Research was conducted to identify the most important factors and main drivers that could lead other companies besides Tesla to opt for lithium iron phosphate chemistry instead of the current cobalt-based ones they are using which include: NCA and NCM to be included in their electric vehicle line up.

A couple of SWOT analysis were applied in order to do the comparison between these chemistries, determine their advantages and disadvantages, and finally their opportunities and strengths.



Figure 10: Swot Analysis (Designedge 2017)

What is a SWOT Analysis?

SWOT analysis is a planning approach that assists businesses in developing a strategic plan to fulfil their objectives, enhance operations, and remain relevant. While conducting a SWOT analysis, businesses analyse their organizational growth, goods and services, business objectives, and market competition's strengths, weaknesses, opportunities, and threats (the four aspects SWOT stands for). (White 2018)

Two-by-two matrices are employed in the creation of a SWOT analysis, which includes the horizontal combinations of internal strengths and weakness, and external opportunity and threats factors and vertical combinations of helpful strengths and opportunities and harmful weaknesses and threats factors. Final analysis results will enable the company to evaluate whether targets, goods, services, initiatives or targets are strategically appropriate. If the internal environment (strengths and weaknesses) matches the external environment, the optimal strategic components are (opportunities and threats). (White 2018)

4.1.1 Strengths and Weaknesses

Internal variables that are reliant on the aim, project, or initiative under consideration are considered strengths and weaknesses. Because it is subjective to the selected purpose, what is regarded as a strength for one objective or project may be regarded as a weakness for a different one. (White 2018)

Strengths are under the control of the company in charge, and this category encompasses everything the company does well while attempting to achieve a certain goal, initiative, project, or aim. This category includes everything that offers the company an edge, helps procedures and projects operate smoothly, or helps the organization achieve corporate goals. (White 2018)

The company also has control over its weaknesses, but this category encompasses everything that prevents the company from keeping on track to meet business or project targets and purposes. These are the things that must be addressed or altered in order for success to be realized. (White 2018)

4.1.2 Opportunities and Threats

Opportunities and threats are part of the outside environment, they contain elements affecting the aim or project outside the organization or product. This might include economic, technological, regulatory and legislative changes, socio-cultural and competitive developments. (White 2018)

Opportunities are elements outside the corporation that the company may use to accomplish business objectives and propel the product ahead. Threats encompass anything that might cause problems for a project in the external environment or that constitute a future threat to be successful in the future. (White 2018)

4.2 Multi Criteria Decision Analysis, Weighted Sum Model

After the Swot analysis was made comparing their characteristics, a MCDA can be done to evaluate the overall score for either chemistries with or without cobalt and nickel, to decide which would be the best bet.

What is Multi Criteria Decision Analysis?

As a decision-making tool that combines both quantitative and qualitative elements, multiple-criteria decision making (MCDM) or multi-criteria decision analysis (MCDA) is considered complicated example, which main stages include:

- Defining the goal
- Representing the criteria
- Define criteria weight
- Mention alternatives
- Rate alternatives

For rating or ranking of the alternatives, a number of different with various algorithms can be implemented on the MCDA such as Weighted sum method, weighted product method, analytical hierarchy process, Topsis and Moora methods.

For the WSM method, which could be one of the most common to work with, where A^* -score is the WSM of the alternative with the most importance, n is the value of the decision criteria, a_{ij} is the absolute value of the i^{th} alternative as regards of the j^{th} criteria, and W_j would indicate the significance of the weight of the j^{th} criteria. (Uppal 2020)

WSM Formula —

$$A_{WSM-score}^* = \max_i \sum_{j=1}^n a_{ij} w_j, \quad \text{for } i = 1, 2, 3, \dots, m.$$

Figure 11: Ranking of entities with Multi-Criteria (Uppal 2020)

4.2.1 Weighted Sum Method Steps

The following steps are needed when trying to accomplish a weighted sum method:

- First thing to do is make a table that will have the different characteristics going from low importance to very high in a grammatical scale. From there give the grammatical criteria scale a number using a 5-point scale for example.
- Create another table showing the decision matrix by replacing the grammatical criteria with the number values, so there should be a total of three tables until this point.
- Make a fourth table where 'A_{ij}' can be the evaluated number of 'ith' attribute of 'jth' criteria. In order to generate the normalized decision matrix, beneficial and non-beneficial attributes need to be classified and then normalized. To get the results, for beneficial attributes the formula $A_{ij}/\text{Max}(A_{ij})$ is applied, whereas for non-beneficial $\text{Min}(A_{ij})/A_{ij}$ is utilized.
- Allocate equal weight to all the criteria, because they have similar importance. Then multiply the weights by the evaluated value of each criterion to come up with the normalized decision matrix.
- Add the normalized and the weighted numbers out of every attribute.
- Set the ranking for the different attributes.

(Loganathan et al. 2021, p. 4)

Since the importance of each criterion used for this report are not of equal value, an Analytical Hierarchy Process will be implemented as an additional method to come up with the different weights.

4.2.2 Analytical Hierarchy Process (AHP)

The Multi Criteria Decision Analysis will have some criteria which will have some added weight; therefore, each criterion will have a different weight to it. To determine how important each criterion is from the others and to add a percentage of weight or importance, there will be an Analytical Hierarchy Process (AHP).

When it comes to handling qualitative and quantitative multi-criteria aspects in decision-making behaviour, Saaty (1980) has produced a powerful and useful instrument. This methodology is based on a hierarchical structure and is termed the Analytical Hierarchy Process (AHP). (Taherdoost 2017, p. 244)

With this method of decision making, a variety of choices were considered, and sensitivity analyses were conducted on the subsequent criteria and benchmarks. In addition, the paired

comparisons make judgements and computations easier. As a result of multi-criteria decision making, it also displays compatibility and incompatibility decisions (Taherdoost 2017, p. 244)

AHP is regarded to be one of the most comprehensive systems for making decisions based on numerous criteria since it allows the problem to be formulated in a hierarchical manner and incorporates quantitative as well as qualitative factors. Creating an issue hierarchy is the first step in solving the problem. As a second stage, each level of the hierarchy is assigned a nominal value, which is then used to build a pairwise comparison judgment matrix. (Taherdoost 2017, p. 244)

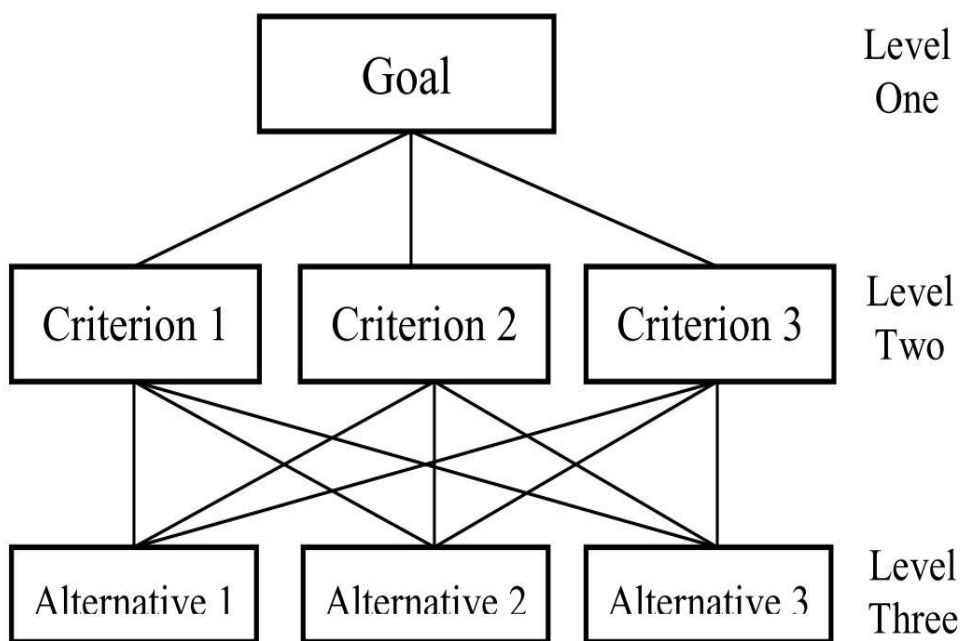


Figure 12: AHP Diagram (Taherdoost 2017, p. 244)

To start this method, objective of choice making, and issue are introduced hierarchically into the scene of the relevant decision factors. There are two components to decision making which are: decision options and decision indicators as shown on figure 12. (Taherdoost 2017, p. 244)

Importance Scale	Definition of Importance Scale
1	Equally Important Preferred
2	Equally to Moderately Important Preferred
3	Moderately Important Preferred
4	Moderately to Strongly Important Preferred
5	Strongly Important Preferred
6	Strongly to Very Strongly Important Preferred
7	Very Strongly Important Preferred
8	Very Strongly to Extremely Important Preferred
9	Extremely Important Preferred

Figure 13: AHP Importance scale (Taherdoost 2017, p. 245)

In the second stage, a set of questions should be created and upon someone's or a groups opinion, information is gathered to perform the different pairwise comparisons, The scale runs from one to nine, with number 1 indicating that the two components are equal in importance. In a paired matrix, number nine, on the other hand, denotes that it is of highly importance, and so on up to the number 2 as shown on figure 13. (Taherdoost 2017, p. 244)

	Stakeholders C	Financial	Strategic	Other Criteria
Stakeholders C	1	1/5	1/9	1
Financial	5	1	1	5
Strategic	9	1	1	5
Other Criteria	1	1/5	1/5	1
Total (Sum)	16.00	2.40	2.31	12.00

Figure 14: AHP matrix table example (Accelerating Microscopy 2019)

As it can be seen on the table on figure 14 as an example, pairwise comparison matrix is done using the following formula on the eigenvector: (Jalaliyoon 2012, p. 6)

$$a_{ik} \cdot a_{kj} = a_{ij}$$

Figure 15: Eigenvector formula (Jalaliyoon 2012, p. 6)

If the results are not corroborated for all k,j,l,s, then the following formula applies (Jalaliyoon 2012, p. 6)

$$a_{12} = 2, a_{23} = 2 \Rightarrow a_{13} \neq a_{12} \times a_{23} = 2 * 2 = 4$$

Figure 16: Eigenvector corroborated formula (Jalaliyoon 2012, p. 6)

As a result, the matrix not being compatible, the matrix cannot be utilized as a normalizing column in the situation of incomplete consistency pair comparisons to get the W_i result.

Eigenvector method may be utilized for a positive and inverted matrix like this pairwise comparison matrix in these formulas: (Jalaliyoon 2012, p. 6)

$$e^T = (1, 1, \dots, 1)$$

$$W = \lim_{k \rightarrow \infty} \frac{A^k \cdot e}{e^T \cdot A^k \cdot e}$$

Figure 17: Positive, inverted formula (Jalaliyoon 2012, p. 6)

Calculation should be done multiple times in order to obtain a convergence among the set of responses in successive repetitions of this procedure in order to make a choice when faced with a matrix that is not compatible. The raw data is then turned into understandable absolute values and normalized weights using the formula $w = (w_1, w_2, w_3, \dots, w_n)$: (Taherdoost 2017, p. 245)

$$Aw = \lambda_{\max} w, \quad \lambda_{\max} \geq n$$

$$\lambda_{\max} = \frac{\sum a_j w_j - n}{w_1}$$

$$A = \{a_{ij}\} \text{ with } a_{ij} = 1/a_{ji}$$

A: pair wise comparison

w: normalized weight vector

λ_{\max} : maximum eigen value of matrix A

a_{ij} : numerical comparison between the values i and j

Figure 18: Formula $w = (w_1, w_2, w_3, \dots, w_n)$ (Taherdoost 2017, p. 245)

4.2.2.1 Check Consistency

In the last stage, confirmation of the outcome of the AHP has to be done. The consistency ratio (CR) is computed using the formula $CR = CI/RI$, with the consistency index (CI) being determined using the method: (Taherdoost 2017, p. 245)

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

Figure 19: CI formula (Taherdoost 2017, p. 245)

The dimension of the matrix determines the value of RI, which will be derived from the table below in figure 20. The consistency ratio of less than 0.10 indicates that the comparison findings are acceptable. (Taherdoost 2017, p. 245)

<i>Dimension</i>	<i>RI</i>
1	0
2	0
3	0.5799
4	0.8921
5	1.1159
6	1.2358
7	1.3322
8	1.3952
9	1.4537
10	1.4882

Figure 20: Value of RI (Taherdoost 2017, p. 245)

5 Results

These swot analyses will help differentiating the strengths and weaknesses of battery cells that do not contain cobalt or ones that do, such as NMC and NCA. These chemistries will then be evaluated with a MCDA to define the best battery chemistry of them all when using in an electric vehicle depending on the user's needs.

The threats from the swot will be mentioning mainly new technologies, whereas the opportunities will describe the chances of them evolving with their current chemistry.

LFP was selected out of all the batteries being used in present day that did not contain any cobalt because they seemed to be the best overall and these are a few of the downsides of the other batteries: when compared to LMO, LMO has a very low capacity and a very weak performance . (Ding et al. 2019, p. 10). LTO is safe compared to LFP, but it lacks performance under high power levels. (Miao et al. 2019)

5.1 Swot Analysis for LFP, (Lithium Iron Phosphate)

Table 1: SWOT Analysis LFP

Internal	Strengths Lower cost in the long term Longer life cycle Manufacturing process cylindrical and prismatic very similar, less steps than pouch. Cobalt free, Nickel free Less degradation Durability, longer shelf life Safer Thermal runaway of 270 C Can charge up to 100% every time safely Prismatic Cell to pack, no modules Power density Small, Mid size economic EV's Abundant materials	Weaknesses Lower voltage 3.2, 3.6V Reduced specific energy, 90-120 wh/kg Heavier Mainly prismatic, but might start cylindrical shape for Ev's soon If one cell goes bad, it might compromise the pack Cold temperatures
	External	Opportunities Mix with other chemistries such as manganese Hybrid battery packs Good growth potential for future market overall Affordable EV market Recycle materials

5.2 Swot Analysis for cobalt-based cells (NCA, NMC)

Table 2: SWOT Analysis NCA NMC

Internal	Strengths Lower cost if needed in smaller packages Manufacturing process cylindrical and prismatic very similar, less steps than pouch. High energy density <ul style="list-style-type: none"> NCA 200-260 wh/kg NMC 150-220 wh/kg Reasonable life span High voltage, 3.6 to 4.2V Charging efficiency Lighter If one cell fails in pack, no big deal High performance EV's	Weaknesses More expensive than Lfp in the long term Degradation due to (DOD) and temperature Safe charge up to 80% Cylindrical (NCA) Pouch (NMC) More steps building battery packs (add modules) Less safe Thermal runaway <ul style="list-style-type: none"> NCA 150C NMC 210C Cycle life <ul style="list-style-type: none"> NCA Around 500 NMC 1000-2000 Charge and discharge up to 1C Both have cobalt, less available than FE, P Power Density
	External	Opportunities Hybrid battery packs Nickel rich, less cobalt Manganese replacing cobalt? Recycle materials

5.3 Swot Analysis Comparisons LFP vs NCA NMC

5.3.1 Cycle Life vs Cost differences between LFP, NMC, NCA

5.3.1.1 Cycle Life

According to the Article: "Will nickel reserves fulfil a growing demand for electric vehicles",

- The cycle life for NMC on average is about 1000 to 2000 cycles
- NCA average cycle life is around 500 cycles.

Although it can be inferred that NMC cells last about 50% more than the NCA counterpart and also safer (due to the manganese they contain, which supplies thermal stability), yet NCA cells are 17% less expensive and can reserve up to 30% more energy per unit weight, compared to NMC. The price variance is largely due to the cobalt utilized on each cell.

Normally, two times less cobalt is used in NCA batteries, although this difference may be narrowing as recent improvements in NCM technology focus on decrease cobalt dependency. (Sendino 2021)

According to the journal "Aging of Tesla's 18650 Lithium-Ion Cells: Correlating Solid-Electrolyte-Interphase Evolution with Fading in Capacity and Power", a series of studies took place using the Tesla Model S batteries which are the NCA Panasonic 18650. Studies were made at different C rates going from 0.33 C to 1 C at different temperatures (25°C, 40°C, 60°C). After the first 500 cycles at 25°C, 40°C, a decrease of 13% in capacity was recorded, However, after doing the same 500 cycles at 60°C, the capacity fading increased to 22%. The 46% (25C), 60% (40C), and 138% (60C) rise in direct current impedance after 500 cycles demonstrate the same pattern. Capacity fades with rising temperature and SOC during calendar aging, reaching its maximum levels at 80 percent SOC. (Uitz et al. 2017)

LFP chemistry cycle life is at least 3000 cycles. (Lima 2021)

LFP cells can have a cycle life that can go from 2000 to many times that, depending on the Depth of discharge, temperature, and C rate when discharging. (Power Tech 2021)

Depending on DOD, the number of cycles can be determined with the LFP chemistry. For example: if the cycles run at 100 DOD, they can go up to 3000 cycles, at 80%DOD they may go up to 4500 and at 60% DOD, 10 000 cycles could be achieved. (Power Tech 2021)

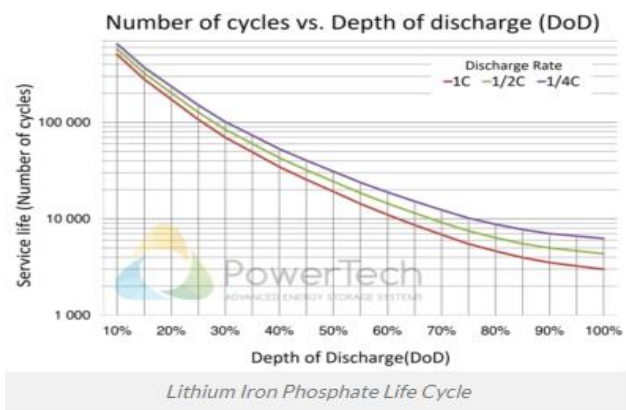


Figure 21: No. of cycles vs DOD (Power Tech 2021)

When a battery in an electric vehicle reaches the end of its usable life, it still has around 80% of its SOH. Battery makers aspire for a longevity of up to 15 years, the average lifespan is presently about 8–10 years. (Volan et al. 2021)

5.3.1.2 Cost per kWh

The majority of EV manufacturers utilize NMC battery cells; Tesla employs NCA (Roberts 2021)

According to the report: “Tesla’s cost per kWh for cells from suppliers revealed, and it’s much lower than competitors” from March 2021, Tesla packs buys cells for around 142 dollars, 120 euros per kWh, while the whole pack which includes modules costs them around 187 dollars, 158 euros. . (Klender 2021)

Tesla obtains most of their battery cells from a third-party manufacturers such as: Panasonic, LG Chem and CATL. Due to the huge volume at which Tesla purchases these cells, they pay much less per kWh than most of their competitors.

GM cell price per kWh is 169 dollars, 143 euros and their packs around 207 dollars, 175 euros. . (Klender 2021)

Other competitors besides these two companies pay around 186 dollars, 157 euros per kWh and for a pack, 246 dollars, 208 euros. (Klender 2021)

The majority of EV’s use NMC in their battery packs.

Ultium cells from General Motors employ an NMCA chemistry, NMC with aluminium, this results in 70% less cobalt concentration. (Abuelsamid 2020)

On the other hand, LFP is a lot less expensive than the cobalt-based chemistries, as reported on the article: “This is why BYD Blade battery is ahead of competition”, the price of a battery pack made with LFP could range from 55 to 85 euros per kWh. (Lima 2021)

BYD has a new technology where they skip the modules and go straight from cell to pack which will be mentioned in the later chapters.

As shown in the above data, the battery pack that is less expensive is the one with LFP chemistry followed by the NCA and then NCM which is the most commonly used.

If a manufacturer wants to build a battery pack that for example has 50kWh, the manufacturer will have to pay around 2750 to 4250 for one that contains LFP cells, for the same 50kWh with a NCA chemistry with the price that Tesla can get for example, it will cost about 6000 euros. General Motors was mentioned, and their cells contain aluminium which as stated earlier, cut 70% out of the cobalt used by other manufacturers in the NMC cells, so a pack with 50 kWh NCMA would be at around 7150 euros at their price. And lastly, according to the quoted estimates and assuming that the rest of manufacturers use NMC at 208 kWh per pack, an NCM battery pack that an average manufacturer pays for 50 kWh would cost 10400 euros.

There has to be also consideration the cycle life in the total cost when a customer purchase any of these battery chemistries. LFP can achieve a lot more cycles than NCA and NMC.

5.3.2 Prismatic vs Cylindrical vs Pouch Cells

Another major difference between the use of the LFP vs the cobalt based li-ion battery cells in electric vehicles is the shape which are cylindrical and prismatic which have very similar manufacturing processes if not identical as shown on the manufacturing chapter and less steps than the pouch cells. (Locke Marc et al. 2018) But they do have some differences when it comes to the shape that will be discussed in this chapter. Li-ion (NCA, NCM) are used in cylindrical shape, according to (Lima Pedro 2020). And there are new LFP technologies which are barely being manufactured in China and the main ones come from BYD and CATL, both prismatic. (Xiao 2020)

According to Beck Anton cylindrical and prismatic have their own advantages and disadvantages when comparing to each other, these include the following:

Cylindrical advantages:

- Cylindrical cells have an advantage of being able to be manufactured faster and have a lesser cost per kilo watt hour.
- Even though cylindrical cells do not have a large capacity, there are thousands of them connected in series and in parallel in a battery pack, this means that designers and engineers of such battery packs do not have to worry about the pack not working properly if one or two cells goes bad. It would have a minimal effect.

- Because of their cylindrical shape, cylindrical Li batteries tend to dissipate heat (and hence manage their own temperature) easier, compared to prismatic cells.

Cylindrical disadvantages:

- In the long run, (NCA) cylindrical cells might cost more than prismatic, if the prismatic cell has is composed of lithium iron phosphate.

Prismatic cell advantages:

- Prismatic cells have large capacity, when connected together with other prismatic cells, makes it relatively simple to do so such as if it is needed to make a 12 volt module, for example 4 cells would be needed in series.

Prismatic cell disadvantages:

- Having a large volume though, comes at a price. However, this is especially true when it comes to what occurs if something goes wrong. If one cell in a prismatic battery fails for whatever reason, the whole battery pack of which it is a part is effectively jeopardized, and therefore the EV would also will not work properly.
- Because of the way prismatic cells can be arranged next to each other, this undoubtedly increases capacity, but it also increases the likelihood of design inconsistencies and short circuiting.
- The greater size of the prismatic cell may be appealing in some applications, but it also reduces the likelihood that such a battery will be utilized in a fully automated system. The bigger cell size also causes arguably the most significant drawback for prismatic batteries: the higher capacity makes it considerably more difficult for the battery management system to effectively balance heat and avoid the battery from overcharging.

(Beck 2019)

Pouch cell advantages

- Where one cell fails, another one takes its place, and the cycle continues. Single defective components can be replaced while the remainder of the system continues to work normally. This enhances the system's dependability.
- Comparatively to cylindrical cells, pouch cells have a considerably higher energy storage capacity per unit of physical space.
- A pouch battery may be used for almost any purpose, depending on its shape and parameters.
- Pouch cells are often lighter than prismatic or cylindrical batteries.

Pouch cell disadvantages

- Stacking pouch cell batteries are significantly more difficult to produce than flat pouch cells, thus this is a test of the battery manufacturer's production process. (Lam 2019)

- To prevent damage from sharp edges and because pouch cells are made of soft material, they require a support framework. (Arar 2020b)

5.3.2.1 How are they arranged in packs?

5.3.2.1.1 Cylindrical Packs

When merging cylindrical cells into modules, then packs, the circular cross-section of the cell prevents us from using the space available efficiently. Because of this, the density of a battery pack containing cylindrical cells is poor. Thermal management of a pack of cylindrical cells, on the other hand, can be simplified since the spaces in between the cells allow coolant to move freely around the cells within a battery pack. (Arar 2020b)

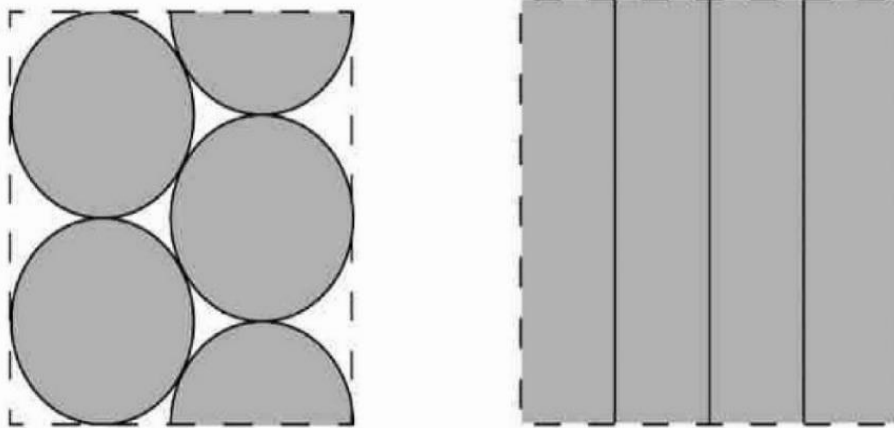


Figure 22: Cylindrical cells (Arar 2020b)

5.3.2.1.2 Pouch Packs

As stated above by (Lam 2019), A pouch battery may be used for almost any purpose, depending on its shape and parameters.

Compared to cylindrical and prismatic battery packs it can be shown in the pictures that the pouch battery pack is similar to a prismatic pack, but the pouch and cylindrical packs so far need modules before they are assembled to complete the pack.

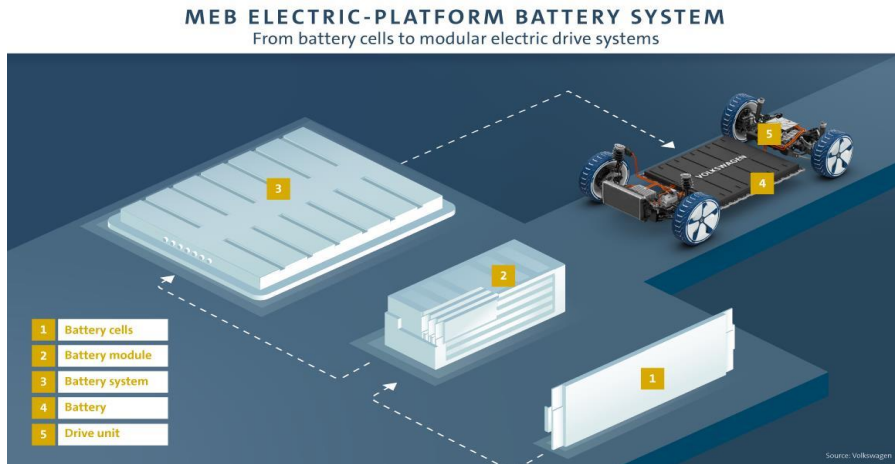


Figure 23: Pouch Cells (Accelerating Microscopy 2019)

5.3.2.1.3 Prismatic Packs

When merging prismatic cells into packs, the cell box-like form allows for the most efficient use of available space. However, this optimum space comes at the expense of more difficult heat management. This is due to the lack of space voids between the cells, which are present in a pack of cylindrical cells. (Arar 2020b)



Figure 24: Prismatic Cells (Arar 2020b)

5.3.2.1.3.1 Cell to Pack

Many companies like CATL, LG Chem, SVOLT planned or have created rumours that they are working on this new technology to save costs and manufacturing processes with either cylindrical or prismatic cells when building the pack. However, there has been only one company that has made this into reality with lithium iron phosphate chemistry using their own prismatic cells. (BatteryBits 2020)

The traditional battery production process involves building battery packs from cell to module, then from that module to the whole battery pack. This intermediate phase separates the battery into distinct modules, each with its own battery management and diagnostic systems. This permits cell malfunctions to be managed at the module level and allows modules to be changed individually rather than as a whole pack. Modules can also offer structural assist for the pack. However, the advantage of this design is that a module's terminal plates, side plates, and internal connections take up space and weight. In a traditional battery pack, this restricts the GCTPR (gravimetric cell-to-pack ratio) to 77 percent or less, while the VCTPR (volumetric cell-to-pack ratio) is generally about 50 percent, but may be as low as 40 percent. The extra steps required for assembly raises the production cost. (BatteryBits 2020)

Module-free batteries have gained popularity as a result of better manufacturing technologies at the material and cell levels, as well as an upgraded battery management system (BMS). Battery packs are built directly from cells using CTP technology, eliminating the requirement for modules. CTP technology is being investigated by a number of battery manufacturers, including BYD Auto, CATL, LG Chem, and SVOLT. However, BYD, a Chinese battery company has already accomplished this and has been able to manufacture an EV called Han already with this new. (BatteryBits 2020)

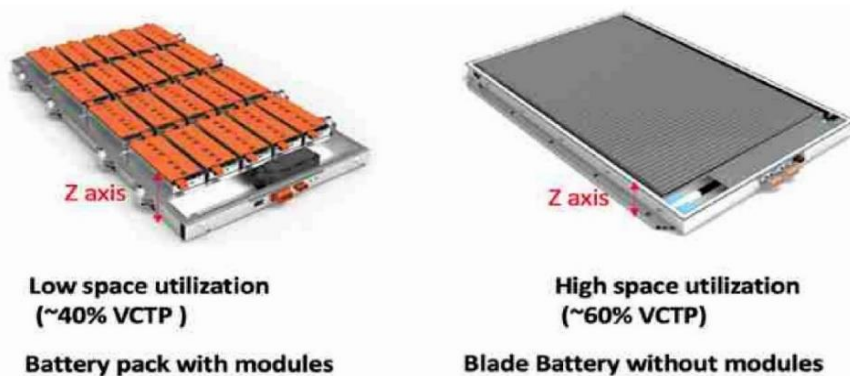


Figure 25: The Next-Generation Battery Pack Design (BatteryBits 2020)

5.3.3 Main cathode materials found in NCM, NCA, LFP, the good and the bad

One of the main points when deciding on the battery chemical properties for a future EV might depend on the main materials that are blended into the 3 types of cells. In this chapter, the major materials will be looked at and will be discussed why or why not we may take them

into consideration. The main materials aside from lithium that will be discussed are cobalt, nickel, manganese and iron. Cobalt and nickel can be found in the NCA and NMC chemistries. Aluminium oxide can be found in NCA. NMC for the most part is composed of almost equal parts of cobalt, manganese and nickel. (Cobalt Institute 2021). In some new ratio compositions like the NMC811, nickel is 80%, manganese 10%, and cobalt 10%. (Miao et al. 2019). LFP contains LiFePO_4 olivines.

5.3.3.1 Cobalt in NCA, NMC

Cobalt is a glossy material that can be found in the cathode, the negatively charged electrode, it is also characterized for its short supply, and it is very toxic. Cobalt is expensive, heavy and associated with unethical mining operations. It can have a dramatic cost inconstancy and a fragile supply chain. It is no surprise, that most battery manufacturers want to get rid of cobalt in their production lines. However, the material is very important when stabilizing batteries and increasing their energy density. (Oberhaus 2020)

Cobalt can make up one-fifth of the material found in the cathode, which mainly comes in 2 types of batteries and those are the NMC and the NCA chemistries. The cobalt in these cells act as a stabilizer that prevents the cathode to corrode, which can lead to battery fire. It can also increase the charging rate of the cell, but like mentioned before, the material is quite expensive and difficult to obtain. It also carries certain social issues. Almost sixty-six percent of the world cobalt is produced as a by product of large-scale nickel and copper mining in the Democratic Republic of Congo. Nevertheless, the Democratic Republic of Congo also has a considerable number of artistic and independent miners that work efficiently without being detected. This has resulted in many human right violations in the Congolese cobalt mines, mainly for the employment of children. (Oberhaus 2020)

The Democratic Republic of Congo has more than half of the world's reserves of cobalt (7.1 million metric tons). Following by Australia with 1.4 million metric tons. (Garside 2021a)

Ranking overall 32nd between metals worldwide, and not particularly uncommon, cobalt has been very sought after lately because of it being integrated in car batteries, ceramics, alloys, among other applications. Worldwide demand for cobalt for 2025 is expected to be 117,000 tons, not to mention another 105,00 for other various uses. The demand for this material for use in electric vehicle battery cells has had a big effect in its price, making it expensive. (Garside 2021a)

Cobalt particles may potentially have an impact on ecosystems if they accumulate in fruit or plant seeds grown in polluted soils. Cobalt comes into touch with soil, water, rocks, and

plants in the natural environment, and once there, it cannot be eliminated. (Farjana et al. 2019)

5.3.3.2 Nickel in NCA, NMC

Nickel is an important element in lithium-ion batteries, which are utilized in EV's. It allows manufacturers to utilize less cobalt, which is more expensive and has a less transparent supply chain, while yet packing more energy into batteries. (Li 2021)

Nickel is mostly utilized in the production of high-quality steel but is also progressively being employed in EV batteries. The global mining output of nickel was expected to equal 2.5 million metric tons by 2020. Nickel deposits have the fewest life years of any metal or mineral, however, because it is easy to recycle, this is less of a concern. (Garside 2021b)

Excessive exposure to blends of water-soluble and more complicated nickel blends that can not be mixed, has been linked to having an increased risk of respiratory cancer in employees that have to do with the mining manufacturing, refining and also in the development of sulfidic nickel ores. There has been no tracks of respiratory cancer risks having to do with alloy manufacture, electroplating or with workers that work in lateritic ore refineries.

However, there was a study made by the INNCOM, International Committee on Nickel Carcinogenesis in Man that researched the risks in 10 groups of approximately 80,000 nickel manufacturing and nickel processing employees and they found a link between the employees that were exposed to certain oxidic and sulfidic water-soluble nickel blends, and respiratory cancer. There was no link between the exposure to metallic nickel. Other forms of nickel chemistries seem to have different carcinogenic effects and strengths in these studies. (Buxton et al. 2019)

According to the paper "Life cycle assessment of cobalt extraction process" cobalt mining steps were analysed in contrast with those of nickel and after evaluating the results, nickel was found to affect more in the sense of global warming, eutrophication and ecotoxicity. The logic for these outcomes is because nickel extraction is the most energy-intensive operation, requiring high and low voltage electricity derived from coal, hydropower, and heavy fuel oils, all of these cause harm ecosystems and contribute to global warming. (Farjana et al. 2019)

5.3.3.3 Aluminium Oxide in NCA

Despite the fact that aluminium is the second most prevalent metallic element in the Earth's crust after silicon, it is a relatively recent industrial metal that has only been manufactured in commercial amounts for a little more than a century. (USGS 2020)

In NCA composition, the role of the aluminium mixed in the cathode is to increase the overall thermal and structural ability of the cell. (Westfälische Wilhelms Universität 2021)

5.3.3.4 Manganese in NMC

Manganese is very important when it comes to the manufacturing of steel which will keep increasing over time. It is commonly utilized in metallurgy and its the fourth metal mostly used after iron, aluminium and copper. In addition, during the last 10 years, the world has generated a rising amount of steel.

Manganese market will also be growing due to the demand for lithium batteries such as NMC and nickel-metal hydride (NIHM) for the EV sector. (Palaside Research 2017)

Long term Manganese poisoning is a known health risk that is linked with manganese ore mining and manufacturing. Despite the fact that food and water are the most common sources of Mn exposure in humans, others may include air contaminated with emissions. Mn toxicity has been connected to motor skill impairment, cognitive problems and metabolic abnormalities. Mn long term effects on the health of children that live around mining regions and contamination in the environment are of serious concerns. (Duka et al. 2011)

5.3.3.5 Lifepo4 Olivines in LFP

On the other hand, Lithium iron phosphate contains iron, and cathode blends that are based in iron are very promising as there is plenty of Fe available, it is less toxic and less expensive compared to the other materials mentioned above. The LiFePO_4 phospho-olivine is now under thorough study, because to its inexpensive cost, low toxicity, excellent thermal stability and high capacity of 170mAhg^{-1} . (Buxton et al. 2019)

LFP also has a superiority over the chemistries that contain cobalt and that is that it contains iron and phosphate, which are very accessible and can be found easily. (Li and Ma 2019, p. 3)

On the journal "Environmental impacts of electric vehicle batteries weighed up", studies were conducted between LFP and NMC chemistries. LFP provided more overall environmental advantages, owing to its longer lifespan and the use of components that are less harmful to the environment when mined and/or acquired. (Majeau-Bettez 2011)

5.3.4 Safety

When it comes to safety, lithium iron phosphate is a relatively safe chemistry, making it more stable than other lithium chemistries when used in the form of a cathode in the cell. Thermal runaway is considerably minimized using lithium iron phosphate, a phenomenon that occurs when the chemical reaction inside a battery cell exceeds its ability to distribute heat, following in an explosion. Thermal runaway could happen when a cell has an internal defect,

it has been used in high temperatures, has been over charger or it has been damaged somehow. (Lindsay 2018)

The thermal runaway temperature of lithium iron phosphate is 270°C, which is considerably higher than that of other lithium batteries (as shown on the table below). LFP battery cells could be charged and discharged fast, and this would only produce relatively low heat. These batteries can sustain higher temperatures without degradation, and they need less ventilation. When accidentally exposed to oxygen and somehow the casing is pierced or broken, the LFP chemistry has no reaction with oxygen, and so it does not generate an explosion or fire. (Lindsay 2018)

Because LFP lacks cobalt, a chemically unstable material, it could be said that this chemistry is very safe. Lithium batteries that contain cobalt or manganese tend to degrade at considerably lower temperatures, releasing significantly more potentially harmful energy. In normal battery operation, cobalt based li ion batteries create heat, increasing the risk of thermal runaway. A cobalt fire efficient extinguisher does not exist yet, the only alternative would be to let it burn out on its own. However, if an LFP battery fire arises, it may be extinguished using a standard water sprinkle system. (Lindsay 2018)

“NMC Thermal runaway is 210°C (410°F)” (Battery University 2010)

“NCA Thermal runaway is 150°C (302°F)” (Battery University 2010)

NMC	★★★	210°C(410°F)
LFP	★★★★★	270°C(518°F)
NCA	★★	150°C(302°F)

Figure 26: NCA,NMC LFP Thermal Runaway (linda 2020)

5.3.4.1 Safety and Energy Density

According to the article: Investigating the Role of Energy Density in Thermal Runaway of Lithium-Ion Batteries with Accelerating Rate Calorimetry, energy density plays a big role when it comes to battery safety. (Lamb et al. 2021, pp. 8–9)

A few experiments were conducted including NMC, NCA and LFP where they used in the form of 18650 cells heating them up 50C and then incrementing the temperature 5C at a time, followed by a 30-minute holding at this temperature until the total temperature reached 400C. And according to the results obtained at the end, they have concluded that their

research shows that thermal runaway reactions can have significantly linked to the density of energy in certain battery cells with different chemistries. Increase in energy density will have an effect to a higher thermal runaway aftermath. As the heat release is dramatically quicker with a larger energy density, thermal runaway may be simpler to surpass any heat dissipation into the environment, which might lead to more damage (Lamb et al. 2021, pp. 8–9)

NCA batteries has currently energy density of 236 to 260 WH/kg being used by different Tesla models. (Ding et al. 2019, p. 9)

Current technologies indicate that the energy density of commercial NMC lithium batteries is about 200 WH/kg, NCA has a bit more, it will most likely hit 300 WH/kg soon, while the energy density of the LFP lithium batteries is nearly 100~110 WH/kg, but new technology could achieve 130~190Wh/kg, but never more than 200Wh/kg. (Huang 2020)

So, as it can be shown, The NCA chemistry has the highest energy density, but also the least thermal runaway, followed by NMC in the middle and last but not least the LFP which has the least energy density so far, but this is why it can be considered the safest out of the three chemistries.

5.3.5 Specific Power Comparison

In this chapter there will be a small description of what specific power is and a small comparison between the 3 chemistries (LFP, NCA, NMC)

Engine performance is measured by the specific power or power-to-weight ratio. Typically expressed in terms of W/kg or hp/lb, it is the product of the power output and the mass of the machine. There is a definite power value that is independent of the vehicle or power plant's size with this value: Specific Power= Power/Mass. (Afework and Hanania 2018)

A regular cell with the NMC chemistry was rated to have a specific power of 2300 W/KG (Nikolian et al. 2016)

According to the paper "Thermal Managements System", LFP cells have a nominal specific power of 2400 W/kg (Alaoui C. 2017)

NCA batteries have an range of 1500-1900 W/Kg (Warner 2015, p. 77)

5.3.6 Operating in winter temperatures comparison LFP vs NCA, NMC

Different lithium battery chemistries have different energy densities, therefore different performance while in use. But can other factors have an effect on LFP, NCA and NMC? This chapter will discuss about the different effects the weather may have on these 3 battery

chemistries. When it comes to higher operating temperature however, LFP has an advantage over NCA, NMC because it has a higher thermal runaway as it has been discussed on the safety chapter. (Huang 2020)

LFP does have a higher temperature resistance, but the NCA/NMC has a greater resistance to a low temperature. The Lithium NMC battery can release a capacity of 70.14% at a temperature of -20°C ; the Lithium Iron phosphate battery (LFP) can release just 54.94%. The NMC lithium battery's discharge voltage is much greater, starting earlier than the low-temperature LFP battery. For applications with low temperatures, NMC battery is therefore a preferable alternative. (Huang 2020)

In the journal: "Effects of temperature on charge / discharge behaviours of LiFePO_4 cathode for Li-ion batteries" where the researchers made some experiments based on the LFP chemistry in different temperatures, where at the same temperature they charged and discharged the batteries at 20°C , then at 0 , -10 and finally at -20°C . In their experiment, they concluded, that as the temperature went lower, so did the capacity dramatically, mainly at -20°C . Their findings in the picture below, demonstrate that the temperature influence on the LFP electrodes discharge behaviour is more severe than when charging as well as the impact of the lithium-ion diffusion among solid phase requirement for more activation energy from charge-transfer during the discharge process. (Lixia Liao 2021, pp. 271–273)

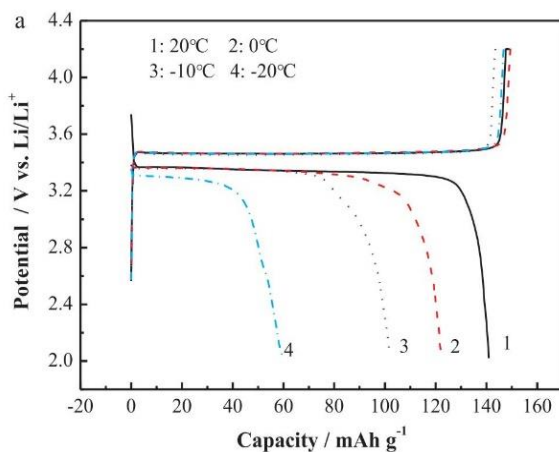


Figure 27: Li ion Temperature Effects (Lixia Liao 2021, p. 271)

5.3.7 Degradation Comparison (LFP vs cobalt-based Li ion)

5.3.7.1 Factors that affect lifespan of the cell while in Storage

5.3.7.1.1 Self Discharge and temperature

Self-discharge rate depends mostly on the chemistry and the kind of battery being considered, the rate goes up with the battery cycling number and age. Normally, Li-ion cells

lose 5 percent of their charge after the first 24 hours, after that they lose about 1 to 2 percent each month in addition to the 3 percent loss caused by the safety circuit. The 3 major factors that influence self-discharge rate are temperature, SOC and DOD during storage and cycling. Depending on how high the battery discharge-rate is, the higher there will be a capacity loss. Meaning that the battery will deteriorate as it contains smaller accessible energy from the same input. Abnormal elevated self-discharge rate can be related to a battery that is no longer working properly. (Xiong 2019a, pp. 23–24)

Self-discharge processes are important for battery manufacturers to understand because they come in a variety of forms and involve various levels of power loss in single batteries. To prevent battery failure in a battery system that is made up of multiple battery cells, the self-discharge rate of each and every cell must be tested. Furthermore, to prevent elevated self-discharge, batteries should be stored at the correct temperature and SOC. (Xiong 2019a, p. 24)

In short, to reduce Li-ion battery self-discharge, the battery temperature should be kept close to 0 °C, as an increase in temperature speeds up this process. To prevent harm done to the battery caused from deep discharge and full discharge, the SOC must be kept between 40 and 60 percent. (Xiong 2019a, p. 26)

The most common cause of battery capacity loss while storage is in fact temperature. Thermal breakdown of the electrodes and electrolyte occurs at high temperatures. Degradation of the electrolyte thickens the SEI film on the anode, eating up lithium ions, increasing cell IR, and lowering the capacity. Furthermore, gases are produced during the breakdown, increasing the internal pressure in the cell and posing safety concerns. Temperatures over 30°C are considered harsh conditions for lithium-ion batteries and can result in considerable battery calendar-life loss. Li-ion batteries should be stored at temperatures ranging from 5°C to 20°C to maximize battery life. (Xiong 2019a, p. 33)

For LFP, however, they do not show a high over charge rate, even for extended lengths of time, there is no issue to store them for a year, one just has to make sure it is charged before putting it away with about 50 to 60 % would be preferable, since this will allow the battery a very long time before this LFP battery would give any signs of self discharge.

Storing batteries below freezing is permissible, even at extremely low temperatures such as -40 degrees, or even lower! Because the electrolyte of LiFePO₄ cells is not aqueous and so it does not expand or harm the cells when it freezes (which can occur at temperatures as low as -40 degrees Celsius depending on the formulation). Just let your battery to warm up a little before you reboot, which is OK around -20 degrees or higher. When discharging at below-freezing temperatures, there will be a noticeable loss of capacity that will reverse

when the battery temperature rises above freezing, as well as a slightly faster impact on aging. It is surely much preferable to store them at low temperatures than to store at high temperatures: At cold temperatures, calendar aging slows considerably. These batteries have to not be stored above 45 degrees and at full charge as well. (Solacity Inc. 2018)

5.3.7.1.2 State of Charge

For maximum storage life, batteries should be stored with a 40% charge (3.6 V) (Hoffart 2008)

For LFP, 50 to 60% charging while stored would be preferable (Solacity Inc. 2018)

Everlasting capacity loss refers, as the name suggests, a damage that will not revert back by charging the battery. The permanent capacity degrading is mainly caused by the charging and discharging cycles that can be fully made, cell temperature and voltage. The more often the charge stays at 4.2V, or fully charged 3.6 V for Lithium iron phosphate, the quicker the loss of capacity will occur. This is a fact also weather the battery is kept charging and it is already at full capacity or its stored fully charged, which leads to shorten the battery lifespan.

So in this case, not one battery has advantage over the other, capacity loss is inevitable on all battery types but may be decreased by implementing good battery habits when charging or discharging of the battery and even storing it. Partial discharge cycles can noticeably increase cycle life and battery life can be prolonged by charging to a bit less than 100%. (Hoffart 2008)

5.3.7.2 Factors that affect lifespan of the cell While in Cycle

5.3.7.2.1 Depth of Discharge (DOD)

Often, manufacturers use the 80-20 DOD formula to charge a battery. This indicates that only 80% of the battery charge is conducted while the other 20% is left over to prolong the battery life. Although lower DOD could prolong Li-ion battery life, not enough DOD can follow a poor battery run time and this leads to not being able to complete determined tasks. Manufacturers recommend 50% DOD while cycling to get the highest potential of the battery life, also is recommended to perform optimal maintenance. (Xiong 2019a, 37,38)

Depth of discharges over 50% are considered deep discharges. When Li-ion cells are discharged from 4.2V to 3V, a 95% of their energy is lost, and if its eventually used like this continuously, it would have a very short lifespan. Discharging from 100% to 0 should not be done if the battery life wants to be prolonged, doing so in smaller percentages is better for the battery's life cycle and can reduce the capacity loss. (Xiong 2019a, p. 37)

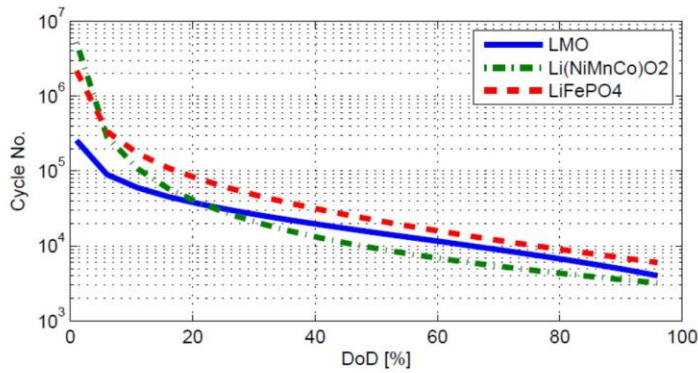


Figure 28: Li ion DOD (Xiong 2019a, p. 37)

The cycle life of Li-ion batteries is affected tremendously by the depth of discharge (DOD). Deep discharges lead to stress and pressure in the Li-ion cells that can impair the negative electrode. This leads to an increase of capacity loss and irreversible cell deterioration. If the DOD is increased, that will affect the battery life cycle by making it shorter. (Xiong 2019a, p. 37)

On the other hand, LFP batteries can be charged and discharged safely to 80% DOD and not to 50% like the other Li-ion batteries containing cobalt. According to the Journal: Capacity Fading Mechanism of The Commercial 18650 LiFePO₄-Based Lithium Ion Batteries, where they conducted a series of tests using commercial 18650 LiFePO₄ cells, under regular cycling conditions, all used from the exact batch, that made sure that all the materials and the manufacturing processes would also be the same. (Liu Qi et al. 2018)

Sample	1 st cycle	After 500 cycles	After 1000 cycles	After 1500 cycles	After 2000 cycles	After 2500 cycles
Capacity retention after cycle ¹ (%)	100	97.4	90.2	89.2	86.1	79.3
Capacity retention after cycle ² (%)	100	97.5	91.2	88.2	85.6	79.8

¹ Capacity retention vs cycling number obtained from the electrochemical data

Figure 29: LFP Cycle Capacity (Liu Qi et al. 2018)

As it can be shown on table 29, even after 2500 cycles, the LFP batteries that were tested kept almost 80% of their capacity.

According to the experiment, physical deterioration of the LiFePO₄ cathode and graphite anode is very uncommon to occur until the cell reaches 80% of its initially capacity, the primary cause of capacity loss is the loss of lithium-ion source active in the system whereas the FePO₄ phase appears proportional to the decrease in

lithium ion source available in a cycle; The deterioration of solid solutions, which is connected with the degeneration of LiFePO₄'s speed performance at higher cycling numbers, is apparent with the increased cycle numbers. (Liu Qi et al. 2018)

5.3.7.2.2 Over Voltage

High voltage charging provides high capacity and allows longer battery cycles in Li-ion batteries, nevertheless, is not advised to do so. Charging the cells over 4.1V creates lithium plating, this diminishes the number of lithium ions while forming metal lithium in the anode. This not only reduces the capacity of the battery, but also could lead to internal short circuits and fires. The higher the voltage, the quicker the capacity will decrease and will also lead to reduced lifespan. (Xiong 2019a, p. 38)

A voltage over 4.10 V is reflected as high voltage in most Li-ion batteries and increases considerably loss of performance of the battery. The lower charging voltage extends the lifespan of the battery but gives the user fewer run times. In addition, Li-ion batteries should not be discharged under 2.5V. The optimum charging voltage is 3.92V, enabling the batteries to last longer. (Xiong 2019a, p. 39)

Charge level (V/cell)	Discharge cycles	Available stored energy
[4.30]	[150–250]	[110–115%]
4.25	200–350	105–110%
4.20	300–500	100%
4.15	400–700	90–95%
4.10	600–1,000	85–90%
4.05	850–1,500	80–85%
4.00	1,200–2,000	70–75%
3.90	2,400–4,000	60–65%
3.80	See note	35–40%
3.70	See note	30% and less

Figure 30: Li ion Over voltage (Xiong 2019a, p. 39)

For a comparison against the LFP chemistry, in many research papers and for example such as the one quoted above from (Liu Qi et al. 2018), the LFP cells can be fully charged to their 3.6V max, and this can be safely done to charge to 100% SOC every time and safely without any drastic capacity loss over time, unlike the cobalt based li-ion cells. as seen also on the graph above that shows the kind of capacity loss they would show if charged at 100% constantly. (Liu Qi et al. 2018)

5.3.7.3 Overall

According to the Journal: Degradation of Commercial Lithium-Ion Cells as a Function of Chemistry and Cycling Conditions, the lifespan of LFP batteries is longer than that of li ion batteries, specially NMC. These figures contradict the general idea that li-ion batteries last longer and are more durable. A few tests were created at the Sandia National Laboratories, under very strict conditions. Lithium batteries of both kinds were frequently discharged and charged from 0 to 100 percent. According to the paper, the LFP cells display significantly higher cycle life spans. Temperature, depth of discharge (DOD) and charge current were examined to determine how it affected the long-term deterioration.

All cells were charged and discharged at 0.5 C rate for 2 hours, the amount of time required to deplete a battery's capacity.

On figure 31, it clearly shows that the discharge capacity retention for the LFP battery (blue dots) considerably outweighed the NMC battery (black dots) of each of the charge and discharge cycles. The graph shows that the NMC declines nearly twice as fast as the LFP, demonstrating the LFP higher overall performance.

LFP outperformed NMC in terms of round-trip efficiency, which was determined by dividing the discharge energy by the charge energy. This calculation demonstrates that the LFP is more efficient and cost-effective option.

This experiment also included a lithium nickel cobalt aluminium oxide battery, or NCA, which performed similarly to or worse than NMC.

NMC and NCA cells both showed a high reliance on the depth of discharge, with NMC cells being more sensitive to complete state of charge range cycling than LFP cells.

(Preger Yuliya et al. 2020)

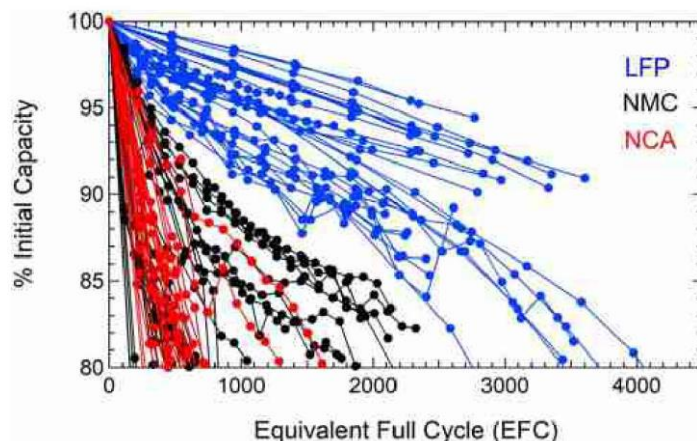


Figure 31: Degradation of Commercial Lithium-Ion Cells (Preger Yuliya et al. 2020)

5.3.8 Opportunities for LFP, NCA, NMC

5.3.8.1 New Mixes of Materials

5.3.8.1.1 LMFP

As it can be shown on the previous chapters, LFP is far better when it comes to safety compared to cobalt-based Li-Ion chemistries, but the downside is that it lacks energy density. Nonetheless, adding materials to the mix to upgrade the energy density can be possible and a company in Australia, VSPC appears to be successful by adding manganese to their mix, LMFP. (Birney 2020)

As stated in the article: "Lithium Australia ups battery performance with manganese", their new LMFP battery cell would be the high volt model of the regular LFP, containing 25% higher energy density without affecting the battery's excellent characteristics. Something that according to the firm, the other big LFP cell manufacturers world-wide are still aiming for fiddling with manganese addition. (Birney 2020)

According to Lithium Australia Managing Director, Adrian Griffin, VSPC patented technology has demonstrated great success in synthesizing LMFP battery cells with high energy density compared to regular LFP and keep the excellent safety features. He also said that VSPC will give their customers the better mix of safety, energy density and low cost.

On the safety side, Lithium Australia stated that lithium-ion batteries, or "LIB," may be classified depending on the crystal structure of the cathode materials used in the battery cell. According to Lithium Australia, although the improved chemical composition and crystal structure enhances the safety of the LFP and LMFP battery cells, the use of manganese, iron, and phosphorous over nickel or cobalt saves cost and provides a more dependable supply chain.

VSPC is also aiming to further decrease its costs and enhance sustainability through evaluation of the usage of industrial waste materials as feedstocks for the new range of battery cathode LFP and LMFP powders. (Birney 2020)

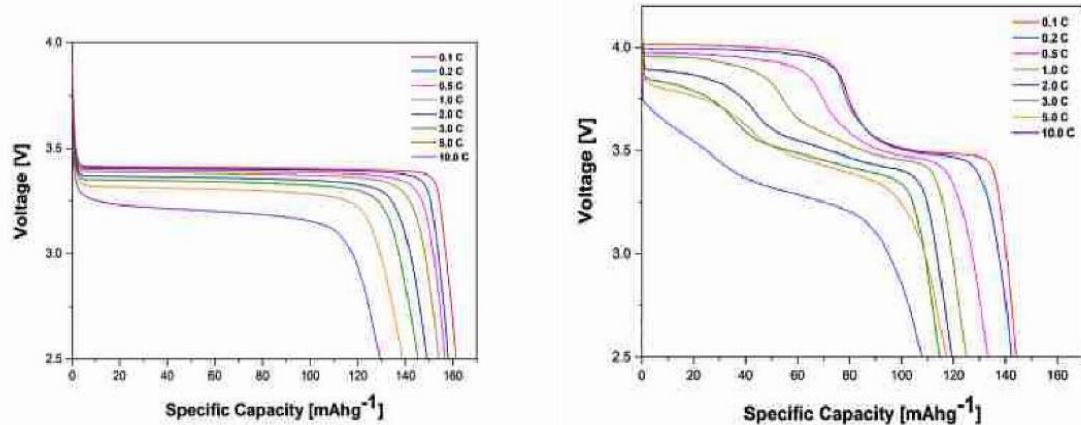


Figure 32: LMFP Testing (Lithium Australia 2021)

The discharge curves shown above are presented for VSPC LFP cells (left) and LMFP made from VSPC (right). In comparison to LFP cell voltages (energy density is approximated by area beneath curves), the greater energy delivery of LMFP cell results in an increase of energy density up to 25 percent. (Lithium Australia 2021)

This company announcement from May 2021 shows that this technology will be in the testing phase soon after, giving the chance to a number of VSPC clients to do so in the EV sector. (Lithium Australia 2021)

5.3.8.1.2 Nickel-Rich Cathodes

Initially, lithium-ion batteries consisted of lithium cobalt oxide cathodes and graphite anodes. Cobalt has been substituted by other metals such as manganese, nickel and aluminium. This was how current NMC and NCA cathodes were created for electric cars used today. Inactivity and stabilization of Mn and Al is maintained. When added to the cathode, they enhance the characteristics and can achieve more cycles.

The higher Ni content increases the amount of Li that can be cycled in and out of the cathode without producing structural instability and thus, the energy density increases. Nickel in the most part can replace cobalt, which is more expensive and today, most state-of-the-art cathodes contain up to 80 percent nickel, which is manufactured in bigger quantities, and has a geographical advantage, however, these cathodes may have some threats when cycling and in their thermal stability.

The industry is increasing the manufacturing of NMC and NCA batteries in the following areas with regard to the decreased cobalt content: NMC532 which has 50% nickel, 30% manganese and 20% cobalt, NMC622, NMC721 and NMC811 which has the least amount of cobalt at 10% and 80% nickel. (Biswas 2020)

According to Fred Lambert's article from Feb 2021, Tesla is looking into nickel rich cathode formulas, and it is planning to join a new supply chain with Indonesia, which is a nickel rich country. There are also talks about building a battery factory there. Tesla is looking into cutting out the most part of cobalt in their batteries and replace it with nickel. (Lambert 2021a)

There is also another new mix when it comes to NCM, and LG Energy Solution in accord to Tesla as well, is developing it. It is the new NCMA cells which contain 90% nickel. The main materials are nickel, cobalt, manganese and aluminium but with a less content of cobalt.

LG has reportedly been working on this cell for a while, which contains more nickel and less cobalt and also it is supposed to have higher in energy density.

This new battery technology is expected to be used in the new Tesla Model Y, manufactured in the Gigafactory in Shanghai. (Lambert 2021b)

5.3.8.2 Hybrid battery packs (LFP, NCA NMC)

Having two chemistries of cells in a single pack and being able to interchange between the two depending on the weather and or length of trip is now possible.

According to Inside EV's, the battery manufacturer from China named NIO announced the debut of a new 75kWh battery pack that is "hybrid". It does not have any hybrid cells, but the actual pack has 2 battery chemistries (NMC and LFP), the percentage of each chemistry in the pack has not been announced. (Kane 2021)

The reason of his mix is to have the best attributes of each cell chemistry. LFP is known for being less costly and safer, while NMC is known for having more capacity and having better performance in cold weather. (Kane 2021)

This new battery pack also has the new technology called cell to pack that skips modules in the production which in the end lowers expenses and employs that space for more batteries, this would equal to more capacity as well. (Kane 2021)

5.3.8.3 Great growth potential for future market in entry level EV's (LFP)

EV manufacturers are being aware of the LFP technology and they are recently introducing their vehicles to the market such as Xpeng, VW, the made in China Tesla Model 3, and the BYD Han. The following are just a couple of examples showing how companies are looking for other options other than NCM and NCA which contain cobalt and nickel which as mentioned before are toxic and involve human rights and are not environmentally friendly.

In the article: “Cobalt, nickel free electric car batteries are a runaway success”, it mentions how tesla stunned the EV industry when it declared that some new Model 3s would be made in China with LFP technology, made by CATL, Contemporary Amperex Technology, which appeared to be a bit strange, since tesla is known for their fast, sporty, luxury EV’s. Up until then, NCA and NCM were so popular among EV manufacturers. Elon Musk, Tesla’s CEO has made evident that he is worried about the nickel supply and then mentioned LFP to have “standard range” for future Tesla’s. Only after 2 months of being launched, the Tesla model 3 took place of 5.9% of the world’s car market, then it was introduced to the European market, and it captured 46% of all Model 3 sales in January 2021. This has saved Tesla millions of dollars due to Cobalt has increased a lot in price along with nickel.

According to this article, battery manufacturers have caught up to Tesla’s success and now are in the search for increasing LFP capacity. The new technology has also made huge steps with the cell to pack battery production, which lessens weight and process steps making up for the LFP volume. (Els 2021)

According to the article: “Volkswagen partner Gotion unveils breakthrough EV battery”, on January 2021, Gotion claimed that they were able to develop an LFP battery with 210 Wh/kg. They did not reveal the projected driving range, but a car with 190 Wh/kg can last for around 400kms on a single charge and that is good, compared to the Chinese made model 3, which has similar range. The company announced a new technology for their battery pack called JTM, jellyroll to module and it can be manufactured in different shapes and forms. Starting in 2023, the firm plans to supply a modular design for a variety of EV battery packages to manufacture Volkswagen's MEB power platform. As part of the German automaker's objective to sell 1,5 million EVs in China by 2025, the businesses entered into a cooperation in May. (Shen 2021)

5.3.8.4 Recycle materials / second life to the battery packs,

This chapter will discuss about one of the main opportunities for all type of Li-ion battery cells and the fact that they can be re-used or recycled to recover the materials found in the cathodes. This would have so much significance for the recycling of NMC and NCA mostly because this would avoid the mining of expensive and toxic materials such as cobalt and nickel. LFP could also gain from this since iron and phosphate can also be recovered, even though the materials are not toxic or as expensive.

When the first period of an EV battery life comes to an end, they will end up either being disposed of, reused or recycled to extract the costly materials. They are disposed usually because they are in poor condition or because they are in the areas where there is no option to reuse or recycle. Mass dumping is avoided in most areas due to regulations. Success in

recycling might work if the electrodes in the battery involve costly metals, such as cobalt and nickel, since the projected tight supply of nickel and future cobalt in the 2020s could create a sufficient difference between procurement and recycling costs. Although recycling as an alternate battery source could be appealing to manufacturers to ensure they will get their supply, it would be of great importance to create cost effective recycling processes that could compete with mining of raw materials. (Engel et al. 2019, NOTE2)

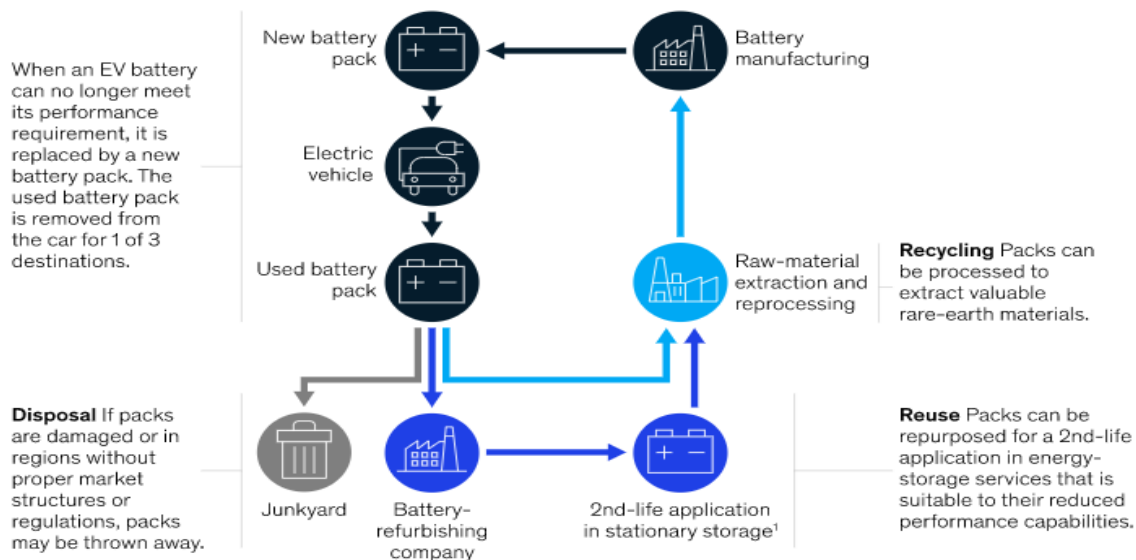


Figure 33: Second-life-EV-batteries (Engel et al. 2019, 3)

5.3.8.4.1 Recycling Materials

After their end of life in an Electric vehicle, Li-ion batteries can be recycled and this can be done by three main methods such as: pyrometallurgy, hydrometallurgy and direct recycling. which according to the journal titled: "Key Challenges and Opportunities for Recycling Electric Vehicle Battery Materials" all of these 3 methods have effect on cobalt-based Li-ion chemistry, but only direct recycling would apply to LFP. It also states that for profitable recycling of LFP based cathode materials is not possible for the use of the standard leaching technique while dissolving the black mass during the recycling processes of many popular chemicals aimed at the recovery of important materials such as: Co, Ni, or Mn. The typical complete black mass dissolution will therefore result in the loss of precious LiFePO₄ nanoparticles and the recovery of low-value components of iron and phosphate. By contrast, LFP nanoparticles may be recovered selectively from LiFePO₄ and FePO₄ (with a maintained olivine structure) nanoparticles can be recovered, followed by their re-lithiation, as the original uncontaminated material with the same activity. There is a process which is patented by a company named Hydro-Quebec in which they recycle LFP batteries where they extract the lithium and they avoid the use of highly corrosive acids by instead using CO₂ to extract the lithium. (Beaudet et al. 2020)

The main purpose of recycling is the extraction of the cathode materials, especially cobalt because of its high cost. These chemistries are preferred due to their higher value compared to chemistries such as LiFePO_4 . (Velázquez-Martínez et al. 2019)

Efforts to recycle cathode chemistries LiFePO_4 and LiMn_2O_4 have been limited, largely because of their very low manufacturing value. These chemicals nevertheless cover a higher market proportion of demand for energy with 22% for LiFePO_4 . Furthermore, between the years 2008 to 2014, the cathode chemistry market share for LiFePO_4 climbed from 4% to 9%, whereas in the same period LiCoO_2 share was dropped from 61% to 40%. (Velázquez-Martínez et al. 2019)

Basic Lithium is not a major target for LIB recycling, largely as part of the cathode materials being retrieved. Lithium is normally lost in other ways like in electrolyte form for example. The recycling process for Lithium is difficult and not followed by standard recycling procedures as it can be found in at least 2 different compounds. Furthermore, Li is not regarded by the EU as an essential material, and global Li supplies seem to be sufficient. Li recuperation is therefore at a disadvantage compared with other LIB components. Li's losses into trash, however, add to needless mining. In addition, the importance of this metal can rise and its recycling can be justified by increasing LIB demand. (Velázquez-Martínez et al. 2019)

Although the battery recycling sector is currently not particularly interested in graphite, the reintegration into the economic cycle is legitimate from the CE standpoint as it will reduce exploitation and the related environmental effect of mineral deposits (Velázquez-Martínez et al. 2019)

5.3.8.4.1.1 How much material can be recycled?

Besides direct recycling, mechanochemical treatment can also be applied in the recycling of LiFePO_4 for a better percentage recovery of metals. Spent LiFePO_4 is combined in a ball mill with inexpensive citric acid ingredients. The mixture is dissolved and filtered after grinding it in deionized water. The extraction efficiency of Li with the addition of H_2O_2 reaches 99.35 percent. In contrast, with a poor extraction efficiency of only 3.86 percent, Fe is scarcely removed, showing a selective recovery of the important Li element. Additionally, when H_2O is utilized in the place of H_2O_2 , the mechanochemical reactions and extraction efficiencies of Li and Fe reach 97.82 and 95.62 percent respectively at optimum circumstances. This straightforward and easy to use technology has little negative environmental effect and has significant promise in industrial applications. (Li et al. 2019)

Companies such as Duesenfeld, which is a li-ion battery recycling firm based in Germany claim that only cobalt and nickel are recovered in most industrial hydrometallurgical methods currently used for treatment of the black mass. In these processes, lithium manganese, and graphite may be lost in the material cycle. Duesenfeld has created and patented its own technique which makes full cycle management possible through the development of electrode-active battery grade raw materials. (Duesenfeld 2021)

They claim to be able to achieve up to 72% percent of material recovery through their mechanical recycling process, while in addition to also their hydrometallurgical process they claim to be able to attain up to 91%. Just elements that have high boiling points are unable to be recycled such as electrolyte materials and the separator film. (Duesenfeld 2021)

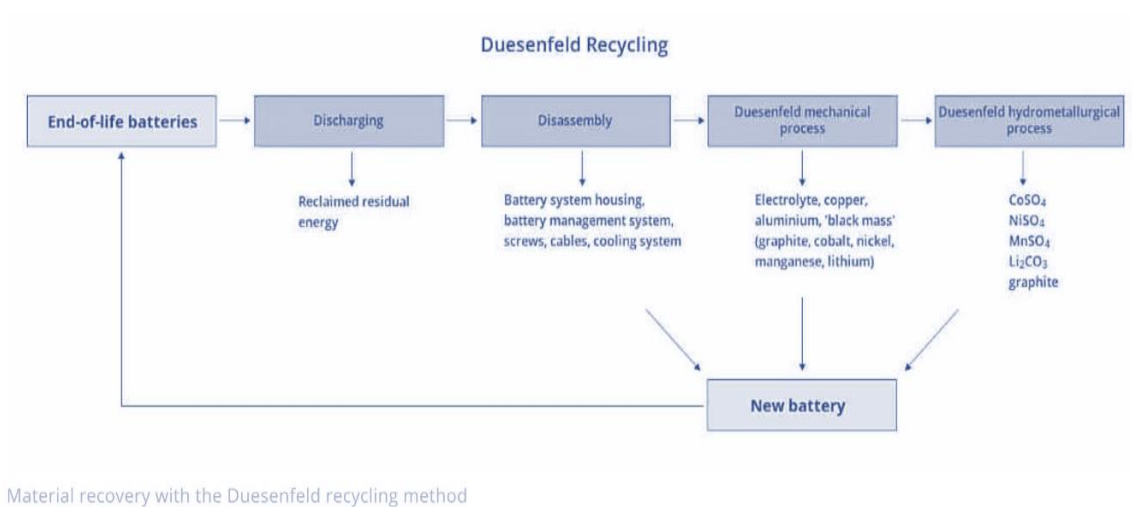


Figure 34: Duesenfeld Recycling (Duesenfeld 2021)

5.3.8.4.2 Refurbish / Reuse

Second life batteries could be set to be delivered to the new customer at 30 to 70 percent cheaper than brand new ones by the year 2025, requiring substantially less capital per cycle. (Engel et al. 2019, NOTE2)

Lithium batteries used in EV's normally keep more than 66 percent of the usable capacity after a period of eight to twelve years. The use of EV batteries could provide a further five to eight years of operation in secondary applications, depending on the shape they're in. (Hanjiro 2020)

A battery's ability to store electricity and quickly discharge it degrades the battery over time. The degradation function is classified as how many cycles a battery can charge and discharge at a given rate. The repeated charging and discharging at maximum potential and the high temperature the battery might face all depend on how the battery will degrade.

Based on the duty cycles acquired by EV batteries which are not numerous, certain battery modules with no defects and little deterioration could be refurbished and reused as substitutes for the same EV type. Leading automotive manufacturers such as Nissan and Tesla are known to provide refurbished battery packs to replace the original ones in EV's which can be bought or swapped for warranty purposes. (Hanjiro 2020)

5.3.9 Threats for LFP, NCA, NMC

5.3.9.1 Shortage of Materials

Materials in the LFP blends are abundant but lithium might face a shortage in the near future, however, the shortage of materials would affect NMC and NCA since the main materials found in their chemistries are cobalt and nickel. So far as we know, these materials, especially cobalt are limited and in the next few years they could run out and be harder to come by. Up to now, the cost of Li-ion batteries has been going down for the last few years, but if materials are hard to come by, this could mean a rise in price yet again for these types of batteries.

In the article: "Future Energy – How Electric Vehicles Transform Battery Demand", it states that lithium is the most demand-intensive, with the battery industry facing an increment of six-fold up to the year 2030. However, the supply base is quite diversified, and the market may be provided to respond to growing demand in underdeveloped, accessible from countries such as: Australia, Argentina and Chile.

At the end of this decade, Nickel also plunges into a shortage. Although nickel sources are not lacking, there are substantial environmental, social and governance hurdles to new mines, for example, Indonesia. It can also take 5-10 years to supply a large new project with nickel. The mining firms in the wake of the 2020 crisis focus instead of investing in capital-intensive new projects on cashflow generations and dividends.

Cobalt would be the delicate case when it comes to its supply chain attached to the substantial environmental, social and governance difficulties in the Democratic Republic of Congo. DRC currently provides over 70% of the market and, in spite of rising production from Australia and Indonesia, will maintain this dominance even with increasing demand over the course of this decade. The cobalt market will most likely run into a shortage from the year 2027, and when EV sales start in the 2030s, about half of mined and recycled cobalt will only be able to satisfy the anticipated demand by the middle of the decade.

Unless new battery technologies arise out of NMC cells, the world will become even more reliant on DRC (which could probably step-up cobalt production to cover the gap).

(Mackenzie 2021)

But then again, this is where new recycle companies could rise up with new technologies to extract the rawest materials possible out of the end-of-life batteries that come out of EV's.

5.3.9.2 New Tech and Materials

As it has been covered in the previous chapter, LFP, NCA and NMC can only get so much range by making new blends or add different ratios of the blends already used. One of the major threats for these battery chemistries is the number of kilometers they are able to travel with one charge and out of the three, NMC is the chemistry that can achieve the most energy density.

Even though there are general benefits of lithium-ion batteries, their toxicity and damaging environment practices in connection with the extraction of resource-limited lithium are a key disadvantage. This is why scientists are striving to reduce some of this strain towards eco-friendly materials. (Advanced Science News 2020)

In the future, to obtain driving length that go farther than 300 miles / 480 kilometers, the energy of the actual Lithium-ion batteries need to be greater than 300WH kg⁻¹ and over. NMC, which are lithium transition metal oxides that are layered, are the most sought after to this day. In consideration to the future of cathode material generation, some of the up-and-coming contenders in the NMC line, will take advantage from further expansion due to the associated battery technology being somewhat well developed. In this respect, enhanced performances like NMC-811 with superior energy and lower battery expense can be achieved by adapting the content ratios of Ni, Mn and Co in the NMC compound. However, NMC-811 may just be a transient Li-ion technology in view of the restricted theoretical capacity of NMC blends. In the long run, to obtain energy densities of ~500 Wh kg⁻¹ or higher, new elevated-energy battery chemical systems such as Lithium air, lithium sulphur, lithium silicon, all solid state batteries, etc. need to be further researched and developed (Ding et al. 2019, pp. 12–13)

Many additional technologies are being researched that can contribute to the shift to a more efficient wireless world. All inventive and innovative solutions include unconventional examples such as batteries made of, foam, sand, folding paper or charged by wi-fi. However, there is still a lot of research to look into at this point to exceed the proven and tested lithium-ion battery by alternative battery technologies. (Advanced Science News 2020)

5.4 Multi Criteria Decision Analysis WSM

This chapter will help deciding the best chemistry overall with the use of the multi criteria decision analysis. The most important strengths and weaknesses from the SWOT analysis from LFP, NCA and NMC were taken into consideration to do this evaluation.

First an equal weight was given to each of the criterion without the use of AHP.,

After that, AHP was added on the last two steps of the MCDA to evaluate two different scenarios also to come up with the different overall scores at the end.

Table 3: MCDA Linguistic Terms

Linguistic Terms								
Criteria	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh
LFP	Very High	Very High	Average	Very High	Very High	Very high	Very High	Low
NCA	Average	Average	Very High	Average	Average	High	High	High
NMC	High	High	High	High	High	Average	High	Very High

Table 4: MCDA 5 Point Scale

5 Point Scale				
Very low	Low	Average	High	Very high
1	2	3	4	5

First thing to do is make a table that will have the different characteristics going from low importance to very high in a grammatical scale. From there give the grammatical criteria scale a number using a 5-point scale. (Loganathan et al. 2021, p. 4)

Safety: When it comes to safety, lithium iron phosphate is a relatively safe chemistry, making it more stable than other lithium chemistries, and because it has the highest thermal runaway **Very High** (Lindsay 2018). NMC is a bit less safe also considering its thermal runaway which is a bit lower than LFP **High** (Battery University 2010). In the last place would be the NCA which contains the least thermal runaway **Average** (Battery University 2010). Both NCA and NMC could also catch in fire if punctured due to the fact that they contain cobalt and this happens if suddenly they come in contact with oxygen. (Lindsay 2018).

Specific Power: Out of all three chemistries, LFP has the most specific power, with 2400, W/kg, **Very High** (Alaoui C. 2017). Followed by NMC which contains a bit less, 2300 W/KG, **High** (Nikolian et al. 2016). And Lastly the NCA, which contains around 1500-1900 W/Kg, **Average** (Warner 2015, p. 77).

Energy Density, Capacity: NCA energy density is currently around 236 to 260 WH/kg **Very High** (Ding et al. 2019, p. 9). Commercial NMC lithium batteries energy density is about 200

WH/kg **High** (Huang 2020). LFP has the least energy density out of the three, because it lacks cobalt, it has around 100~110 WH/kg, but new technology could achieve 130~190Wh/kg, but never more than 200Wh/kg. **Average** (Huang 2020).

Thermal Runaway: Thermal Runaway of LFP is around 270°C, which is considerably higher than that of other lithium batteries **Very High** (Lindsay 2018).“NMC Thermal runaway is 210°C (410°F)” **High** (Battery University 2010).“NCA Thermal runaway is 150°C (302°F)” **Average** (Battery University 2010)

Battery Lifespan: With the lowest in cycle time, the NCA chemistry has a lifespan of about 500 cycles, **Average** (Sendino 2021). NMC comes next getting around 1000 to 2000 lifecycles, **High** (Sendino 2021). The chemistry with the most lifecycles out of these chemistries is the LFP which can go around 3000 lifecycles at 100 DOD, **Very High**, (Lima 2021). At an 80% DOD, LFP lifespan could last up to 4500 lifecycles, (Power Tech 2021)

Materials Availability: Nickel’s demand is high, however, because it is easy to recycle there is no concern about it running out. (Buxton et al. 2019). The difference between NCA, NMC and LFP would have to do with the availability between the cobalt which is an important element in NCA and NMC. and the availability of the elements found in the LFP cells. Cobalt for the most part can be found in the DR of Congo and Australia, and the demand for it is rising rapidly making it very expensive (Garside 2021a). The rating on NMC would be **Average**, and NCA **High**, since NCA batteries usually contain 2 times less cobalt than NMC. LIFEP04 olivines on the other hand, contains iron and phosphate, which are very accessible and can be found easily, **Very High** (Li and Ma 2019, p. 3).

Easier to build in packs: The majority of EV manufacturers utilize NMC battery cells; Tesla employs NCA (Roberts 2021)

Traditional battery pack manufacturing process goes from cell, module and finally the pack and this goes for cylindrical, pouch and prismatic cells. And there has been one company that has skipped the module step using LFP technology, which cuts costs in manufacturing process steps. BYD has done this successfully and has manufactured an EV called HAN with this new technology called cell to pack using prismatic cells. (BatteryBits 2020).And so since most batteries are made with NMC, NCA cells by using either prismatic, pouch or cylindrical, all contain modules the rating would have to be a bit lower (**High**)than that of what BYD has accomplished with the LFP prismatic cells (**Very High**).

Cost per kWh: The following prices are probably the cheapest a company can get either because they buy in large quantities, or the make the battery packs themselves, cutting manufacturing costs.

Less expensive chemistry per Kilowatt hour would be the LFP, this according to BYD and their cell to pack technology with an estimated cost of about 55 to 85 euros per kWh, **Low** (Lima 2021). Up next, even though they get discounted prices because they buy in high volumes, Tesla is able to pay 158 euros per kWh per pack, **High** (Klender 2021). Lastly comes General Motors which uses NMC but with aluminium in their chemistry to reduce the cobalt in their ultium cells (Abuelsamid 2020), and even though they do this, it still more expensive than what Tesla pays, they spend around 175 per kWh in their packs, **Very High** (Klender 2021).

Table 5: MCDA Decision Matrix

Decision Matrix								
Criteria	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh
LFP	5	5	3	5	5	5	5	2
NCA	3	3	5	3	3	4	4	4
NMC	4	4	4	4	4	3	4	5

The decision matrix is then done, creating another table by replacing the grammatical criteria with the number values. (Loganathan et al. 2021, p. 4).

Table 6: MCDA Normalized Decision Matrix

Criteria	Beneficial Criteria							Non Beneficial
	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh
LFP	1.00	1.00	0.60	1.00	1.00	1.00	1.00	1.00
NCA	0.60	0.60	1.00	0.60	0.60	0.80	0.60	0.50
NMC	0.80	0.80	0.80	0.80	0.80	0.60	0.80	0.40

' A_{ij} ' can be the evaluated number of 'ith' attribute of 'jth' criteria. In order to generate the normalized decision matrix, beneficial and non-beneficial attributes need to be classified and then normalized. To get the results, for beneficial attributes the formula $A_{ij}/\text{Max}(A_{ij})$ is applied, whereas for non-beneficial $\text{Min}(A_{ij})/A_{ij}$ is utilized. (Loganathan et al. 2021, p. 4).

Beneficial criteria are all the criteria except for the cost per kWh which is non beneficial.

The formula $A_{ij}/\text{Max}(A_{ij})$ is used for the beneficial criteria and as an example LFP is the one with the highest rating at 5. Each attribute would be divided by 5 and so NCA is $3/5=0.60$, NMC $4/5=0.80$, and so on.

For the Beneficial criteria which is cost per kWh, the formula used is $\text{Min}(A_{ij})/A_{ij}$

For LFP which is the minimum value, the 2 is taken for the rest of the ratings as the numerator dividing by the other attribute's performance values for each chemistry. LFP $2/2=1$, NCA $2/4=0.50$ and NCA $2/5=0.40$

Table 7: MCDA Normalized and Weighted Decision Matrix (equal weights)

Normalized and Weighted Decision Matrix									
Weightage Percentage	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	1.00
Criteria	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh	Score
LFP	0.125	0.125	0.075	0.125	0.125	0.125	0.125	0.125	0.950
NCA	0.075	0.075	0.125	0.075	0.075	0.100	0.075	0.063	0.663
NMC	0.100	0.100	0.100	0.100	0.100	0.075	0.100	0.050	0.725

Second to last step would be to allocate equal weight to all the criteria, as if they had similar importance. Then multiply the weights by the evaluated value of each criteria to come up with the normalized decision matrix (Loganathan et al. 2021, p. 4). For this step everything was multiplied by 1/8 to give the criteria equal weights, then added up to get the final score for each chemistry.

Table 8: MCDA Overall Score and Ranking (equal weights)

Performance Score and Ranking			
Chemistry	LFP	NCA	NMC
Overall Score	0.950	0.663	0.725
Ranking	1	3	2

Performance Score and Ranking Table

Add the normalized and the weighted numbers out of every attribute. Set the ranking for the different attributes(Loganathan et al. 2021, p. 4).

So far, the LFP has the best ranking scores but with the help of the AHP tables, a percentage for each weight was given in the next chapter depending on two different scenarios.

5.4.1 Analytic Hierarchy Process (AHP)

This AHP analysis will help give the criteria a weight of importance depending on different scenarios which will be on deciding weather to buy an EV with it’s chemistry based on LFP or NCA, NMC, so then the Normalized weight and Decision matrix can be evaluated and finally ranking of the different battery chemistries can be set for a decision.

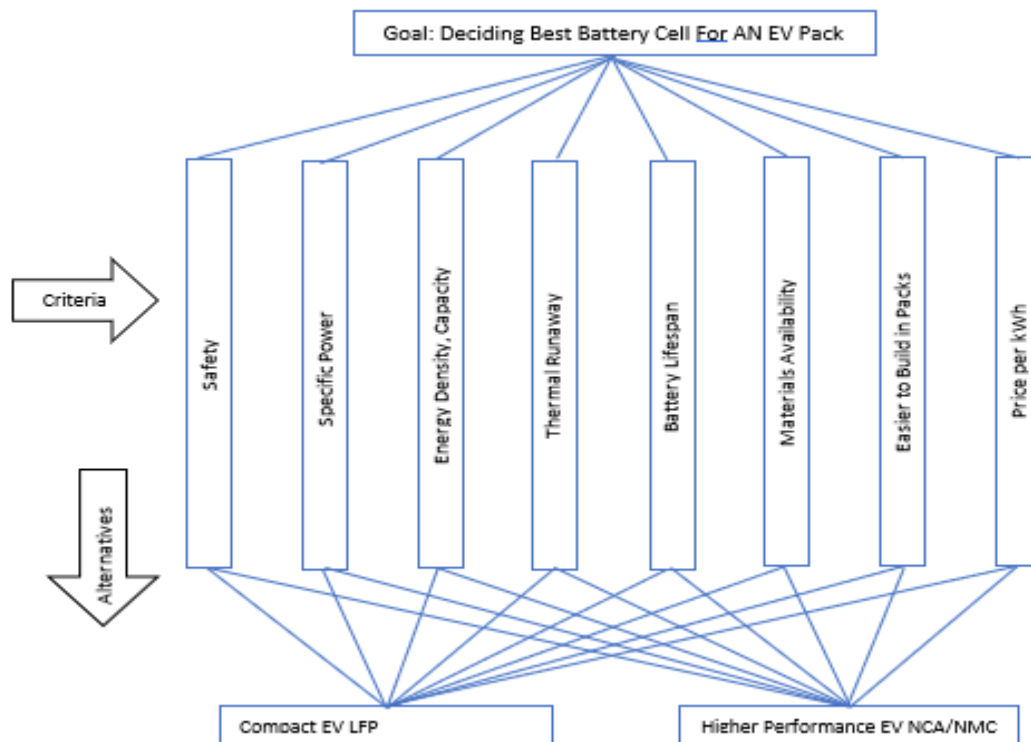


Figure 35: AHP Diagram 2

Creating an issue hierarchy is the first step in solving the problem. As a second stage, each level of the hierarchy is assigned a nominal value, which is then used to build a pairwise comparison judgment matrix. (Taherdoost 2017)

5.4.1.1 AHP Scenario 1: Compact EV (non-cobalt battery)

Scenario 1 can be someone such as a student, someone looking to buy their first EV, a mother that has low to mid income that does need the EV but not for long trips for work, etc. and safety is very important to them, as well as the life of the battery. The following vehicle would be ideal, and these are the specs this certain customer would look for and what was graded based on their needs.

For this example, a Tesla model 3 that has LFP chemistry would be considered in mind, one that circulates in Germany (Leichsenring 2021) as the perfect vehicle in this case. And the specs of this vehicle would be as follows, according to (EV Database 2022a):

- Usable Battery: 52.5 kWh
- Price Range: 45,560 Euros in Germany
- Real Range: Between 250 and 510 kms
- 0-100kph: 5.6 seconds
- Top Speed: 225 kph
- Total Power: 239 kW (325 HP)

- Drive: Rear wheel drive

Next are different importance scores according to this certain kind of EV user, in the end it will show if it will in fact this chemistry could accommodate this kind of driver.

Table 9: AHP Weight Calculating Attributes (no cobalt)

Weight calculating attributes								
	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh
Safety	1	1	3	1	1/2	1/3	4	1/5
Specific Power	1	1	3	1	1/5	1/7	1/2	1/9
Energy Density	1/3	1/3	1	1/5	1/5	1/6	1/2	1/7
Thermal Runaway	1	1	5	1	1	1/3	3	1/3
Battery Lifespan	2	5	5	1	1	1/3	4	1/3
Materials Availability	3	7	6	3	3	1	7	1
EZ build in packs	1/4	1/3	2	1/3	1/4	1/7	1	1/7
Cost per kWh	5	9	7	3	3	1	7	1

In the second stage, a set of questions should be created and upon someone's or a groups opinion, information is gathered to perform the different pairwise comparisons, The scale runs from one to nine, with number 1 indicating that the two components are equal in importance. In a paired matrix, number nine, on the other hand, denotes that it is of highly importance, and so on up to the number 2, 3, etc (Loganathan et al. 2021, p. 4)

The following formula was applied for table 9: $a_{ik} * a_{kj} = a_{ij}$ (Jalaliyoon 2012, p. 6)

Ratings from 1 to 9 were given at the end of the sentence and ranked according to description on the table 9.

Safety vs Specific power: According to (Alaoui C. 2017)", LFP cells have a nominal specific power of 2400 W/kg which is the most out of the 3 chemistries as well as LFP being the safest because it has the highest thermal runaway (Lindsay 2018). Therefore, a rating of 1 will be given here equal importance.

Safety vs capacity: It should be taken into account the safety first if the driver is a mother and this vehicle would not be intended for long trips. Safety would have a moderate higher importance than capacity. (3)

Safety vs Thermal Runaway: Safety as mentioned above is one of the stronger attributes of LFP because it has the highest thermal runaway. Rating would be a (1) giving them equal importance.

Safety vs Lifespan: Battery lifespan of LFP is higher than cobalt-based ones, 3000 lifecycles at 100 DOD, (Lima 2021). So due to the fact that the person that is acquiring this kind of entry EV has low to mid income these kinds of customers would be looking into something to

have for a long term, and LFP is considered the safest already, this would have an equal to moderate high rating over safety. (2)

Safety vs Materials availability: LFP materials are abundant, therefore making this chemistry very accessible (Li and Ma 2019, p. 3). And because it is very important to keep the cost down. Rating of moderate importance compared to safety. (3)

Safety vs Easier to build in packs: LFP are easier to build in packs due to the fact that they can be made without modules (BatteryBits 2020). That's included in the EV cost. So, safety would be considered of higher importance moderately. Rating would be a 4 in favour of safety.

Safety vs Cost per kWh: Even though safety is important, LFP has the lowest price per kWh compared to the chemistries (Lima 2021), giving this a strong priority when choosing over other chemistries. (7)

Specific Power vs Capacity: more moderated importance (3) would be given in this scenario to the specific power, because LFP already has less capacity and its important to be able to get charged a bit quicker. LFP has the most power density (Alaoui C. 2017)

Specific Power vs Thermal Runaway: As described earlier, LFP has the highest thermal runaway and also the highest specific power, so rating would be equal, (1)

Specific Power vs Battery Lifespan: Entry level car, one should be able to keep for a while or able to sell easy and not lose too much money. Battery lifespan would be here of more importance strongly. (5)

Specific Power vs Material Availability. Material availability is of highly strongly more important than specific power, due to the fact that if the materials were hard to get, the cost of these kind of EV's would be way more expensive. (7)

Specific Power vs Easier to build in Packs: Important here is to bring the costs down, so with cell to packs it will do just that. Simplified manufacturing and assembly by 10% (Kane 2021). So, it'd be equal moderate in favour of Easier to make in packs. (2)

Specific Power vs Price per kWh: Cost overall is way cheaper for LFP therefore affordable, so its extremely more important than SP. (9)

Energy Density vs Thermal Runaway: Meaning that LFP has higher Thermal runaway (Lindsay 2018), would mean its safer, therefore, strongly more important than capacity. (5)

Energy Density vs Bat Lifespan: LFP being able to last longer than cobalt based li ion when it comes to lifespan would be strongly more important in this scenario. (5)

Energy Density vs Mat Availability: Again, in this scenario, extremely important of materials availability to keep low costs due to the abundant materials for LFP. (6)

Energy Density vs Easier to build in Packs: Moderate or equal importance (2) to Easier to build in packs because there is a "simplified manufacturing and assembly by 10%", "increased volume utilization by 5%", "increased energy density by 14% (Kane 2021)"

Energy Density vs Cost per kWh: Cost kWh strongly preferred for the same reason of keeping low costs in this scenario (7).

Thermal Runaway vs Battery Lifespan: Safety and Batter lifespan are of equal importance here. (1)

Thermal Runaway vs Materials Availability: Materials Availability is of higher importance moderately to keep the cost down. (3)

Thermal Runaway vs Easier to build in Packs: Higher thermal runaway means more safety, therefore rating this a bit higher than cell to pack technology to save a bit of money (3)

Thermal Runaway vs Cost per kWh: For this scenario Cost per kWh is of moderate higher importance than thermal runaway. (3)

Battery Lifespan vs Material Availability: Material availability is of moderate higher importance than battery lifespan due lo low cost of overall materials. (3)

Battery Lifespan vs Easier to build in Packs: Battery lifespan has moderate to stronger importance here in this scenario (4)

Battery Lifespan vs Cost per kWh: Cost is of more moderate importance in this scenario, but also is battery lifespan. (3)

Materials Availability vs Easy to build in packs: Materials availability is the stronger factor here that keeps the cost down more than cell to pack technology. (7)

Materials Availability vs Cost per kWh: Materials availability comes hand in hand with Cost per kWh (1)

Easy to build in packs vs Cost per kWh: Easier to build in packs would help save a small percentage of the whole pack overall price (Kane 2021), while cost per kWh as a whole is greater depending on LFP chemistry. (7)

Table 10: AHP Sum of values (no cobalt)

Sum	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh
Safety	1	1	3	1	0.50	0.33	4	0.20
Specific Power	1	1	3	1	0.20	0.14	0.5	0.11
Energy Density	0.33	0.33	1	0.20	0.20	0.17	0.5	0.14
Thermal Runaway	1	1	5	1	1	0.33	3	0.33
Battery Lifespan	2	5	5	1	1	0.33	4	0.33
Materials Availability	3	7	6	3	3	1	7	1
EZ build in packs	0.25	0.33	2	0.33	0.25	0.14	1	0.14
Cost per kWh	5	9	7	3	3	1	7	1
Sum	13.58	24.66	32	10.53	9.15	3.44	27.00	3.25

The matrix must then be normalized. This is accomplished by adding the numbers in each column together (University of Tsukuba 2012, p. 11)

Table 11: Normalized Pairwise Comparison Matrix (no cobalt)

Normalized Pairwise Comparison Matrix								
	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh
Safety	0.07	0.04	0.09	0.09	0.05	0.10	0.15	0.06
Specific Power	0.07	0.04	0.09	0.09	0.02	0.04	0.02	0.03
Energy Density	0.02	0.01	0.03	0.02	0.02	0.05	0.02	0.04
Thermal Runaway	0.07	0.04	0.16	0.09	0.11	0.10	0.11	0.10
Battery Lifespan	0.15	0.20	0.16	0.09	0.11	0.10	0.15	0.10
Materials Availability	0.22	0.28	0.19	0.28	0.33	0.29	0.26	0.31
EZ build in packs	0.02	0.01	0.06	0.03	0.03	0.04	0.04	0.04
Cost per kWh	0.37	0.36	0.22	0.28	0.33	0.29	0.26	0.31

To normalize the relative weight, all elements of the columns were divided by the total sum in each of their column. (University of Tsukuba 2012, p. 12).

For example, in the first column: 1 for safety is divided by 13.58 from table 10, 1 for specific power is divided by 24.66, 3 for energy density is divided into 32, and so on.

Sum of each of the columns is 1.

Table 12: Normalized Criterion Weights Calculation (no cobalt)

Criterion Weights									
	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh	Criterion Weight /8
Safety	0.07	0.04	0.09	0.09	0.05	0.10	0.15	0.06	0.08
Specific Power	0.07	0.04	0.09	0.09	0.02	0.04	0.02	0.03	0.05
Energy Density	0.20	0.01	0.03	0.02	0.02	0.05	0.02	0.04	0.03
Thermal Runaway	0.07	0.04	0.16	0.09	0.11	0.10	0.11	0.10	0.10
Battery Lifespan	0.15	0.20	0.16	0.09	0.11	0.10	0.15	0.10	0.13
Materials Availability	0.22	0.28	0.19	0.28	0.33	0.29	0.26	0.31	0.27
EZ build in packs	0.02	0.01	0.06	0.03	0.03	0.04	0.04	0.04	0.03
Cost per kWh	0.37	0.36	0.22	0.28	0.33	0.29	0.26	0.31	0.30
									1.00

Normalized the main eigenvector is calculated by averaging all elements of each row (Jalaliyoon 2012, p. 6), for example for safety, all values from that row are added (0.07,0.04,0.09,0.09, 0.05,0.1,0.15,0.06) then divided by 8= 0.0775 => 0.08

5.4.1.1.1 Calculate Consistency

Table 13: AHP Calculating Consistency (no cobalt)

Criteria Weights	0.08	0.05	0.03	0.10	0.13	0.27	0.03	0.30
	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh
Safety	1	1	3	1	0.50	0.33	4	0.20
Specific Power	1	1	3	1	0.20	0.14	0.5	0.11
Energy Density	0.33	0.33	1	0.20	0.20	0.17	0.5	0.14
Thermal Runaway	1	1	5	1	1	0.33	3	0.33
Battery Lifespan	2	5	5	1	1	0.33	4	0.33
Materials Availability	3	7	6	3	3	1	7	1
EZ build in packs	0.25	0.33	2	0.33	0.25	0.14	1	0.14
Cost per kWh	5	9	7	3	3	1	7	1

Use PW comparison matrix which is not normalized (table 10), multiply each value in the column with the final criteria weight value. Results are as in table 14.

Table 14: AHP Calculating consistency, Calculate ratio (wsm / cw) (no cobalt)

Criteria Weights	0.08	0.05	0.03	0.10	0.13	0.27	0.03	0.30	Weighted Sum Value	Criteria Weight	WSV CW
Safety	0.08	0.05	0.09	0.10	0.07	0.09	0.12	0.06	0.66	0.08	8.19
Specific Power	0.08	0.05	0.09	0.10	0.03	0.04	0.02	0.03	0.43	0.05	8.66
Energy Density	0.11	0.02	0.03	0.02	0.03	0.05	0.02	0.04	0.31	0.03	10.22
Thermal Runaway	0.08	0.05	0.15	0.10	0.13	0.09	0.09	0.10	0.79	0.10	7.90
Battery Lifespan	0.16	0.25	0.15	0.10	0.13	0.09	0.12	0.10	1.10	0.13	8.46
Materials Availability	0.24	0.35	0.18	0.30	0.39	0.27	0.21	0.30	2.24	0.27	8.30
EZ build in packs	0.02	0.02	0.06	0.03	0.03	0.04	0.03	0.04	0.27	0.03	9.13
Cost per kWh	0.40	0.45	0.21	0.30	0.39	0.27	0.21	0.30	2.53	0.30	8.43
											8.66

Weighted sum value is calculated by adding up each value of each row.

Next to the weighted sum value, the criteria weight is added again.

Finally, the WSV is divided by the Criteria weight for each row. The average of that column is added and divided by 8 to get the average , 8.66 which is lambda Max.

Consistency index (CI) => $L_{max} - n / n - 1$ (Taherdoost 2017, p. 245)

$$\Rightarrow (8.66 - 8) / (8 - 1) \Rightarrow CI = 0.094$$

Matrix size	Random consistency index (RI)
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

Figure 36: Random consistency index (Punthutaecha 2018)

Finally, consistency ratio is calculated $CR = CI / RI$ (Taherdoost 2017, p. 245)

RI 1.41 is taken into account from figure 36, since there are 8 criteria

$0.094 / 1.41 = 0.066$ and this is ok, since the result is less than 0.10, $0.066 < 0.10$

(Taherdoost 2017, p. 245)

5.4.1.1.1 Results with AHP weights (no cobalt)

Here is where we plug in the original table 6 and multiply each row by their given criterion weight percentages. For example: LFP had a rating of 1 in the safety cell, so it was multiplied by 8%, NCA had a value of 0.60 which multiplied by 0.08 = 0.05 rounded up and so on, as it is explained on table number 7.

Table 15: MCDA Normalized and Weighted decision Matrix (no cobalt)

Normalized and Weighted Decision Matrix									
Weightage Percentage	8%	5%	3%	10%	13%	27%	3%	30%	
Criteria	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh	Score
LFP	0.08	0.05	0.02	0.10	0.13	0.27	0.03	0.30	0.978
NCA	0.05	0.03	0.03	0.06	0.08	0.22	0.02	0.15	0.630
NMC	0.06	0.04	0.02	0.08	0.10	0.16	0.02	0.12	0.618

Based on the consistency checking out, criteria weights from table 12 were used for further calculations. Each attribute was multiplied by the specific weight, then all columns were added for the total score on the last column.

Table 16: MCDA Overall Performance Score and Ranking (no cobalt)

Performance Score and Ranking			
Chemistry	LFP	NCA	NMC
Overall Score	0.978	0.630	0.618
Ranking	1	2	3

Finally, the chemistry with the highest score for this scenario is LFP, following by NCA and lastly NMC.

5.4.1.2 AHP Scenario 2: Higher Performance EV (cobalt battery)

For this second scenario, it could be of someone, such as a young adult or a member of a certain group, who is financially stable and is primarily concerned with social status and wishes to demonstrate to others what he has achieved. These kind of people does not really care for special features on the car, but rather on how people see them and for the vehicle to be fast. The following vehicle would be perfect, and these are the specs this certain customer would look for and what was graded based on their needs.

Tesla model S plaid is considered on this second scenario, this model has NCA chemistry. (Merano 2021) and would be perfect for this type of driver. These are the specs According to (EV Database 2022b):

- Usable Battery: 95 kWh
- Price Range: 127,000 Euros in Germany
- Real Range: Between 410 and 795 kms
- 0-100kph: 2.1 seconds
- Top Speed: 322 kph
- Total Power: 760 kW (795 HP)
- Drive: All wheel drive

The following are scores according to this certain kind of EV user, in the end of this chapter it will show if this chemistry will in fact accommodate this kind of driver.

Table 17: AHP Weight Calculating Attributes. (cobalt)

Weight calculating attributes								
	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh
Safety	1	1/6	1/3	1	4	5	5	5
Specific Power	6	1	2	6	6	7	7	5
Energy Density	3	1/2	1	3	7	8	7	4
Thermal Runaway	1	1/6	1/3	1	7	5	7	5
Battery Lifespan	1/4	1/6	1/7	1/7	1	1	1	1/3
Materials Availability	1/5	1/7	1/8	1/5	1	1	5	1
EZ build in packs	1/5	1/7	1/7	1/7	1	1/5	1	1
Cost per kWh	1/5	1/5	1/4	1/5	3	1	1	1

As mentioned above for scenario 1, this is the second stage using a scale from 1-9. 1 being of equal importance, 9 of highly importance, 8 a bit less importance, and so on. (Taherdoost 2017, p. 245)

The following formula was also applied for table 17: $a_{ik} * a_{kj} = a_{ij}$ (Jalaliyoon 2012, p. 6)

Ratings from 1 to 9 were given at the end of the sentence and ranked according to description on the table above.

Safety vs Specific power: Even though NCA battery packs have the least specific power compared to LFP and NMC (Warner 2015, p. 77), specific power be strongly, very more important in this scenario than safety. (6)

Safety vs capacity: For this scenario, capacity would be a bit more important than safety, but not by too much. (3)

Safety vs Thermal Runaway: This would mean equal importance, due to the fact that NCA has less thermal runaway, therefore safety is not that high as compared to LFP. (Battery University 2010) (1),

Safety vs Lifespan: Safety would be a bit more important, since this person might be turning in the vehicle to get a new one every x number of years. (4)

Safety vs Materials availability: NCA is the least safe compared to LFP and NMC. (Battery University 2010) And even though nickel and cobalt are a bit hard to get compared to LFP (Li and Ma 2019, p. 3), the customer in this scenario might be strongly to very strongly leaning towards the safety. (5)

Safety vs Easier to build in packs: Money would not be an issue to save the money from cell to pack, therefore having modules in the battery (BatteryBits 2020). So, safety would be of strong importance in this case. (5)

Safety vs Cost per kWh: Even though tesla gets their NCA batteries at a discounted price (Klender 2021), in this scenario the EV is significantly more expensive than the model 3 and taking into consideration that the person acquiring his vehicle does not care about the cost, safety would stronger. (5)

Specific Power vs Capacity: Since in this scenario, the customer is looking for more of a high-performance car, the balance would highly go towards Specific power, even though the tesla model s plaid has a pretty big capacity consisting of 95 kWh. (EV Database 2022b) So in this case, it would be equally to moderately more important towards specific power (2)

Specific Power vs Thermal Runaway: Even though NCA has the lowest thermal runaway, (Battery University 2010), specific power would be considered a bit higher in this case, since the customer is after high performance. (8)

Specific Power vs Battery Lifespan: Specific person buying this type of EV's would be turning in their car every couple of years to get the newest technology not really giving too much importance to the lifespan of the battery, so specific power would have rather higher importance. (8)

Specific Power vs Material Availability: This certain customer for this scenario would put high performance first, even if he has to pay a bit more for this battery that contains cobalt and nickel, which are harder to obtain. (Garside 2021a) (9)

Specific Power vs Easier to build in Packs: Specific Power in this case has higher importance even though NCA involves traditional battery production process involves building battery packs from cell to module, then from that module to the whole battery pack. Which is a bit more expensive than cell to pack for the LFP chemistry. (BatteryBits 2020) (7)

Specific Power vs Price per kWh: NCA has the least specific power (Warner 2015, p. 77), but the specific buyer in this scenario would be after the high performance and would have no problem with money and so specific power would be of strongly more importance. (5)

Energy Density vs Thermal Runaway: Compared to LFP and NMC, NCA has the highest energy density. (Huang 2020) This causes the thermal runaway to be the lowest, making it the less safe of the three.)” (Battery University 2010) In this scenario the balance would go slightly higher towards energy density because this would mean less wasted time to charge, so it would be very strongly preferred in this case. (6)

Energy Density vs Battery Lifespan: Energy density would mean longer trips, less time wasted at a place if a charge is needed, NCA has the most energy density, (Huang 2020)and so this would be of strong, very strong importance to the consumer compared to the battery lifespan. (6)

Energy Density vs Mat Availability: Consumer in this scenario would not care to pay a bit more for cobalt or nickel which are in NCA. (Miao et al. 2019) Therefore, he would put energy density in very strongly importance because of less hassle of charging more often. (7)

Energy Density vs Easier to build in Packs: Even though NCA cant be made from cell to pack without skipping the modules like it can be done with LFP, (BatteryBits 2020) NCA still has more energy density in the whole pack. But therefore its a bit more expensive. (Miao et al. 2019) in this comparison, balance would be very strongly preferred towards energy density because customer would not care to pay a bit more for these extra costs to build the pack to have all the extra capacity. (7)

Energy Density vs Cost per kWh: NCA has the highest energy density. (Huang 2020) Tesla can obtain their cells from other manufacturers and due to the high volume, they get discounted prices, this goes towards what the customer pays, saves. (Klender 2021) Energy Density in this case would have to be moderate to strongly preferred. (4)

Thermal Runaway vs Battery Lifespan: NCA contains cobalt, therefore has the least thermal runaway, making it a bit unsafe compared to LFP and NMC. (Battery University 2010). Battery lifespan is also the lowest compared to LFP and NMC. (Sendino 2021). On this comparison thermal runaway would be of a bit more importance because this type of customer would not keep a car for long periods of time, therefore not needing it to have a large battery lifespan. (5)

Thermal Runaway vs Materials Availability: Like mentioned above, NCA has the least thermal runaway compared to the other 2 chemistries. (Battery University 2010) But it would be more important to be safe against heat since this is a high-performance EV than to pay a bit more for chemistry that contains cobalt in this second scenario. (5)

Thermal Runaway vs Easier to build in Packs: Thermal runaway would also be of higher importance than easier to build in packs. Money would not be an issue if the customer had to pay for NCA battery packs, which normally go from battery to module to pack. (BatteryBits 2020) (7)

Thermal Runaway vs Cost per kWh: In this case, the balance would go towards thermal runaway due to its safety it brings. (5)

Battery Lifespan vs Material Availability: Battery lifespan is the lowest compared to NMC and LFP, (Lima 2021) and this would not have too much effect compared to material availability, it would be a bit more expensive since it contains cobalt and nickel, but the type of customer is paying for status. (1)

Battery Lifespan vs Easier to build in Packs: Battery lifespan is the lowest, according to (Lima 2021), but would be of not such importance just like if it was easier to build in packs,

cell, module, pack. Since this EV would most likely be traded in for a new one in not a long period of time. (1)

Battery Lifespan vs Cost per kWh: Battery lifespan is the least, according to . (Battery University 2010) and cost per kWh is in between LFP and NMC, coinciding with (Klender 2021). In this scenario, it would be of somewhat equal importance, but a bit more going to cost per kWh. (3)

Materials Availability vs Easy to build in packs: Both affect the overall cost of the battery pack, but balance goes a bit higher to the materials availability. (5)

Materials Availability vs Cost per kWh: Materials are harder to obtain in this scenario mainly the cobalt, which is really expensive (Oberhaus 2020), but the type of customer would acquire this type of vehicle not minding the cost. (1)

Easy to build in packs vs Cost per kWh: Money would not be a problem in this scenario so this would have an equal importance. (1)

Table 18: AHP Sum of values (cobalt)

Sum	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh
Safety	1	0.17	0.33	1	4	5	5	5
Specific Power	6	1	2	6	6	7	7	5
Energy Density	3	0.50	1	3	7	8	7	4
Thermal Runaway	1	0.17	0.33	1	7	5	7	5
Battery Lifespan	0.25	0.17	0.14	0.14	1	1	1	0.33
Materials Availability	0.20	0.14	0.13	0.20	1	1	5	1
EZ build in packs	0.20	0.14	0.14	0.14	1	0.2	1	1
Cost per kWh	0.20	0.20	0.25	0.20	3	1	1	1
Sum	11.85	2.49	4.32	11.69	30.00	28.20	34.00	22.33

The matrix must then be normalized. This is accomplished by adding the numbers in each column together (University of Tsukuba 2012, p. 11).

Table 19: AHP Normalized Pairwise Comparison Matrix (cobalt)

Normalized Pairwise Comparison Matrix	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh
Safety	0.084	0.067	0.076	0.086	0.133	0.177	0.147	0.224
Specific Power	0.506	0.402	0.463	0.513	0.200	0.248	0.206	0.224
Energy Density	0.253	0.201	0.231	0.257	0.233	0.284	0.206	0.179
Thermal Runaway	0.084	0.067	0.076	0.086	0.233	0.177	0.206	0.224
Battery Lifespan	0.021	0.067	0.033	0.012	0.033	0.035	0.029	0.015
Materials Availability	0.017	0.057	0.029	0.017	0.033	0.035	0.147	0.045
EZ build in packs	0.017	0.057	0.033	0.012	0.033	0.007	0.029	0.045
Cost per kWh	0.017	0.080	0.058	0.017	0.100	0.035	0.029	0.045

To normalize the relative weight, all elements of the columns were divided by the total sum in each of their column. (University of Tsukuba 2012, p. 12).

For example, in the first column: 1 for safety is divided by 11.85 from table 18= 0.084, 0.17 for specific power is divided by 2.49=0.067, 0.33 for energy density into 4.32=0.076, and so on.

Table 20: AHP Criterion Weight Calculation (cobalt)

Criterion Weights	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh	Criterion Weight /8
Safety	0.084	0.067	0.076	0.086	0.133	0.177	0.147	0.224	0.124
Specific Power	0.506	0.402	0.463	0.513	0.200	0.248	0.206	0.224	0.345
Energy Density	0.253	0.201	0.231	0.257	0.233	0.284	0.206	0.179	0.231
Thermal Runaway	0.084	0.067	0.076	0.086	0.233	0.177	0.206	0.224	0.144
Battery Lifespan	0.021	0.067	0.033	0.012	0.033	0.035	0.029	0.015	0.031
Materials Availability	0.017	0.057	0.029	0.017	0.033	0.035	0.147	0.045	0.048
EZ build in packs	0.017	0.057	0.033	0.012	0.033	0.007	0.029	0.045	0.029
Cost per kWh	0.017	0.080	0.058	0.017	0.100	0.035	0.029	0.045	0.048
									1.000

Normalized the main eigenvector is calculated by averaging all elements of each row (Jalaliyoon 2012, p. 6), for example for safety, all values from that row are added (0.084, 0.067, 0.076, 0.086, 0.133, 0.177, 0.147, 0.224) then divided by 8= 0.124, which then would translate to 12.4 %

5.4.1.2.1 Calculate Consistency

Table 21: AHP Calculating Consistency (cobalt)

AHP Calculating Consistency, without normalization								
Criteria Weights	0.124	0.345	0.231	0.144	0.031	0.048	0.029	0.048
	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh
Safety	1	0.17	0.33	1	4	5	5	5
Specific Power	6	1	2	6	6	7	7	5
Energy Density	3	0.50	1	3	7	8	7	4
Thermal Runaway	1	0.17	0.33	1	7	5	7	5
Battery Lifespan	0.25	0.17	0.14	0.14	1	1	1	0.33
Materials Availability	0.20	0.14	0.13	0.20	1	1	5	1
EZ build in packs	0.20	0.14	0.14	0.14	1	0.2	1	1
Cost per kWh	0.20	0.20	0.25	0.20	3	1	1	1

Use PW comparison matrix which is not normalized (table 18), multiply each value in the column with the final criteria weight value. Results are as in table 22.

Table 22: AHP Calculating consistency, Calculate ratio (wsm / cw) (cobalt)

Calculating consistency, Calculate ratio (weighted sum / criteria weight)												
Criteria Weights	0.124	0.345	0.231	0.144	0.031	0.048	0.029	0.048		Weighted Sum Value	Criteria Weight	WSV CW
	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh				
Safety	0.124	0.058	0.076	0.144	0.124	0.240	0.145	0.240	1.027	0.124	8.280	
Specific Power	0.744	0.345	0.462	0.864	0.186	0.336	0.203	0.240	3.380	0.345	9.797	
Energy Density	0.372	0.173	0.231	0.432	0.217	0.384	0.203	0.192	2.204	0.231	9.539	
Thermal Runaway	0.124	0.058	0.076	0.144	0.217	0.240	0.203	0.240	1.302	0.140	9.298	
Battery Lifespan	0.031	0.058	0.033	0.021	0.031	0.048	0.029	0.016	0.266	0.031	8.583	
Materials Availability	0.025	0.049	0.029	0.029	0.031	0.048	0.145	0.048	0.404	0.048	8.412	
EZ build in packs	0.025	0.049	0.033	0.021	0.031	0.010	0.029	0.048	0.245	0.029	8.457	
Cost per kWh	0.025	0.069	0.058	0.029	0.093	0.048	0.029	0.048	0.398	0.048	8.299	
										1.00	8.833	

Weighted sum value is calculated by adding up each value of each row.

Next to the weighted sum value, the criteria weight is added again.

Finally, the WSV is divided by the Criteria weight for each row. The average of that column is added and divided by 8 to get the average, 8.833 which is lambda Max.

Consistency index (CI) => $L_{max} - n / n - 1$ (Taherdoost 2017, p. 245)

$$\Rightarrow (8.833 - 8) / (8 - 1) \Rightarrow CI = 0.119$$

Finally, consistency ratio is calculated $CR = CI / RI$ (Taherdoost 2017, p. 245)

RI 1.41 is considered from figure 36, since there are 8 criteria.

$0.119 / 1.41 = 0.084$ and this is ok, since the result is less than 0.10. (Taherdoost 2017, p. 245)

$$0.084 < 0.10$$

5.4.1.2.1 Results with AHP weights (cobalt)

Here is where we plug in the data to the original table 6 and multiply each row by their given criterion weight percentages. For example: LFP had a rating of 1 in the safety cell, so it was multiplied by 12.4%, NCA had a value of 0.60 which multiplied by 12.4% = 0.074 rounded up and so on, this step is explained in table 7.

Table 23: MCDA Normalized and Weighted decision Matrix (cobalt)

Normalized and Weighted Decision Matrix									
Weightage Percentage	12.40%	34.50%	23.10%	14.40%	3.10%	4.80%	2.90%	4.80%	
Criteria	Safety	Specific Power	Energy Density, Capacity	Thermal Runaway	Battery Lifespan	Materials Availability	Easier to Build in packs	Cost per kWh	Score
LFP	0.12	0.35	0.14	0.14	0.03	0.05	0.03	0.05	0.91
NCA	0.07	0.21	0.23	0.09	0.02	0.04	0.02	0.02	0.70
NMC	0.10	0.28	0.18	0.12	0.02	0.03	0.02	0.02	0.77

Based on the consistency checking out, criteria weights from table 20 were used for further calculations. Each attribute was multiplied by the specific weight, then all columns were added for the total score on the last column.

Table 24: MCDA Overall Performance Score and Ranking (cobalt)

Performance Score and Ranking			
Chemistry	LFP	NCA	NMC
Overall Score	0.91	0.697	0.771
Ranking	1	3	2

Last step shows the overall score. LFP is still on the top ranking in this scenario, followed by NMC and lastly NCA.

6 Summary and Outlook

6.1 Summary

Different lithium-ion batteries are categorized by the materials they are composed of, specially what is included in the electrode. The final mixture of materials that compose a cell is what will determine the way the battery pack will perform.

With today's technology of current EV batteries, manufacturers find it a bit challenging to decide what would be the best chemistry for each of their applications. This decision can be based mainly on the capacity, cost, longevity, safety and reliability of each of the batteries' chemistry. This type of decision also could be considered by a customer who is looking into buying an EV and being able to choose based on the battery type it contains according to their needs for everyday use. This matter in question has been covered in this study.

The main purpose of this research was to contemplate the main differences between the most popular batteries used in EV's as of today such as NCA and NMC (contain cobalt) and evaluate them against chemistries that contain no cobalt, and a good alternative to analyse it against was LFP. This would then indicate if in fact batteries containing cobalt would still be better than batteries that do not.

At first a set of SWOT analyses were implemented in the methods section of this paper. One for LFP and a separate one for NCA, NMC. This was concluded to show the main characteristics of lithium-ion batteries and then assigned to each analysis depending on each of their strengths and weaknesses. This would mainly include for example: safety,

thermal runaway, optimal charging percentage, capacity, specific power, material availability, environmental impact, weight differences, lifespan, cost, among others. In addition, each swot includes a set of opportunities which mention ways of making each battery chemistry such as mixing them with new materials better for each case or even making hybrid included in a battery pack, these could involve having two different chemistries that can be used for example one for long range and the other for performance purposes. Recycling and reusing are also included in this chapter for all chemistries. Lastly the threats are discussed and for NCA, NMC and LFP, this would mean the development of new battery technologies that will have faster charging, cost less, be safer, and have better longevity.

Once the SWOT analyses were made, a Multi Criteria Decision Analysis (weighted sum method) was purposed with the main characteristics attained from the SWOT analysis. Then these were given different scores to come up with different rankings for selecting the most optimal battery chemistry. The MCDA had different criteria as mentioned before which has some added weight. To determine how important each of these were an Analytic Hierarchy Process was also applied into 2 scenarios with their own perspective.

From the first results, just using the MCDA as a foundation and after assigning different scores to each of the main criteria that included: safety, specific power, energy density, thermal runaway, battery lifespan, material availability easier to build in packs and cost per kWh, it was concluded that the best battery chemistry regardless was the LFP, followed by NMC and then NCA. These results were given equal importance weight of 12.5%.

The last step in the results was to add weight or a percentage of importance to each of the criteria by applying an AHP. This was used in two scenarios with different points of view.

In the first scenario, a customer who could be either a student or someone buying their first EV, someone with a limited budget was considered and paired with a Tesla Model 3 Chinese made model which have LFP battery packs. From the findings, it was concluded that for their needs also the LFP chemistry came on top, but followed by NCA, and then NMC.

In the second scenario, a customer with unlimited budget, someone who is concerned mainly with showing his status was considered, and paired with a more expensive, more powerful Tesla Model S Plaid and having battery packs composed by NCA technology. Even after specifying a different importance percentage and making certain criteria less important as opposed to the first scenario and putting specific power / performance as their most important one, results show that overall, the LFP would be the best option also for this kind of proposal in the long run, followed by NMC and lastly NCA.

This research clearly illustrates that LFP is the best li-ion battery chemistry overall in any of the EV applications. The methodology that was used could be important not only to EV technology but can be considered for manufacturers and customers for many other applications such as power walls.

6.2 Outlook

Considering the many basic challenges of the future battery chemistry, it is likely that it will take 10 to 20 years to market new battery materials and ideas, forecasts for future technologies should be carefully considered in terms of marketing. Contemporary Li-ion cells shown on figure below (generations 1 and 2a), will be replaced by a 2b generation technology with nickel-rich cathodes and better energy density, according to the German National Platform for Electromobility, which now are mainly based on LFP, LMO, NCA and NMC cathodes and carbon / graphite anodes. (Lebedeva 2017, p. 24)

Further development is contemplated with the introduction of Generation 3, which is represented by the utilization of carbon silicon anodes. Generations 3a and 3b can afterwards be anticipated to have increased energy density, and higher cut-off voltage. (Lebedeva 2017, p. 24)

Doubling the range or cutting the costs in half, particularly with generation 4 traction battery cells, seems to be possible in the medium to long term. If the challenges affiliated to solid state and lithium-sulphur along with other chemistry changeovers (Generation 4) are solved, they can become very significant parallel technologies synchronized with lithium-ion on the market. (Lebedeva 2017, p. 24)

Whether the theoretically proven benefit of higher energy densities at the cellular level can be effectively applied at battery pack degree is still highly uncertain. Thus, at this point a challenge can is not solved with confidence whether and if there will be a transition to lithium-ion "post conversion" technology of the traction battery cells with transforming materials (Generation 4) and Lithium-air (Generation 5). In the near future, progress to solid state systems (Generation 4) is more likely to happen from today's point of view. (Lebedeva 2017, p. 24)

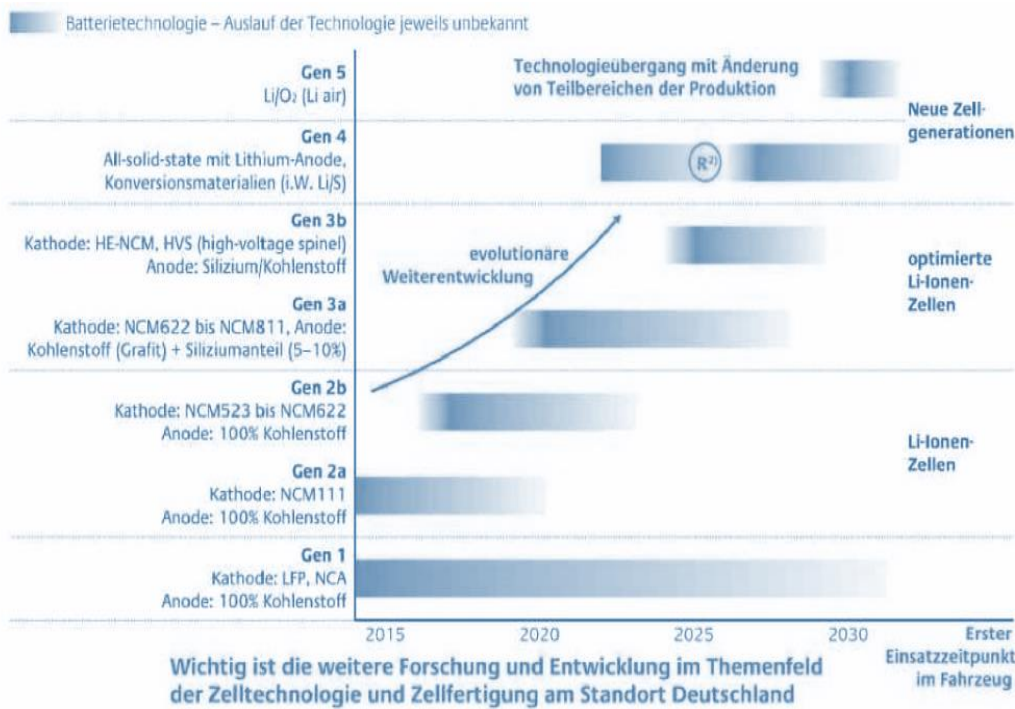


Figure 37: Lithium ion battery value chain (Lebedeva 2017, p. 25)

As of January 2022, the Dongfeng motor co. Announced that their new model E70 had been manufactured with solid state technology and released 50 of these vehicles, however these just contain a solid electrolyte diaphragm and it is considered only semi-solid state, but it is a first good step.

However. According to the Ministry and Information technology's archive of new EV's, the E70 has a 52.56 kWh battery pack that weights 335kg and offers a range of 426 km on a single charge. Sa a result, this battery is catalogued to be of poor energy density of 157 Wh/kg. In comparison, Tesla's 21700 cells in the Panasonic 6752 packs used in the U.S. Model 3 have 260 Wh/kg. Furthermore, the value is far lower than the battery manufacturer's declared specs, which identify it as capable of reaching a 210Wh/kg density.

Essentially, the E70 does not stand out in this measure, but the semi-solid battery packs offer numerous additional advantages, including resistance to puncture and deformation, as well as surviving the high temperature toleration tests noticeably. (Zlatev 2022)

Dongfeng also announced that their battery can be exchanged for another at a battery swap station. A battery exchange could be done in about three minutes to complete. The first Dongfeng swapping station launched in January 2022 in Hengyang City, Hunan Province, in collaboration with GCL Power Port. (Chen 2022)

So far, a semi-solid-state battery is a huge improvement in the right direction. However, these alternative battery technologies still require a lot more study and research to surpass the known and tested lithium-ion battery. (Advanced Science News 2020)

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8 Appendix

8.1 Battery Pack Project (48 volt, 11600 mah)

From the material that was researched and, given the fact that my E-bike's battery was degrading after some time of use, I decided to try and build a battery pack for it. And so, I started looking into the tools and materials needed and started ordering online.

Started with the cells, bought online, they're bak N18650cl 2900, 8.5A for a 13s4p. Went for this chemistry that has cobalt since like mentioned on the report, energy density is greater, and if I had done it with LFP, I would have to have way more space, but space is limited due to the battery box. (390,111,76mm)

This battery pack has 13s4p which translates to:

13 batteries in series, 13*3.7

4 batteries in parallel. 4*2900 and 8.25*4 A output

For a total of 48v, 11600mah and power output of 33A, but the output will be limited with the 20A bms, since also the controller is 20A. $48v \times 11.6Ah = 556.8 \text{ Wh}$, or 0.556 kWh battery pack.



BAK N18650CL 2900mAh - 8.25A

Reviews: Be the first to review this product

Additional Information

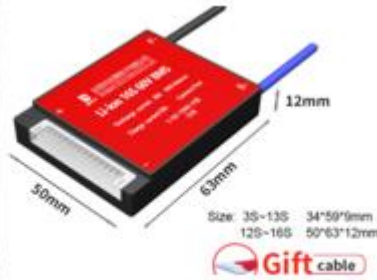
EAN / GTIN	7417940526829
Brand	BAK
Size	18650
Battery chemistry	Li-Ion
Battery	Rechargeable
Voltage	3.6V
Min. capacity in mAh	2,900.00
Battery version	Flat top
Discharge current	8.25
Circuit protection	Unprotected
Height in mm	64.85
Diameter	18.35

<https://www.power-xtra.com/uploads/content/900600503277-dspdf.pdf?v=1561713363>

Additional material needed to build the pack:



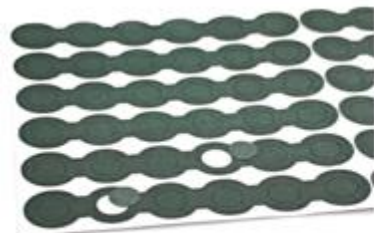
13s4p spacer (247,76mm)



13s, 20 amp bms



0.12mm nickel strip



Positive side insulation



Insulation for around the pack



Kapton tape



14 AWG wires



XT60 connectors



155mm heat shrink wrap



54.6v charger

Pack Assembly:

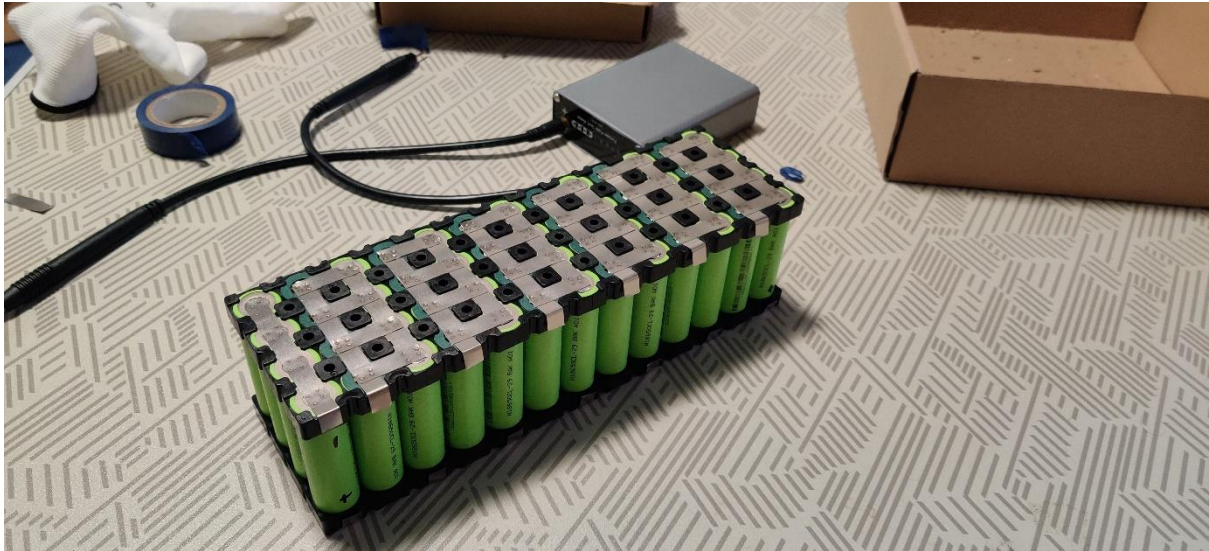


First step was to Check the voltage of each cell, they were new, from a reputable online shop and so every single cell was about 50% charged which is essential for storage. (3.7volts)

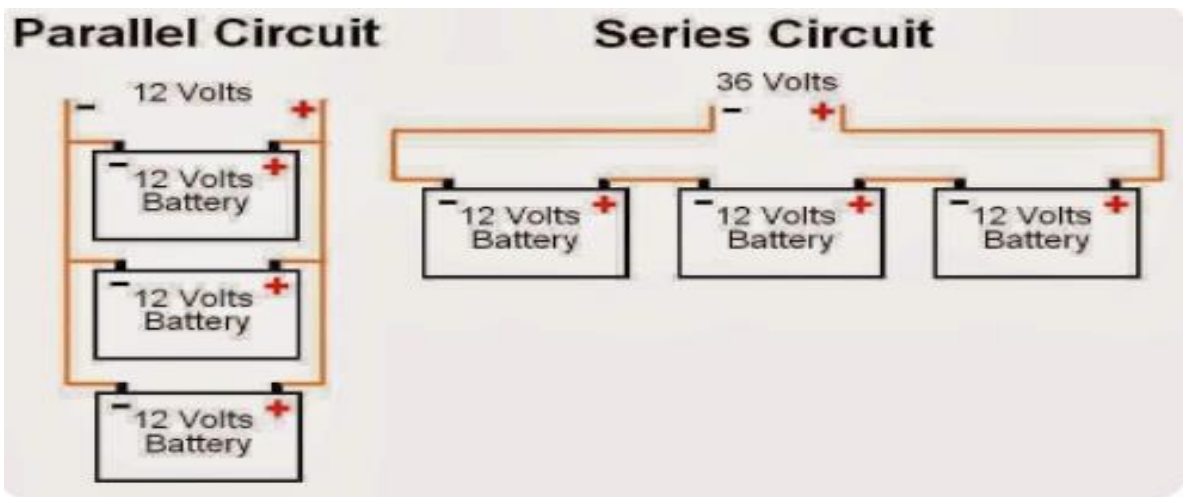
The positive ring insulation was then added to every single cell (prevent short circuits). The cells were then placed in this order inside the 13s4p spacer plastics in a set of 13 series going one series in one direction, then the following in a different direction, this made for the 13 connections in series, 4 in parallel.



The nickel strips for the parallel connections were cut to size and spot welded on both sides of the battery pack, leaving a tab on the first negative (which is at the top left corner) and then each positive to later on solder the bms leads.



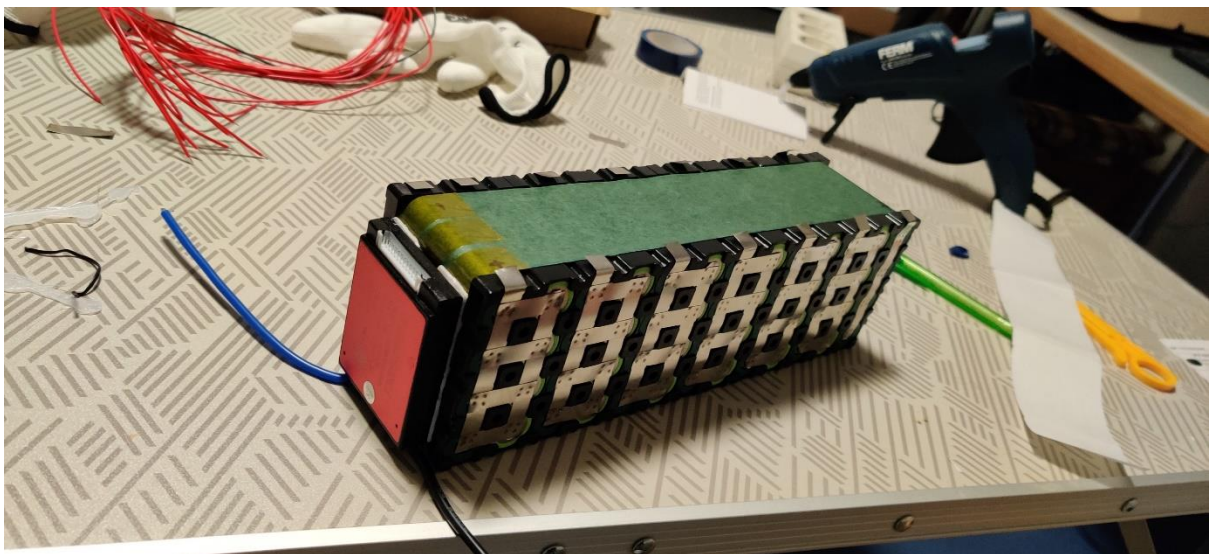
The series connections were then spot welded on, this made it into a big 48v battery.



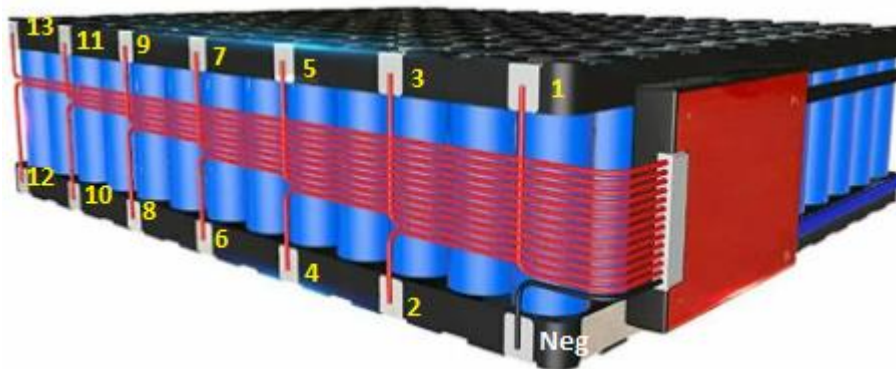
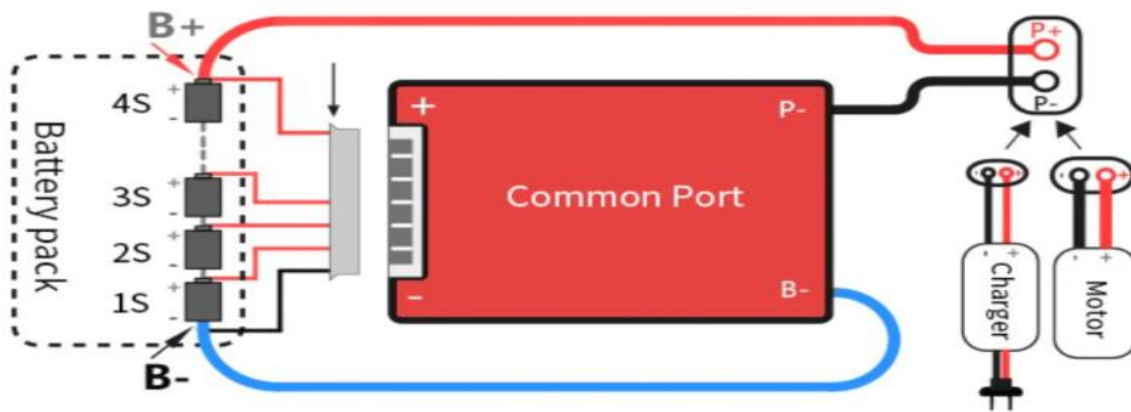
Series connections, parallel connections.



Checked voltage to make sure it was the correct one, before starting to cover the outer terminals with the insulation paper. The connection on the top left is the first negative and the far one on the right, bottom side is the last, positive one.



Insulation paper done and secured with Kapton tape, then placed bms with double sided tape.



This is how it is connected positive most goes straight to the end connection, 13 (top left in this picture above), the B- from the output, along with the negative cable lead from the bms go to the most negative connection of the battery, So as it can be seen on the picture above, the very first bms lead wire is the negative black, then the one that follows goes to the next first positive, the following to the next positive and so on. On each connection voltage goes from 3.7v from the first series to 7.4v, 11.1v, 14.8v.... and so on until the 13th series which will be around 48v and when it is fully charged each series will be 4.2 v, which then multiplied by 13, total voltage will be 54.6v

The bms will make sure each series is balanced and the pack won't get either overcharged or when it reaches a certain level when being discharged, the bms will shut off the power, that way the pack wont have a low DOD or depth of discharge, therefore it wont get damaged.



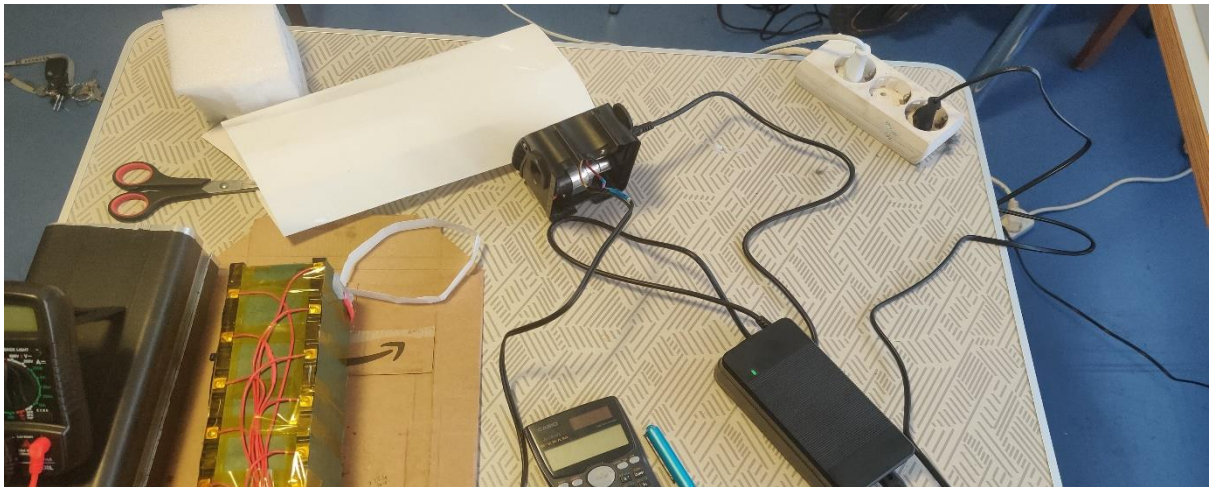
Soldered the power wire to the last positive connection.



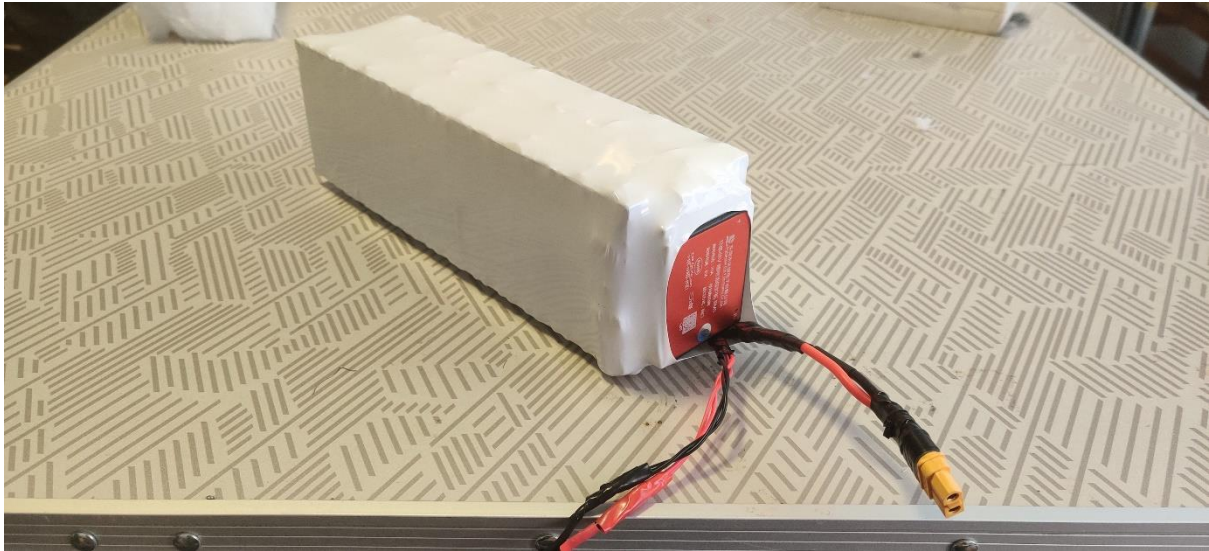
Soldered all the bms leads to the series tabs and then proceeded to add more kapton tape for extra insulation. Since it is a common port bms, the wires for the charger and the output current go to the same place. Soldered the xt60 connector (controller also uses xt60 connector) and checked voltage. Battery is half full, so 48.3 was all right.



Pack needed to be charged, so connected the charger to the wall outlet. Light on the charger was red, which is a good sign, it is charging.



After a few hours, the charger light turned green, and volt meter read 54.6 volts. For a 48v battery, this is the voltage that shows it is fully charged.



After checking that in fact all leads were 4.2 volts each, next safety step was made and added the shrink wrap to cover the whole pack, used a hair blower for it.



Very las step was to fit it in my ebike's batterx box, connected it to the bike and it ran around 74kms on the first cycle. Kept it running for about 200 kms more and was put away with a state charge of 50% when the winter came, so the capacity wouldnt degrade according to what has been researched.

