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AN INVESTIGATION INTO THE SUSTAINABLE LITHIUM BATTERY PACK DESIGN

Investigation of optimal lithium battery pack design in regard to safety, repairability, second life, and mass production.

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Abstract

The global demand for electricity is rising due to the increased electrification of multiple sectors. Whereof electrical vehicles are becoming increasingly popular. In addition, the European Parliament issued a ban on emission vehicles by 2035. Lithium-ion batteries have become one of the main energy storage solutions in modern society the production and use. Its use is expected to continuously increase in the near future. However, the handling of end-of-life lithium-ion batteries must be addressed considering that a massive number of lithium batteries that are not refurbished for second life systems will retire and enter the waste stream at the same rate just at a delay of 8-15 years. Furthermore, the process of EV battery pack repair is currently unutilized except for some trial facilities. While the second life of EV batteries just recently started to exploit the energy and economics that went into battery production by utilizing the remaining battery capacity. While The optimization of recycling processes and technologies, and the current recycling are still under development.

This thesis demonstrates the need for design changes in mass production to facilitate battery repair and the possibility of introducing second life battery systems. In addition to making further development of recycling methods possible.

The four pillars of this thesis are safety, second life, recycling, and mass production. This study contributes to this by identifying factors that affect these pillars in relation to lithium-ion battery packs. This is achieved by a systematic literature review and applying a PEST analysis (political, economic, social, and technological factors). Followed by implementations based on a SWOT (strengths, weaknesses, opportunities, and threats) analysis meant to challenge the current norms in li-ion battery pack production. Furthermore, this thesis presents comprehensive results and a discussion of the interconnection and the contradictory design optimization for the four pillars.

The results indicate that given the proper incentives, industry norms can change to better accommodate the complete life cycle of the lithium-ion battery. Ultimately allowing for battery pack repairs, better conditions for the profitability of second life, and the development of more efficient recycling processes.

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List of Abbreviations

BESS	Battery Energy Storage System
BMS	Battery Management System
BNEF	Bloomberg New Energy Finance
BTMS	Battery thermal management system
CTC	Cell to chassis
CTP	Cell to pack
EOL	End of Life
ESS	Energy storage system
EV	Electric Vehicle
GCTPR	Gravimetric cell-to-pack ratio
IRENA	The International Renewable Energy Agency
kWh	Kilowatt-hour
LCOE	Levelized Cost of Energy
li-ion	Lithium ion
MWh	Megawatt-hour
NCA	Lithium-nickel-cobalt-aluminum
NMC	Lithium-nickel-manganese-cobalt

PEST	political, economic, social and technological
PV	Photovoltaic
SOC	State of Charge
SOH	State of Helth
SWOT	strengths, weaknesses, opportunities, and threats
VCTPR	volumetric cell-to-pack ratio

Gravimetric energy density: Amount of stored energy related to the battery cell, module, pack or system weight expressed in Wh/kg. (ISO 12405).[1]
Volumetric energy density: Amount of stored energy related to the battery cell, module, pack or system volume expressed in Wh/l. (ISO 12405).[1]
Capacity: Total number of ampere-hours that can be withdrawn from a fully charged battery under specified conditions. (ISO 12405) (Ah)[1]
Rated capacity: Capacity value of a cell, module, pack or system determined under specified conditions and declared by the manufacturer. (IEC 61960) (Ah)[1]
Current rate or C-rate: the current that corresponds to the declared capacity by the manufacturer.
State of Charge (SOC): Available capacity in a cell, module, pack or system expressed as a percentage of rated capacity. (IEC 62660) (%)[1]
Depth of Discharge (DOD): Percentage of rated capacity discharged from a cell, module, pack or system battery. (IEC 62281)[1]
Cycle life: The total amount of specified duty cycles a battery cell, module or pack can perform until it reaches its End of Life.
Calendar-life or shelf-life: The time a battery cell, module or pack can be stored under specified conditions (temperature) until it reaches its end of life condition
Nominal voltage: Suitable approximate value (mean value between 0% and 100% DOD) of the voltage during discharge at a specified current density used to designate or identify the voltage of a cell or a battery. (IEC 62620) [1]
Specific energy / Gravimetric energy density: Amount of stored energy related to the battery cell, module, pack or system weight expressed in Wh/kg. (ISO 12405) [1]
Volumetric Energy density: Amount of stored energy related to the battery cell, module, pack or system volume expressed in Wh/l. (ISO 12405) [1]

Abstract

The global demand for electricity is rising due to the increased electrification of multiple sectors. Whereof electrical vehicles are becoming increasingly popular. In addition, the European Parliament issued a ban on emission vehicles by 2035. Lithium-ion batteries have become one of the main energy storage solutions in modern society the production and use. Its use is expected to continuously increase in the near future. However, the handling of end-of-life lithium-ion batteries must be addressed considering that a massive number of lithium batteries that are not refurbished for second life systems will retire and enter the waste stream at the same rate just at a delay of 8-15 years. Furthermore, the process of EV battery pack repair is currently unutilized except for some trial facilities. While the second life of EV batteries just recently started to exploit the energy and economics that went into battery production by utilizing the remaining battery capacity. While The optimization of recycling processes and technologies, and the current recycling are still under development.

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The four pillars of this thesis are safety, second life, recycling, and mass production. This study contributes to this by identifying factors that affect these pillars in relation to lithium-ion battery packs. This is achieved by a systematic literature review and applying a PEST analysis (political, economic, social, and technological factors). Followed by implementations based on a SWOT (strengths, weaknesses, opportunities, and threats) analysis meant to challenge the current norms in li-ion battery pack production. Furthermore, this thesis presents comprehensive results and a discussion of the interconnection and the contradictory design optimization for the four pillars.

The results indicate that given the proper incentives, industry norms can change to better accommodate the complete life cycle of the lithium-ion battery. Ultimately allowing for battery pack repairs, better conditions for the profitability of second life, and the development of more efficient recycling processes.

Chapter 1

Introduction

1.1 General

Climate change, also known as global warming, is a complex and pressing matter with considerable attention in media and academia. The global warming crisis is caused by high amounts of greenhouse gasses emitted into the environment[2]. Consequently, causing hotter temperatures, more severe storms, increased drought, warming that causes the ice to melt and further the oceans to rise, loss of species, food shortage, more health risks, poverty, and weather-related refugees[3]. The most significant contributor to climate change is the use/consumption of fossil fuels, accounting for over 75% of greenhouse gas emissions and nearly 90% of carbon dioxide emissions[3].

Fossil fuels play a major role globally, gas is used for cooking and heat, while oil and coal are burned as fuel-driving generators to produce electricity and stabilize electrical grids[4]. Fossil energy generation accounted for 81% of the primary energy demand in 2019[5].

Substituting fossil fuels used in vehicles and other forms of transportation with an increasing amount of renewable energy in the power grid is one step in the right direction to achieve carbon neutrality[6]. When the grid is clean, the efficiency of implementing electric vehicles or energy storage systems (ESS) for load distribution becomes valuable. The total conversion from fossil sources to renewables requires the grid to support energy needs regarding accessories like heating and transport. The transport alternative most favored to replace the carnot-engines seems to be the fully electric vehicle (EV). However, the reduction in pollution by converting to EV is insignificant if the grid that charges the EV uses high percentages of electrical energy based on fossil fuels. The convenience of fossil energy is mainly due to its inherent ease of regulation, where energy demand can be matched by increasing fuel consumption. Renewables, however, are generating energy using sources that are inherently uncontrollable, including, but not limited to, wind speeds or sun irradiation. Subsequently resulting in an unreliable energy production schedule.

Whereof the power grid requires stability to operate due to load balancing in regard to the consumer- and supply side. An ESS can help as a buffer capacity and provide the needed load shaping during times of limited production [7, 8].

1.2 Buffer Grid-support

The need for systems able to store electrical energy is predicted to increase due to the transient behavior of energy generated by renewable sources. The main sources are wind, solar, and in some cases, hydro, which cannot be regulated to meet consumer demand. Subsequently, a buffer system is required[7]. The buffer system, or ESS, makes the electrical grid able to balance demand and supply by holding excess energy for later use. The excess energy can be stored as chemical, potential, electrical, or mechanical energy. When needed, the stored energy can be extracted as electrical energy.

The ESS can be further divided into long-term and short-term energy storage systems. Examples of effective long-term storage systems include some chemical energy storage systems like hydrogen and ammonia and large scale potential energy storage systems like pumped hydro, compressed-air, and crane energy storage systems[9]. Short-term energy storage systems, able to charge and discharge energy for short periods at rated power, are useful in fluctuating energy needs[9]. Whereof, short-term energy storage like flywheels has the energy capacity diminishing in a span of minutes, and is subsequently mostly used for grid frequency stabilizing[10].

There is no buffer system best suited for all applications. However, lithium ion batteries (li-ion) can address all application areas at a relatively high expense[10]. It is scalable to the requirement and is used in a wide range of applications. Furthermore, the li-ion battery is considered the key technology for the electrification of the transport sector[11]. Essentially extending the reach of the "clean" energy grid to be utilized without a direct grid connection. Li-ion batteries play a crucial role in transitioning to a climate-neutral economy.

1.3 Market Drivers

The research and development within the li-ion battery industry are driven by the increasing demands of the EV industry and the integration of renewable energy sources using battery support like solar panels[12]. Market drivers within the automotive sector like rising fuel prices and CO_2 emissions. Making the transition to EVs becomes more profitable for the consumer. Whereof countries and vehicle manufacturers are phasing out the carnot-engine to accommodate for the increasing demand. By 2040, most cars sold are estimated to be fully electric using li-ion technology [13]. Additionally, on 28 Oct 2022, the European Parliament and Council provisionally agreed that all new vehicles registered in Europe must be zero emission by 2035[14]. A total of 6.6 million EV's sold worldwide during 2021[15]. Subsequently, the li-ion battery part of the EV usually accounts for 200-400kg of the car's total weight and a major portion of the EV's value. Estimating the total use-time of a battery to be approximately 12 years[16], close to 12 million tons of used batteries will require processing by 2033. Additionally, further development and mass production of li-ion batteries for use in EVs has caused a steady decline in battery prices, expected to reach 75USD/kWh by 2030 [17]. Humans also have an inherent fear of the unknown, further impeding the transition from fossil fuelled vehicles to EVs. The risks of explosion and fire associated with fossil fuelled vehicles are known and accepted by society.

1.4 Battery Pack

In EVs and BESS, the battery is mostly referred to as a battery pack consisting of multiple battery modules that further contain battery cells. These battery cells have characteristic design features that will affect some design choices of the overall pack. The most common battery cell types being used are pouch, cylindrical, or prismatic cells. Some new designs in the EV market have led to a development in Cell to pack (CTP) or Cell to chassis (CTC) technology. Whereof the module part is being replaced by integrating the cells directly into the battery pack or the vehicle's body, respectively. The CTP and CTC designs are, however, not the focus of this report. These will be introduced and discussed further in the report's later stages. This thesis will focus on the cell-module-pack layout. The goal is to define, clarify, and optimize for problems and challenges within present-day battery pack manufacturing regarding mass production, safety, second life, repairability, and recycling.

Chapter 2

State of the Art

The following chapter reviews the implemented and used methods of production, safety, second life, repairability, and recycling of battery packs. The intention is to characterize and provide a solid foundation for the development of the method chapter. The focus areas of the state of the art are based on European standards and regulations.

2.1 Mass Production

2.1.1 Battery Pack Explained

A battery pack is a device that can store electrical energy for later use. The battery packs that are in focus in this thesis are larger battery packs like the ones found in EVs or ESS. The single li-ion cell has low power characteristics shown in table 4.1 in the theory chapter. Subsequently, cells need to be arranged in series to boost voltage and in parallel to boost capacity.
The battery pack is a complex system consisting of a wide range of components, scematic summary shown in Figure 2.1.

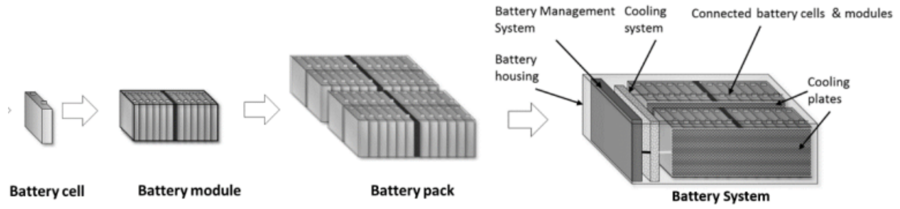

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Figure 2.1: Scematic summary of cell to pack [18]

- Battery cell is the most important component of the battery pack. It can differ in chemistry used in anode and cathode material. However, the industry uses cathode material for clasification purposes, further explained in section 4.1

- Battery housing is used as a protective shell to separate the battery from the potentially damaging environment.
- Battery management system (BMS) is a protection system that monitors key parameters like cell voltages, currents, and temperatures. The BMS is responsible for cell voltage balancing, temperature control, and protection device.
- Cooling system or battery thermal management system (BTMS) controls the thermal energy of the battery. It can supply or remove heat depending on design to achieve optimal cell operating conditions.
- The electrical connectors connecting the cells and modules consist of busbars, wires, or other distribution conductors. These connectors create the series and parallel connections of the cells previously mentioned.

2.1.2 Auxiliaries

It is beneficial for an individual module to have its thermal management system to regulate temperature. It also helps provide internal insulation preventing heat and current transfer between cells.The battery pack charging and discharging is a chemical reaction that generates heat as a by-product. Heated battery cells degrade the battery and reduce its lifespan. Subsequently, a Battery Thermal Management System, or BTMS for short, is needed. Additionally, the power electronics used in the battery suffer conductivity loss resulting in lower efficiency at higher temperatures[19]. Some components of an effective BTMS include heat exchangers, tubes, hoses, cold plates, pumps, valves, and temperature sensors.

The battery management system, BMS for short, is a controlling system responsible for monitoring temperatures, voltages and currents, maintenance scheduling, battery performance optimization, failure prediction and/or prevention, and battery data collection/analysis [20]. The need for the BMS stems from li-ion cells failing or exploding if undercharged or overcharged, respectively. It subsequently requires its operating area to be absolute for safe operating conditions. The cell operating area is shown in table 4.1 in the theory chapter. And the overcharge is mentioned in subchapter 4.1.3.

2.1.3 Housing

In automotive use, the housing is a complete hard shell that separates passengers from the battery-cells in case of battery failure. The same requirements for outer casing do not apply to stationary battery storage regarding battery housing. Due to this, the stationary BESS can benefit from a freely aspirated air cooling method, with the advantage of structure simplicity[21], like an open cabinet or a direct wall mount, essentially removing the need for housing entirely.

However, there is no standardization in regard to fixings used for the housing. As a result, the placement of the fixings and the tools required to open them are manufacture specific[22]. The lack of standardization heavily reduces the recyclability of the pack[23].

2.1.4 Modules

Modules that are used in applications like automotive and other nonstationary battery energy storage systems need extra design features. These are aimed at reducing the impact of extrinsic fault conditions like vibrations, temperature, and impact force while keeping volume and weight as low as possible. The battery pack can consist of multiple modules, where the conjoining of modules can be done with mechanical fixings for ease of disassembly and servicing purposes. The automotive industry uses welding due to the reduced risk of vibration induced disassembly. Different welding methods are mentioned in Table 2.1 along with their advantages and disadvantages[24]. Additionally, the number of modules in the battery pack can vary depending on the requirements for a battery pack's voltage, current, and capacity.

2.1.5 Cell Design and Interconnections

The framework starts with cell sorting, where voltage, capacity, and internal impedance are matched using barcode scanners. The sorted cells are then stacked and fitted together using welding, adhesives fittings/screws, or cell spacers/battery holders. With the overall intention of minimizing/restricting the movement of the cells to reduce the risk of wear and tear on the connections and components. The choice of movement restrictors is usually dependent on the use case and cell type. Where Heimes et.al[25] recommends fittings related to cell type.:

- Pouch cells: Housings where the casings are fitted with flexible springs. To accommodate for expansion and shrinking of the cells.

- Cylindrical cells: Cell holder, where the cells are fixed by module case.

- Prismatic cells: Individual cells are glued together and further clamped together with a bandage and/or a plastic or metal housing.

Battery holders are used to reduce internal movement or acquire proper cell spacing for ventilation purposes[25].

2.1.6 From Cell to Pack

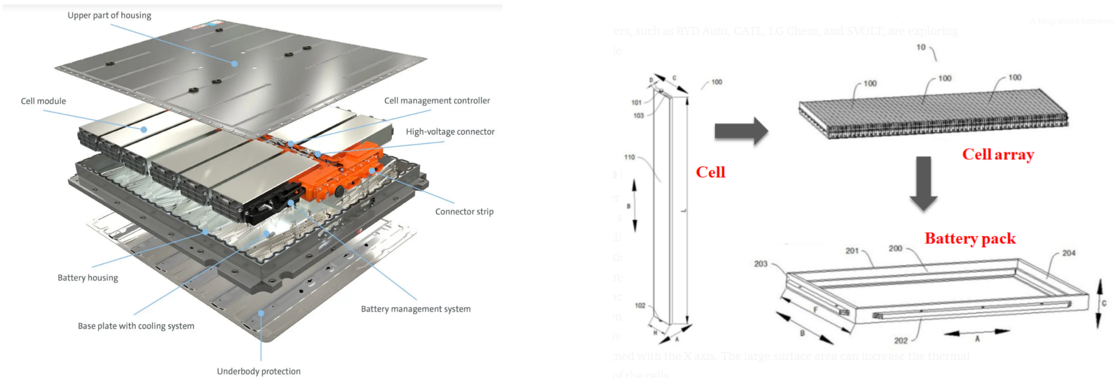
Today's mass production and assembly of li-ion packs consist of several procedures. Whereof the module assembly entails the process of establishing the framework, cooling systems, electrical components, and cell fitting[26]. The assembly of cells in a structural and/or shock-resistant container is defined as the module. The module casing defines the geometry in addition to minimizing problems caused by swelling[25]. The assembly of battery cells into a battery module is an increasingly automated process mostly performed by specialized manufacturing robots[27]. Where the conjoining methods used can differ. A summary of conjoining methods is presented in Table 2.1 along with advantages, disadvantages, and related issues and concerns.

Joining thecnology	Advantages	Disadvantages	Issues and Conserns
Ultrasonic welding	Fast process, high strength and low resistance, able to join dissimilar materials, low energy consumption	Only suitable for pouch cells, two sided access, slow joining, hard to disassemble	Access of anvil and sonotrode needs to be well designed
Resistance spot/projection welding	Fast process, low cost, good quality control, easy automation	Difficult for highly conductive and dissimilar materials, hard to disassemble	Difficulty to produce large joints, joining of more than two layers
Micro-TIG/pulsed arc welding	Low cost, high joint strength and low resistance, able to join dissimilar materials, easy automation	High thermal input and heat affected zone, porosity, hard to disassemble	Difficult to join aluminum to steel
Ultrasonic wedge bonding	Fast process, acting as fuses, able to join dissimilar materials, low energy consumption and easy automation	Only suitable for small wires, low wire and joint strength, hard to disassemble	Clamping of the batteries is critical
Micro-Clinching	Cold process, no additional part, clean process, able to join dissimilar materials	Only suitable for pouch cells, two side access, slow joining, hard to disassemble	Loosening under vibration, moisture ingress
Soldering	Joining dissimilar materials, wide spread in electronics industry, can be disassembled	High heat, fluxes required	Joint strength, debris, neutralisation of fluxes
Laser welding	High speed, less thermal input, non-contact process, easy Automation	High initial cost, additional shielding system may required, hard to disassemble	Need good joint fit-up (intimate contact), high reflective materials
Magnetic pulse welding	Solid state process, able to join dissimilar materials, high joint strength, dissimilar materials	Potential large distortion, rigid support required, hard to disassemble	Possibility of eddy current passing through the cells
Mechanical assembly	Easy dismounting and recycling, easy repair, cold process	Additional weight, high resistance, expensive	Potential mechanical damage and go loose

Table 2.1: Revised conjoining methods used in industry for module assembly[24].

Some of the joining technologies mentioned in Table 2.1 have specific use cases due to their interactions with cell designs and materials. For example, ultrasonic metal welding not being recommended for the terminal to busbar joints for prismatic and cylindrical due to pressure and vibrations having negative effects on structural integrity. While welding and gluing, in general, excludes the opportunity for non-destructive disassembly in regard to second life and recycling. Welding and gluing are, however, used due to simplicity and being the fastest and cheapest known way of conjoining terminals and modules, where the end goal is a compact design able to withstand vibrations and other extrinsically damaging factors at a low cost.

Some of the leading battery pack manufacturers today are developing battery packs with reduced complexity while increasing the overall efficiency with solutions like modular electric drive matrix Figure 2.2a by Volkswagen and CTP/module-free design by CATL and BYD Figure 2.2b. These are meant to optimize the design for NMC(Lithium-nickel-manganese-cobalt) and LFP(Lithium-iron-phosphate-cobalt) chemistry, respectively. The modular electric drive matrix design introduced in 2018 shifted the focus towards a less complex, almost LEGO-like design where the number of cells can be varied according to customer specifications and demand, while the overall fundamental structure remains the same. The scaleability the modular electric drive matrix provides, makes for a more customized and affordable EV[28, 29, 30, 31, 32]. The CTP technology takes the reduced complexity one step further by removing the need for modules altogether while increasing the individual cell size. The Cell-to-Pack design focuses on increasing the overall volume efficiency of LFP battery packs. Volume efficiency can be quantified by the volumetric cell-to-pack ratio (VCTPR). The usual VCTPR of EVs is below 0.4. However, CATL and BYD technology using CTP increase VCTPR to 0.62, while additionally increasing the gravimetric cell-to-pack ratio (GCTPR), meaning the ratio of the total mass of the cells divided by the mass of the complete battery pack from EV standard GCTPR of 0.55-0.65, goes to 0.85. Achieved by removing the need for inactive elements like metal cases, cabling etc. that usually take up 35-45% of the total battery pack weight[33].



(a) modular electric drive matrix[30]

(b) CTP[34]

Figure 2.2: Design representation of (a)modular electric drive matrix and (b)Cell-to-Pack.

2.2 Safety

Accidents and faults are in high quantities or, for extended periods, unavoidable. The more units in operation, the more apparent the product flaws become. Safety is defined as the freedom from unacceptable risk involving physical injury or damage to the health of people or damage to property or the environment.

The li-ion battery pack can hold large amounts of power that can be discharged in a short amount of time when shorted or faulty, causing li-ion batteries to be high-risk equipment that requires high safety standards and quality consistency. The goal of the standards is to ensure the overall safety of the product, activities, and processes, thereby reducing the use risk of the user/customer. Standards are to be relied upon in accordance with specifications, instructions, and information provided by the supplier. Thereby ensuring safe use in a way that is not intended by the supplier but may result from human behavior. Cells and packs are subsequently designed and constructed to be safe under the conditions of intended use and reasonably foreseeable misuse. It is further expected that cells and batteries under intended use shall continue to function in all respects. At the same time, the batteries subjected to misuse may fail to function. However, even if such a situation occurs, they shall not present any significant hazards due to standards of safety. Safety measures included in a battery pack prevent thermal runaway, over-charge/discharge, external short circuits, and physical abuse tests. Multiple standards have been developed to grade the overall performance within these sections and more.

The design needs to be such that abnormal temperature-rise conditions are prevented. Where battery systems are designed to limit voltage, current, and temperature according to chemistry is in place. Safety systems like the BMS need to provide specifications and charging instructions so that associated chargers are designed to maintain charging within the voltage, current, and temperature limits specified. Internal wiring and insulation shall be able to withstand the maximum anticipated voltage in accordance with current, temperature, altitude, and humidity requirements. The design of the wiring should provide adequate clearances and creepage distances between conductors. And the overall mechanical integrity and connections should accommodate for conditions of reasonably foreseeable misuse. The casing of a cell, module, battery pack, and battery system requires a pressure relief function that will preclude rupture or explosion. Additionally, if the battery pack is surrounded by solid housing, it shall neither cause the battery system to overheat during normal operation nor inhibit pressure relief. Battery pack terminals require clear polarity markings on the external surface. With the terminal contact designs in such a way, they minimize the risk of short circuits. The terminals should have sufficient size and shape to carry the battery's maximum current. Voltage control functions inherent in the battery design shall ensure the voltage is limited within the operating region of the cells to ensure safe use. It is recommended that the voltages of any one of the single cells or cell blocks do not exceed the upper limit of the charging voltage.

Damaged li-ion batteries have a risk of self-igniting or reigniting after being extinguished. Making use of and handling such damaged li-ion batteries is extra hazardous. This information regarding the damaged state of the li-ion battery is important and detrimental in handling procedures like towing, workshop, scrapyard, or recycling activities[35]. The li-ion batteries' safety depends on chemistry, operating environment, and abuse tolerance. Safety standards for new batteries are under constant development to ensure the battery performs without future safety problems under normal working conditions. Strict and high standards like the GB/T 31485–2015 standard developed in China[36] makes the currently produced li-ion batteries safer than the previous generations.

2.3 Repairability and Second Life

In this subchapter, the repairability and subsequently second life are investigated. A single damaged cell can affect the module's overall state of health and, in some cases, lead to an otherwise healthy battery pack being replaced. By making it possible to replace a single faulty cell when damaged, losses and costs can be kept to a minimum. A US-based company named Spiers New Technologies (SNT) specializes in 4R services (repair, remanufacturing, refurbishing, and repurposing) for EV packs. And by collaborating with the original manufacturer of the pack, aim to make specialized and optimized processes. Currently the SNT can provide 4R services for manufacturers such as Nissan and General Motors. With plans to extend to the European and China automotive market. And in Namie, Japan, Nissan has built a facility to remanufacture EV batteries for Leaf[37]. Despite this, the author finds little to no academic or other information that goes further than mentioning the startup of these test factories and programs in regard to cell replacement. However, other aspects of battery pack repair include the replacement or refurbishment of the BTMS, BMS, conductors, etc. In an article [38] by H.Rallo et al. done in Spain using engineer labor cost at 50 €/hour excluding facilities costs, electric cost, and machine cost estimated costs for EV battery removal at 117€. Post-auto battery assessment, including inspection and handling, battery characterization, and inspection at 442€, and further the removal of individual parts presented in table 2.2 and table 2.3.

Activity	Human power	Time [minutes]	Cost [€]
Removal of package	2	30	50€
Extraction of battery junction box	2	45	75€
Disconnection and extraction of cell module controllers	2	45	50€
Disconnection and extraction of BMS	2	30	50€
Dismantling of pre-charge circuit	2	30	50€
Extraction of modules	2	60	100€
Separation of HV battery base from HV battery support frame	2	20	33€
Removal of humidity buffer	2	20	33€
Removal of cooling plates	2	20	33€
Total		**300**	**500€**

Table 2.2: Price estimation of EV battery pack disassembly to modules by H.Rallo et al.(2020)[38]

Activity	Human power	Time [minutes]	Cost [€]
Removal of top metallic structure	2	60	100€
Removal of sensor wiring and connectors	2	30	50€
Removal of bottom metallic structure	2	45	75€
Disassembly of cell stack	2	30	50€
Total		**165**	**275€**

Table 2.3: Price estimation of EV battery module to cell disassembly by H.Rallo et al.(2020)[38]

The battery pack disassembly cost is vital for the pack's overall repairability and second life possibilities. Where second life refers to battery components deemed end of life (EOL) in the manufacturer's intended purpose, application, function, or context[39]. In the case of an EV battery pack, the battery pack can be remodeled to be used as a BESS.

In order to create a viable circular economy, society needs to be ready to receive and process the high amount of li-ion batteries reaching EOL. The primary source of the li-ion batteries is the automotive industry. With more than 2.3 million EVs sold in Europe in the year 2021 a 63% increase from the 1.45 million sales of 2020 shown in Figure 2.3.

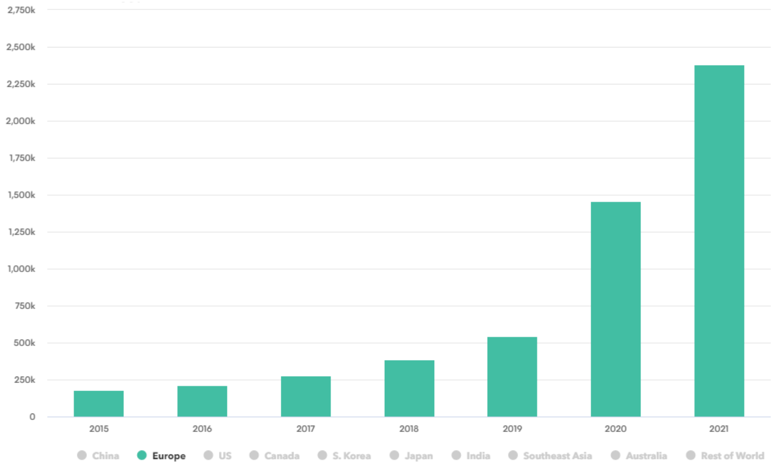


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Figure 2.3: Sales of electric vehicles in Europe by year [15].

Studies have been performed to evaluate what stakeholders have the most impact on the EOL scenario of li-ion batteries. Governments and battery-related businesses are considered the most impactful when considering a circular business model study performed by Wrålsen et.al[40]. Here it is argued that the businesses and government must work together to create and develop new standards and regulations based on product valorization from production to recycling[40].

The EV industry labels the li-ion battery as end life when the state of health (SOH) is approximately 80%[39]. This usually accrues after a use period of 8 to 15 years[38, 41]. This gives a foundation for the estimation of batteries available for second life and recycling according to the yearly sales of EVs[42].

At the EVs battery pack EOL the batteries are still valuable for applications where weight and volume requirements are lowered. BESS is not limited by weight or volume in the same way as EVs. For BESS purposes, the overall loss of energy density is of little to no concern. Thereby providing the foundation for a secondary market for used batteries to emerge. Due to the high energy demand of critical materials in tandem with a high amount of fossil energy in grids, high specific energy li-ion batteries are indicated to be better suited for recycling rather than second life. However, this estimate was done with material refining using up to 50% penetration of renewable energy sources into the supplying power grid, performed by Tao et al.[43].

The need for li-ion battery reusability is well documented in academia, where the improvement of overall sustainability is researched. Several high-quality reviews performed on profitability and viability of second-life BESS have yielded positive results in regard to emission reduction and economic performance[43].

However, there is a common consensus that guidelines regarding an echo-friendly design will be necessary to ensure profitability[16, 44, 38, 45, 46]. Thereby providing further incentives for companies to develop procedures and shift manufacturing to accommodate for second life li-ion battery technology.

The echo design will need to adhere to safety standards and regulations. Things that make for poor echo design, like foams, welding, and gluing, are directly linked to good internal battery integrity and subsequent safety. Additionally, the housing, covers, and screw terminals used to open the li-ion battery packs are varied in design and layout, possibly to avoid consumer tampering that can have a negative effect on battery safety. However, this further impedes the battery dismantling process in terms of time/cost benefit. Whereof, a battery pack designed towards non-destructive dismantling might greatly affect procedure safety and value preservation in regard to battery reusability.

Second life of li-ion battery cells has good backing by the literature with positive conclusions. Furthermore, it has been demonstrated that the remaining life of a li-ion using a daily charge/discharge cycle is ten years, where the remaining SOH is expected to be approximately 65% [47]. Ultimately the overall lifetime of li-ion batteries is 20 years when utilizing primary and secondary applications[16]. The literature primarily focuses on environmental impact, technical limitations, and possibilities in addition to economic gain and its overall potential.

2.4 Recycling

The seemingly ever-increasing sales of li-ion batteries create the requirement for recycling to meet the demands following the up-scaling of the li-ion battery production. The overall efficiency of procedures regarding material recovery and energy usage in the recycling of li-ion batteries today is lacking. Steps are needed in regard to procedures to develop the tech and procedures needed to sufficiently handle the surge of end-life batteries.

In an article presented by Mossali et al. [46] it is mentioned that pyrometallurgy is the most used recycling technique as of 2020. A process based on using high temperatures in three phases:

- Pyrolysis: the act of burning and degradation of organic components.
- Metals reduction: the separation of metal alloys utilizing high temperatures ≈1500C° and proper reductive agents.
- Gas incineration: the pyrolysis and quenching of gasses at ≈1000C°

The best economic value comes from the extraction of Co, Cu, steel, Ni, and Al collected while plastics, Li, Mn, and graphite are rarely considered more than the rest products[46, 39]. The profitability of recycling is heavily reliant on high Co content and other precious metals.

The recycling processes of li-ion batteries, in general, allow for the extraction of materials at a lower cost and lower CO_2 emissions compared to the mining and import of virgin materials. While additionally avoiding spillage of toxic materials like cobalt and fluoride into nature. Some of the battery materials are additionally relatively rare or have high extraction emission making use of second life more valuable[45]. The high benefit of li-ion battery recycling is both economic and environmental regarding some materials used having a potential supply risk like natural graphite, lithium, and cobalt where a well-developed recycling process can keep these materials circulating[39]. There is high potential for development within the recycling of li-ion batteries due to the overall extraction rate of materials and the high amount of energy used in pyrometallurgical procedures. There are practices that directly impede the overall development of li-ion battery pack recycling processes, these being:

- Fast-developing chemical difference in the cathode material[48, 49]
- Pack design where non-destructive disassembly is infeasible due to welding[48, 39, 46, 50]
- Lack of sufficient labeling of battery pack containing cell type, cathode material etc.[51, 46, 39]
- Non-standardised disassembly procedures[48, 39, 46, 50].

The pyrometallurgical processes can separate the metals despite chemical differences in the cathode material. However, it comes at a high capital cost, high emissions of hazardous gasses, high loss of about 60% lithium, and a high energy consumption[13].
The continuous development of li-ion chemistry aims to reduce the dependency on critical materials like cobalt. However, reducing cobalt content reduces the overall profitability from a recycling perspective. Incentives can be made to valorize all extractable materials related to the recycling processes might stimulate a more circular economy[39].
Li-ion batteries tend to be built into devices and equipment. This interferes with the separation of the li-ion and device before disposal. It was subsequently contributing to a lower collection rate than other battery types like lead batteries. The best-case scenario delays the time for batteries to reach recycling facilities increasing the transportation and labor required. Worst case, the battery containing valuable and potentially toxic materials is lost from the loop, completely corroding in a landfill. The most effective solution to improving the sustainability of li-ion batteries is to avoid or reduce the usage of these critical materials, according to the waste management hierarchy designed to guide and rank waste management approaches towards what is most beneficial for the environment[43].

A perfect recycling outcome would be close to 100% material extraction by simple dismantling and separation. Rolling out and separating the cathode aluminum and li-oxide layer and the anode copper and graphite layer, collecting the separator, and separating the cell casing and auxiliary electronics in the pack. A process able to perform this task would be unequivocally tailored to a specific pack design using automation. Of which all other iterations in regard to design would require independently tailored processes making for an impossible recycling model for general recycling purposes.
Recycling processes of li-ion are unfortunately still underdeveloped when it comes to energy consumption and overall emissions. In an effort to optimize the overall recycling procedures, some guidelines and incentives have to be implemented. The simplest and least taxing on producers is the labeling of packs. By adequately labeling chemistry on packs and cells, the sorting can be automatized, and specialized chemical procedures can be developed targeting the specific cathode material chemistry. Additionally, modern battery-pack designs are still not optimized in regard to recycling. Essentially reducing the overall value of the discarded battery packs. This may contribute to an unfavorable amount of discarded batteries corroding in landfills without recycling.
The current EU battery directive 2006/66/EC considers all batteries independent of cell chemistries. In comparison, the collection for recycling of lead-based batteries is 99 and 95% for lead automotive and industrial batteries, respectively. The directive proves lacking when incentivizing the same closed loop economy for li-

ion batteries where the collection rates remain unsatisfactory [52]. The collection rates for Li-ion batteries are low due to the high cost and energy consummation for material recovery[52].

Chapter 3

Problem Statement and Thesis Structure

3.1 Research Question

This thesis reviews the barriers to achieving sustainable lithium battery pack production considering economic, development, political, and industrial factors in regard to safety, repairability, second life, and mass production.

Investigate the requirements for optimal battery pack design in regard to safety, repairability, second life, and mass production.

3.2 Problem Statement

Since the research on design is aimed to accommodate end-of-life battery pack utilization is limited, and further how absent areas such as safety, work environment, and transport are in the overall literature. This thesis seeks to review the feasible improvements of battery pack design that can balance mass production, safety, second life, and recyclability in a viable way. By addressing issues that impede effective recycling and second life without impairing mass production capabilities or reducing safety measures.

3.2.1 Mass Production

The barriers of battery pack mass production

- Labor-intense
- Energy consumption
- Manufacturing cost

- Material supply
- Electrical and thermal challenges
- Material and metallurgical challenges
- Durable joint strength

The conjoining of dissimilar materials while keeping costs down makes welding and gluing the preferred conjoining method. These are able to provide and account for high joint strength, meeting material, metallurgical, and durability challenges mentioned in both safety and mass production. Welding and gluing, however, make non-destructive disassembly of the battery pack virtually impossible. The utilization of these permanent assembly methods should be considered the battery's complete life cycle. The goal is to develop guidelines for manufacturers of large-scale systems where the foundation for reusability is sufficiently accommodated. As the current trend in welding or gluing as a fastening method to conjoin individual parts of the battery creates problems for both second life and recyclability.

The material supply and cost incentivize the recycling of batteries to keep down the cost of essential materials. While electrical and thermal challenges arise from an ever-increasing demand for higher performance and charge rates by the consumer. The increased charge rates lead to safety concerns.

3.2.2 Safety

Academically and industrially practiced safety focus aspects

- Battery chemistry
- Design
- Thermal abuse
- Electrical requirements
- Mechanical abuse

Welding and gluing have high tolerance toward mechanical abuse and vibration. It does, however, brings challenges to the cell tab joining due to high operating temperatures, which the high temperatures can cause serious failures and shortcomings in the li-ion battery, defined as thermal abuse. The main issues are increased connection resistance, thermal expansion, and/or thermal fatigue resulting in a damaged tab joint. The increased tab resistance will, at best, cause energy loss through heat dissipation, eventually leading to cell degradation or, worst case, thermal runaway[50]. Other methods of tab joining should be considered. However, battery manufacturers seem content with utilizing and further developing the welding technology mostly due to the low manufacturing cost of about 7% and the low energy consumption of less than two percent of the energy used in the manufacturing process[50]. Whereof the available literature focuses on comparing the welding technology available rather than developing or testing new solutions for tab joining.

High charge rates, design, and battery chemistry are all interconnected with thermal abuse and each other. Reduced time of charging decreases charging efficiency, causing heat buildup. Some cell chemistries are more susceptible to thermal abuse. While module and cell configurations can be adjusted through pack design to be better suited for faster charging. Cell chemistry still has an impact on the overall pack safety, visualized in Chapter 4.1.1, the abuse tolerance concerning the operating environment, and the internal electrochemical instability[36]. Further design features like the BMS control the internal battery reactions by observing and regulating voltage and temperature. Where the BMS receives data from sensors, subsequently regulating voltage and temperature in real time[53]. A failure to regulate might cause sufficient temperature or overcharge for the cell to enter thermal runaway, further explained in Chapter 4.1.3.

3.2.3 Repairability and Second Life

Barriers for second life use of battery packs.

- Post-use collection
- Battery transportation
- Thecnology/R&D
- Cell characterization
- Standardised battery pack design
- Standardised battery cells
- Non-destructive disassembly
- Safe disassembly

The need for energy storage systems can be supplemented by a growing supply of end-of-life battery packs. However, concern has yet to be made by the battery manufacturer regarding the design for the reusability of these packs. The non-destructive disassembly of modern packs is time-consuming and, in some cases, nearly impossible. Some design adjustments might drastically increase the overall recyclability, reusability, and repairability, increasing the overall use time of lithium batteries. Ultimately making the reuse and recycling processes more viable and profitable. The everchanging battery cell chemistry is a part of the producer's necessary R&D to keep up with competitors. However, the constant changing in chemistry and the endless variations makes it hard to interchangeably use cells to make second life BSS, or make specialized recycling processes to increase efficiency. R&D also influences the design and shape of the battery cells internally and externally, further impeeding standardization.

3.2.4 Recycling

Barriers to efficient battery pack recycling.

- Design
- Labeling
- Profitability
- Standardised battery pack design
- Standardised battery cells
- Battery chemistry
- Post-use collection
- Scalability

Materials related to li-ion battery production are expected to rise in global demand. Subsequently, the need for recycling increases drastically. Recycling is one potential strategy for increasing supplies and mitigating price fluctuations in critical materials for LIB. However, recycling will be undertaken in a given region only when raw materials are equal to or greater than the economically viable price for recycled materials where the viability of recycling is dependent on profitability. Potential recyclers must also weigh the long-term outlook for raw material prices and consider the future size and stability of the reverse supply chain of spent batteries. Therefore, accurate predictions of virgin and recycled material supply and price trends (i.e., a supply curve) are critical for potential recyclers. While recycling is an essential factor in the integration of a circular economy. Production of batteries containing less and less valuable materials decreases the overall economic gain of recycling[51]. One can implement a more specialized method of recycling to increase process valorization. However, this specialized process depends on cell chemistry and requires a sorting system where the cells are separated accordingly[52]. A pack design that focuses on recycling would not require destructive disassembly. However, this is not feasible for the battery pack producers due to safety and overall cost. Some battery pack manufacturers reduce the complexity of their battery pack designs to make more versatile and scalable solutions while increasing the overall recyclability and reusability of the pack.

3.3 Thesis Structure

The thesis is divided into eight chapters, one intro, one theory, and six chapters containing sub-sections relating directly to mass production, safety, second life, and recycling. Chapter one introduces the thesis with an overview of the motivation, background, and, ultimately, the goals that the thesis aims to satiate. Chapter two, state of the art, is in great focus, where it builds the foundation for most of the challenges to come. Chapter 3 presents the challenges that are further addressed in chapters five, six, and seven being, the method, results, and discussion chapters, respectively. While chapter four contains the theory necessary to appreciate the more complicated sections of the thesis. Chapter eight concludes the thesis by addressing the most important findings and suggestions for further work.

Chapter 4

Theory on battery storage and pack design

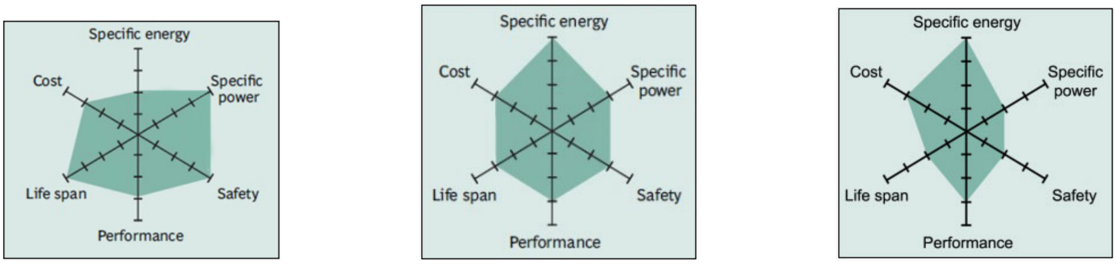
The theory chapter is made to assist the reader in a complete understanding of the results and discussion presented. And will be referred back to in sections of the report where the reader might require further clarification and guidance. Subsequently, the more advanced and experienced readers within the field of battery storage might find the theory section expendable.

4.1 Battery

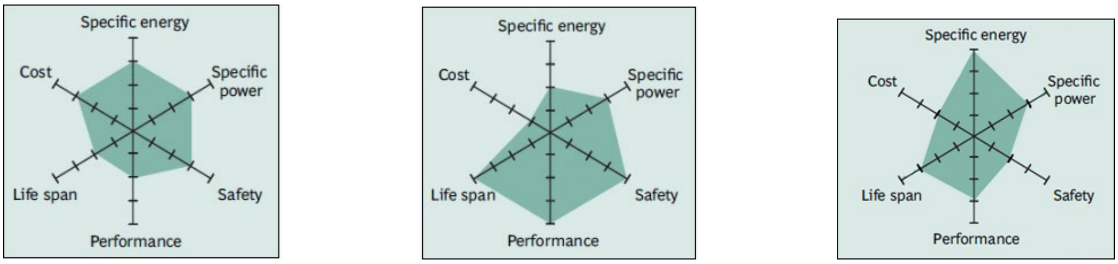
The main use of a battery is to provide electric power for chord-less appliances. The specifications and power requirements of the appliances vary greatly. This demands for batteries in many shapes and sizes, where the design and material are directly linked to the characteristics. The li-ion battery cell can differ in chemical composition for both the anode and cathode. Where the chemical composition is chosen to meet the use requirement. The industry uses the cathode material for classification purposes for li-ion cells.

4.1.1 Battery Cell Chemistry

The cathode and anode chemical composition directly impact the voltage, specific energy, specific power, safety, performance, life span, and cost of the battery cell illustrated in Figures 4.1(a-f) [54].



(a) LFP (b) NMC (c) Li-cobalt



(d) LMO (e) LTO (f) NCA

Figure 4.1: Average battery performance based on battery chemistry [54].

4.1.2 Cell Design

The cell's design can further impact the battery characteristics. Li-ion cell is usually designed in one of four ways illustrated in Figure 4.2 (a)cylindrical cell, (b)prismatic cell, (c)button/coin cell, or (d)pouch cell. The design is chosen based on ease of manufacturing, mechanical stability, voltage requirements, and capacity/space optimization, along others. The type of cell used affects the requirements for the overall pack design.

The coin cell is designed for testing and small low-voltage devices. The design allows for long service life and is not suitable for larger battery packs due to its relatively small size. The cylindrical cells are primarily used for medium-sized equipment and have a high safety due to individual cells having built-in safety measures in the form of a gas release vent that disconnects the positive terminal when triggered. The metal housing prevents cell expansion[25]. At the same time, the stacking of cylindrical cells leaves much to be desired in terms of volume utilization. However, one can argue that it assists in cooling and overall pack flexibility. Additionally, cylindrical cells have a relatively low cost of production. However, the cylindrical cell is one of the most mature li-ion formats. It is not expected to be to keep up with prismatic or pouch cells in industrial or automotive applications.

Prismatic cells are easier to integrate into a battery pack compared to cylindrical cells due to their simple rectangular design. The most common stacking method

Type	NCA	li-cobalt	LMO	NMC	LFP	LTO
V Nom[V]	3.60V	3.60	3.70 (3.80)	3.60, 3.70	3.20, 3.30	2.40
V Op[V/cell]	3.0-4.2	3.0-4.2	3.0-4.2	3.0-4.2	2.5-3.65	1.8-2.85
S E [Wh/kg]	200-260	150-200	100-150	150-220	90-120	50-80
(C)C-rate	0.7C	0.7-1C	0.7-1C	0.7-1C	1C	1C
(C)C-rate Max		1C	3C	1C		5C
(D)C-rate	1C	1C	1C	1C	1C	10C
(D)C-rate Max	1C	1C	10C,30C	2C	25C, 40C	30C
Cycles	500	500-1000	300-700	1000-2000	2000 and higher	3,000-7,000
$TR(^\circ C)$	150	150	250	210	270	Safest
Cost $/kWh	∼$350			∼$420	∼$580	∼$1005

Table 4.1: li-ion cell chemistry specific specifications for Nominal Voltage, Operating Voltage, Specific Energy, Charge Rate, Maximum Charge Rate, Discharge Rate, Maximum Discharge Rate, Cycle Life, Thermal Runaway, and Approximated Cost

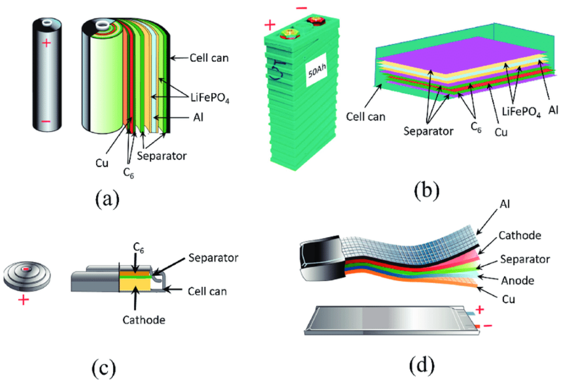


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Figure 4.2: Representation of the design and internal components of various Li-ion battery configurations: (a) cylindrical, (b) prismatic ,(c) coin and (d) pouch cell [55]

is gluing cells together where the glue has a low thermal conductivity, providing a thermal insulation layer to prevent or delay accidents[25].

Pouch cells do not have the same rigid packaging, of which the cells contents are stacked inside a pouch package. By not including the packaging, the pouch cells have the highest package efficiency and high energy density. However, this makes the cells more vulnerable to mechanical damage. Subsequently, they require external structure support. In addition, the pouch cells tend to expand/shrink during the charging and discharge cycle, respectively[25].

The li-ion battery packs have mostly the same structural concept. Cells are joined together to create modules, and modules, in turn, are joined together to form packs. The cells are connected in an arrangement of parallel(P) and series(S), whereof the connection can be classified in accordance to a set number of series (a) connections and an additional number of parallel (b) connections giving the classification (a)S(b)P for simplification.

4.1.3 Thermal Runaway

Lithium-ion cells operate within a nominal lower and an upper charge voltage controlled by the BMS to avoid performance loss or thermal runaway. Thermal runaway as the name implies occurs when the heat generated within the battery exceeds the amount of heat dissipation. In turn causing the release of highly flammable gasses. The high heat causes said gasses to spontaneously combust or explode given the right fuel-to-air ratio. Thermal runaway is not limited to but most likely to occur when the battery is subjected to overcharge at 20% or higher. Thermal runaway can also occur due to cell damage causing separator breach[56, 57].

Electrolyte

The electrolyte provides for the free flow of electrons from the anode to the cathode in battery discharge and from the cathode to anode when charged, visualized in Figure 4.3. The electrolyte is usually an organic salt solution containing lithium. Where the electrolyte vapor is flammable and paired with the heat generated from an overcharged cell able to self-ignite. The vaporized electrolyte given the right fuel-to-air ratio can be explosive. Subsequently some flame retardants are added phosphates, phosphazenes, phosphides, and ethers to reduce the flammability [58, 57].

Separator

The separator divides the anode reactions from interfering with the cathode reactions shown in Figure 4.3. Allowing for the free flow of li-ions while halting the electrons. Small amounts of current(leakage current) can penetrate the separator, causing self-discharge. Whereof the cell eventually depletes the charge over an extended period of non-use[59]. The three main separators used in li-ion batteries are composite separators, nonwoven mats, and porous polymeric membranes. Where polymeric separators are most common due to their low cost and ease of manufacturing[60, 61, 57].

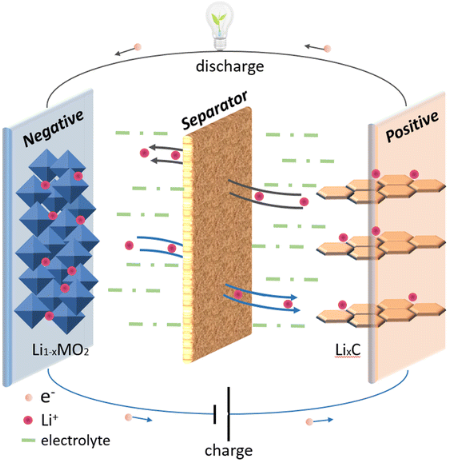

Figure 4.3: Path of current drivers in a standard li-ion Cell for Charge (blue) and Discharge (black) [62].

Chapter 5

Method

The following review of literature for mass production, safety, repairability, second life, and recycling of battery packs is performed to gain an understanding of the different drives and challenges regarding battery price development. This will provide a holistic view in regard to the applicability of the thesis findings. The work done is academic, whereof little examples and data are extrapolated from open sources. In regard to sources, the time-relevancy of the information and the foundation of the gathered source material is essential to the rapidly evolving nature of the lithium-ion market and the battery performance. When reviewing time-sensitive information, reports published before 2018 were rejected. Thereby reducing the gap in knowledge regarding market development. While ensuring that the models are based on the newest findings and field discoveries. Area-specific information is also revised on which variables like labor costs heavily differ based on factory placement, where the legislative and production aspects make incomparable regional differences. Only papers regarding European conditions are used in regard to prices, regulations, material availability, legislative issues, etc. The thesis uses sources like industry publications, market analyses, academic publications, and media reports.

5.1 Boundry Conditions

The chemistries focused on are NMC and NCA because both are exogenous to the automotive industry. When reviewing the pack production, we assume the battery cells to be up to production standards. Production errors resulting in faulty cells are considered scope outliers. The thesis is aimed to address the situation in developed countries subsequently reassuring safety and work ethic standards.

5.2 Literature Review

A structured literature review of academic, industrial, and legislative stakeholders is performed. Utilizing the scholarly literature available for the author. The articles, reports, review documents etc., used in this report were mostly obtained using academic publishers such as Elsevier, MDPI, and IEEE. Some resources like market analysis and media reports were gathered using more general search engines such as Google. However, other sources with new and more specific information are used according to prudence.

To acquire specialized information regarding mass production, safety, repairability, second life, and recycling, defining keywords were used in addition to:

- li-ion batteries,
- lithium ion batteries,
- EV batteries,
- or lithium battery pack.

The articles found were sorted after relevance and a scan of the abstract was used to determine the relevance in relation to the problem statement and further classify the texts in different sub-areas within their respective areas. Articles used were limited to University licensing and open-source material. When reviewing the articles special care was taken to not misinterpret the work or the author's intended meaning.

The literature review study regarded challenges directly mentioned/discussed in the literature. The challenges found are directly linked to their area of influence, like mass production, safety, repairability, second life, and recycling. The challenges are primarily found in the discussion, conclusion, and further work sections, which are mentioned as limiting or areas requiring further investigation and/or change. The results are presented in a normalized fashion, with five or more academic articles used to minimize misrepresentation due to a shortage of data.

Graphical Representation

The graphical representation of the barriers found in the literature review is presented in a bar chart. The bar chart has the different barriers presented displayed on the X-axis and the normalized, in accordance with equation 5.1 on the Y-axis. Where ΣB represents the sum of barriers found and ΣA is the sum of all the articles used in regard to the pillar. The normalization subsequently becomes a number between zero and one, where one states that the barrier is mentioned in all academic articles found. Making the values a scale to measure the frequency of mentions from academic articles used. Where the mentioning is limited to once per article. Whereof the article has directly mentioned it as a barrier or challenge that hinders or might impede further development within the respective area.

$$N = \frac{\Sigma B}{\Sigma A} \tag{5.1}$$

Furthermore, the barriers were classified using PEST analysis (political, eco- nomic, social, and technological factors). And presented using color-coded to blue, orange, yellow, and purple representing "economic", "development", "political and legal", and "social and industrial" factors respectively illustrated in Figure 5.1.

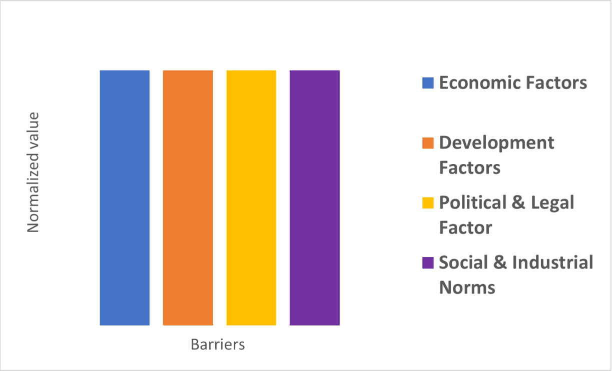

Figure 5.1: Legend used for figure 6.1-6.4.

5.2.1 Mass Production

Mass production-specific keywords utilized in the gathering of articles:

- Battery joining,
- Welding,
- Automated assembly,
- Battery module assembly,
- Eco-design,
- Automated assembly of li-ion battery.

5.2.2 Safety

Keywords used for the topic of safety:

- Safety,
- Standards,
- Fire risks,

It can be argued that the three abuse tolerances can be classified as barriers related to political and legal factors or social and industrial norms due to the required certification or strict manufacturing standards. However, the author chose to use the development factor as the academic articles are pushing the standards further, rather than the standards being the drive for further development.

5.2.3 Repairability and Second Life

Repairability and second life specific keywords:

- Battery reuse
- Battery second life
- Environmental sustainability
- Circular economy
- Disassembly

It can be argued that the standardized battery pack section can be extended to include modules and cell standardization. However, the author finds this unprecise given the argumentation in the literature.

5.2.4 Recycling

Recycling specific keywords:

- Recycling li-ion
- Environmental sustainability
- Circular economy
- Environmental sustainability

5.3 Comparative Study

Further extending on the literature review a comparison of the possible solutions and their effects is performed. This is done by using the literature to survey the possible impact factors of the implemented changes and in what regard they affect the overall Mass production, second life and repairability, and recycling of the battery pack. First, a table is made where the barriers can be ranked according to the relation to mass production, safety repairability, and second life, and recycling. Where table 5.1 uses a V "Good", X "Bad", - "No impact", and / "Slightly worse". Where the implementation refers to the steps that can be implemented to find a compromise in regard to the pillars presented. The implementations are based on a SWOT(strengths, weaknesses, opportunities, and threats) analysis. Where the ideas are meant to challenge the current norms in li-ion battery pack production. Where the barriers and/or assisting aspects of the safety, second life, repairability, and mass production are intertwined. The author does not claim one or any of the implementations as their own ideas, but rather as a byproduct of the literature review performed. And are meant to identify and analyze internal strengths and weaknesses and external opportunities and threats that shape current and future development and strategic goals.

Implementation	Mass production	Safety	Second life	Repairability	Recycling
implementation 1					
implementation 2					
implementation 3					
implementation 4					
implementation 5					
implementation 6					
implementation 7					

Table 5.1: Implementation table

Chapter 6

Results

Section 6.1-6.4 presents the results of the literature review performed using the method presented in Chapter 5.2.

6.1 Mass Production

Figure 6.1 shows the most mentioned challenges in the literature review, regarding the mass production of li-ion batteries.

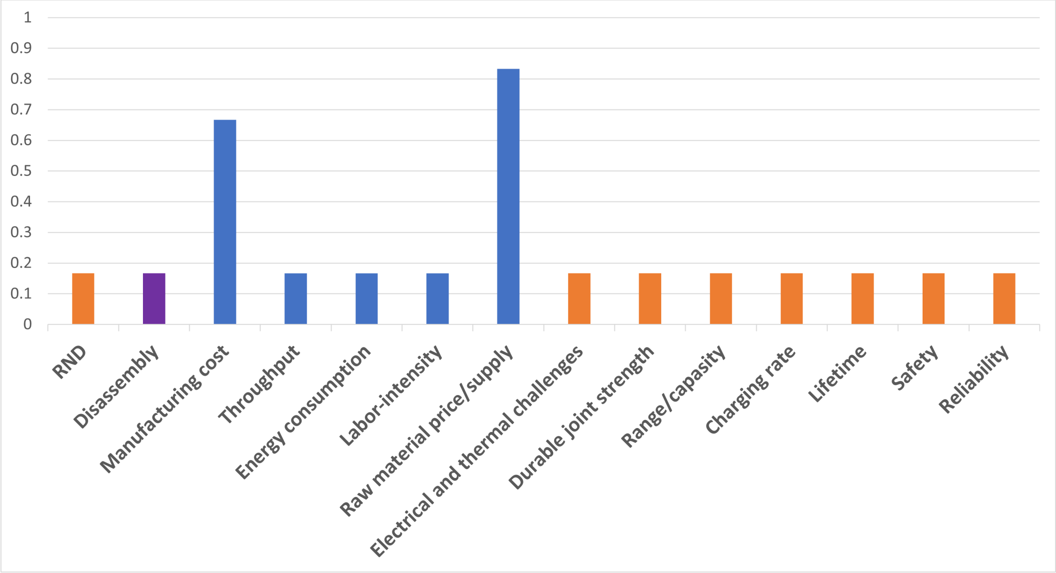

Figure 6.1: Normalized bar graph depicting the barriers mentioned in relation to li-ion battery pack mass production. Legend in Figure 5.1.

6.2 Safety

Figure 6.2 illustrates the results regarding the literature review performed in relation to the barriers for li-ion battery pack safety features.

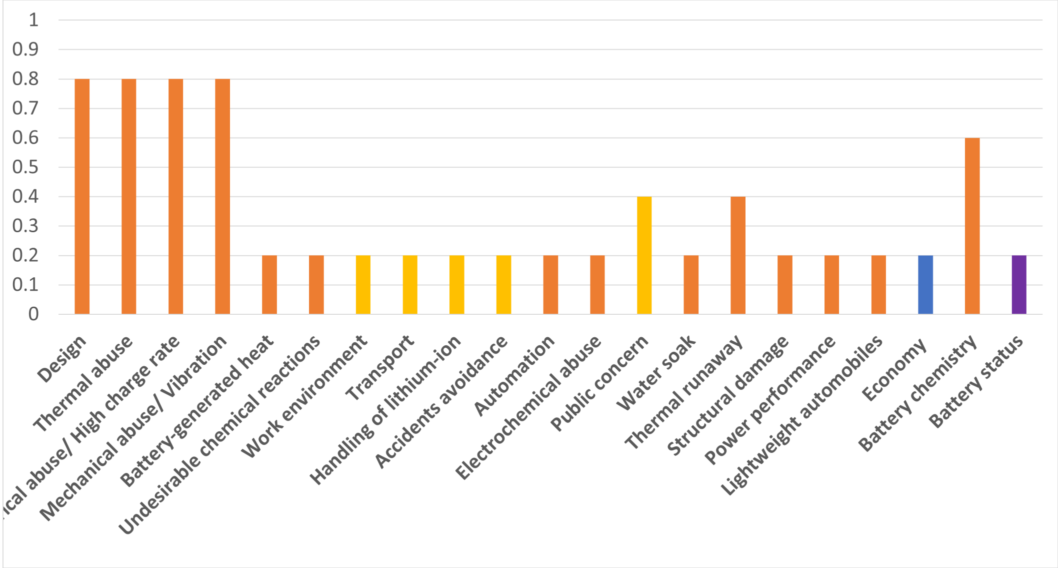

Figure 6.2: Normalized bar graph depicting the barriers mentioned in relation to li-ion battery pack safety. Legend in Figure 5.1.

6.3 Second Life and Repairability

Figure 6.3 displays the barriers for the second life and repairability of battery packs.

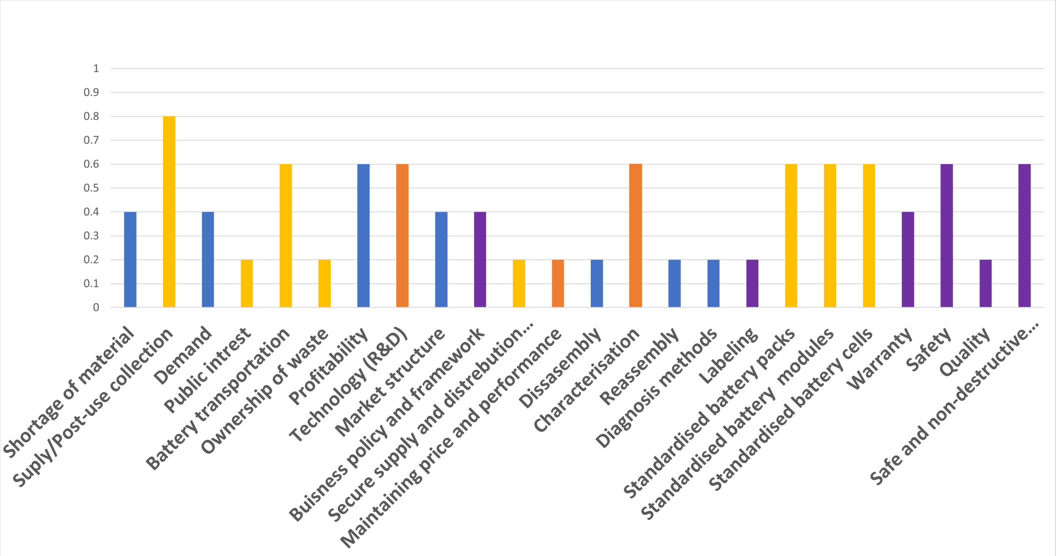

Figure 6.3: Normalized bar graph depicting the barriers mentioned in relation to the Second life of li-ion battery packs. Legend in Figure 5.1.

6.4 Recycling

The main barrier recycling is illustrated in Figure 6.4.

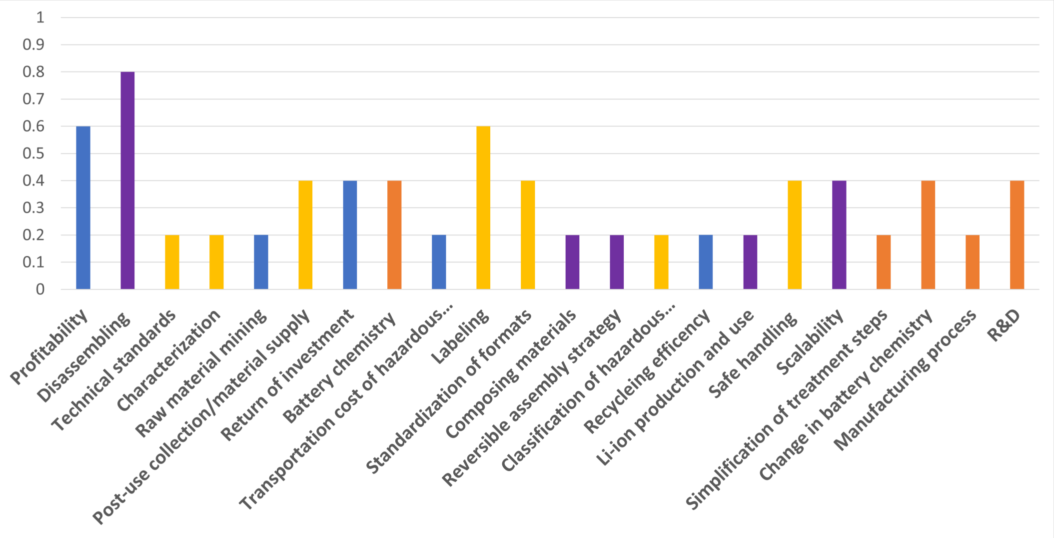

Figure 6.4: Normalized bar graph depicting the barriers mentioned in relation to recycling. Legend in Figure 5.1.

6.5 Comparative Study Findings

In table 6.1 implementations are presented along with their impact on mass production, safety, repairability, second life, and recycling.

	Mass production	Safety	Second life	Repairability	Recycling
Standardized assembly /disassembly steps	X	V	V	V	V
Architecture standardization	X	-	V	-	V
Screw fixings	X	X	V	V	V
Clip fixings	X	-	V	V	V
Modularization	X	X	V	V	V
Labeling of components	-	V	V	V	V
Labeling of materials	X	-	V	V	V
Information traceability	\	V	V	V	-
Manufacturer responsibility of design	V	-	-	V	V
Manufacturer responsibility of waste	X	-	V	V	V
Deposit refund for EVBs	-	-	V	V	V
Certification/standard for conflict-free minerals	V	-	-	-	V
Maximising the separability of materials	X	-	-	-	V
Minimizing module weight	V	X	-	-	V
Reduced pack complexity	V	V	V	V	V
Increased cell sizes	-	V	V	V	V

Table 6.1: Result table for impact of design implementations. Where V "Good", X "Bad", - "No impact", and / "Slightly worse"

Chapter 7

Discussions

7.1 Mass production

The results from the literature review show that the articles that relate to mass production are focused on product improvement. Where the overall echo design of the battery pack is omitted, and its improvements and future profitability are in focus. The literature review found concerns in regard to the price change of critical materials and explores ways to reduce the overall production costs of the battery pack. Whereof the academic articles published regarding the production of the battery pack predominantly focus on economic and development factors.

The literature shows the highest concerns in regard to the price change of critical materials. Further, it explores ways to reduce the overall production costs of the battery pack. The reduction of battery pack prices is expected to continue for some years, and thus creates the need for battery pack Manufacturers to be ahead of the curve. By increasing battery cell sizes reductions are made to the overall casing/active material ratio of the cell. When regarding systems that aim toward a compact design where volume, weight, and energy density are key factors in addition to cost the trend seems to be bigger equals better. Larger cells will additionally increase the ease of cell dismantling which can in turn increase recycling efficiency. From reviewing available literature for use in industrial applications like BESS or EVs. There seems to be a trend towards the use of pouch and prismatic cells due to versatility in regard to power output and energy. The individual cells are additionally trending towards larger cell formats. This reduces the overall supportive electronics that add about 20% of the overall costs[63]. The current trend in welding or gluing the individual parts and joints of the battery pack is performed on the basis of maximizing the production throughput, whereof the welding or gluing process has low energy consumption and is performed in a fraction of a second. Whereof, the increased cell sizes make the prospect of using other methods of tab joining like clips or screws more due to the decreased amount of terminal connections needed.

Modularization has the potential to become a highly effective method of design when given time to mature. The are countless opportunities for the standardization of the interconnections used and the standard for the locking and connection. Whereof, mechanisms can be developed in relation to factors like the generation of the part when new standards are needed. And by limiting the interconnect ability, dangerous attempts at unfavorable cell or module matching can be avoided.

7.2 Safety

All systems that might have large consequences upon failure should be designed with possible failures in mind. This is mainly to reduce the actual failure scenario. There are multiple tests done to assure the battery pack is up to standard, these are meant to test the pack to failure. Whereof all systems eventually will fail however it is of utmost importance that the consequences of said failure are minimized. Safety becomes an issue when you expect high power and capacity, this safety issue becomes larger when you add extrinsic factors like vibration or collisions. When handling li-ion battery packs, modules, or cells the terminals should be covered to avoid accidental short circuits.

From the graph presented in figure 6.2 it becomes apparent that the five most mentioned factors are related to the development factors. Where three of the factors mentioned are related to different forms of battery abuse. The design is slightly more mentioned than the chemistry when it comes to the overall room for improvement of safety. The design of li-ion battery packs used in EVs, are designed for the abuse tolerances and safety features needed for high speeds and potential collision hazards that this entails. While also keeping impedances of metal contacts down and keeping an even heat distribution in the pack. In this regard, the pack design itself is mentioned as a barrier due to the high potential for optimization. However, the pack design is not expected to be fully developed and improved for years to come. Chemistry is another large in regard to safety. Whereof chemistries like LFP tolerate a larger percentage of overcharge and a significantly higher operating temperature.

EV battery pack is under strong supervision by the standards and regulations imposed on the EVs production. These standards cover what is today considered reasonable misuse and an acceptable degree of failure. However, by implementing a simplification of disassembly for battery packs the degree of reasonable misuse increases. one can expect the layman to consider it a good idea to tinker with the pack. Making DIY repairs within the reasonable misuse of the battery, the design will be required to account for inexperienced and underqualified repairmen unaccustomed to electric equipment operating at high voltage. The risk of short-circuiting a battery pack is ever present when opening battery packs even for experienced battery engineers. The general idea of short circuit prevention is clear labeling and keeping terminals with the largest positive and negative voltage as far apart as possible. In case of thermal runaway, the design of the pack should minimize heat transfer between modules to reduce/hinder cascading heat dissipation.

7.3 Second life and Repairability

The post-use collection is the most mentioned barrier in the literature review. While 4 out of 7 of the most mentioned barriers are related to the political and legal factors shown by the yellow color presented in Figure 5.1.

7.3.1 Second Life

The main idea of second life batteries entails the extension of the pack's useful lifetime beyond the use as a battery pack in an EV. Where the pack's usefulness fades at 80% SOH after 8-15 years of use. At this point, it is estimated that the battery can be used as a BESS for another 10-15 years to 60% SOH. When the battery measures 60% SOH the battery cells tend to reach sudden death. To achieve profitability in second life battery systems you need to:

- Keep technician labor to a minimum
- Avoid purchasing modules containing faulty cells

The manufacturers of EVs often have available data on the battery pack. This gives a good indication regarding the feasibility of use in a second life system. However, this battery diagnostic should be available as open source. The data provided can remove some of the risk factors involved in using a second life system. Additionally, some changes need to be made to the energy grid infrastructure to allow for these battery systems to be used for peak-shaving purposes.

7.3.2 Repairability

When it comes to battery pack repair one would think it is within the battery pack Manufacturer's best interest that warranty issues within the battery pack are fixed at the lowest possible cost. This would in the case of a large-scale battery pack be to replace the faulty cell/cells. Replacing damaged with new cells is a valid option when the pack has a low amount of aging. Whereof the company Global Battery Solutions goes as far as stating that the remanufactured batteries can cut replacement costs by more than 70%[37].

7.4 Recycling

The ideal recycling method is one where all the material is separated at the lowest consumption of energy and at the lowest cost possible. The current pretreatment for recycling battery packs is usually shredding the pack into powder due to the high costs of dismantling and sorting. A more standardized dismantling method along with proper labeling can make the process of material separation more profitable and efficient. The R&D of the battery pack develops new designs in form of cell sizes and layouts. Which requires a more versatile prepossessing in terms of material separation. Additionally, R&D makes changes in chemistry directly impeding the development of a precise chemical process optimal recycling process. With detailed labeling of chemical cell composition and a manufacturer in dialog with the recyclers, can create battery packs that can be sorted to facilities able to recycle the pack at high efficiency.

The barriers mentioned in the literature review illustrated in 6.4 is the disassembling, referring to the inseparability of materials in the battery pack. The barriers regarding the disassembly process hinder more effective and less energy-consuming recycling methods. Whereof, chapter 2.4 presents the pyrometallurgy as the most used method despite its low efficiency and high energy demand. Profitability and labeling are the shared number two most mentioned in relation to recycling.

7.5 Comparative Study

The implementation of **standardized assembly/disassembly steps** will have positive impacts on second life and recycling where specialized methods of dismantling and separation can be developed. The safety of the work done in battery pack repair will increase due to the technician being more accustomed to the process of disassembly. While standardization limits the freedom of design and production for the manufacturers. In turn, hindering the further development of production methods and designs. Standardized assembly/disassembly steps can make the process of battery pack disassembly fully automated. This removes the labor risks regarding battery pack disassembly and can reduce costs significantly. The main beneficiary of standardized assembly/disassembly steps is second life, whereof labor cost for dismantling plays a significant role in the overall profitability of the endeavor illustrated in Figure 6.3. The implementation of standardized assembly/disassembly is not likely to affect the production cost of the battery. However, the standardization of steps might force a specific design pattern that is sub-optimal.

Screw fixings increases the overall cost, production time, and weight of the battery. The welding process used today is performed in a fraction of a second using the bare minimum of required material. The screw terminal will add the cost and weight of each screw in addition to time to the overall production process. They will additionally be at risk of vibration-induced disassembly.

The use of screw or **clip fixings** might be considered advantageous by the pack manufacturers.

Clip fixings remove the risk of vibration-induced disassembly however increases the overall production cost of the pack. Of which the screw is less expensive to produce due to a higher degree of complexity. It will, however, have the same positive effect of making the dismantling process of a battery pack non-destructive, which is positive for safety, second life, and recycling.

Modularization refers to the pack components being made into interchangeable modules with similar or standard connection terminals and space allocations. Where there is no set placement of the components. EV mass production is affected in a negative regard due to the space requirement and the added auxiliary electronics required. In regard to pack safety, the thermal management systems like fans and cold plates either have low scalability or deliver marginal performance[64] when modularized making the pack more susceptible to thermal abuse. For the second life, modularization would make the prospect of rebuilding packs efficient and easy once the housing is removed. The same principle applies to repairability whereof the replacement of the offending module would require minimum effort. Recycling would additionally gain on the added separability of components. Modularization is an interesting idea that can with maturity prove advantageous. The positives are the standardization of interconnection methods sizes and solutions that can be decided by the manufacturers. However, in EVs the applicability is limited due to the volume and weight sensitivity of the battery packs.

Labelling in general require such a small amount of effort for the manufacturers in term of material and production time, it is marked as having no impact on mass production.

Labeling of components being as simple as providing a QR code redirecting to a link containing the user manual and/or a site where replacement parts can be acquired. Additionally warning labels and instruction pictures can increase safety in handling and dismantling or provide guidance for automated disassembly.

Labeling of materials present in a battery cell increases the viability of automated sorting systems. This is vital for the development of specialized recycling processes. However, the labeling would create transparency of battery chemistry that is competitively unfavorable. The development and research to optimize battery cell chemistry are expensive and time-consuming, subsequently often treated as a secret recipe. In terms of second life use, the battery chemistry is important in regard to cell matching. The resistance and voltage of the cell need additional characterization. However, the matching of chemistries provides the first step in the sorting of battery cells.

Labeling components and materials is a low-cost high reward procedure that provides necessary information for future use.

Battery pack **information traceability** impact for the battery manufacturers will be depending on whether or not the responsibility for the storage of this information would fall on the original battery manufacturers. Although the price of information storage in terms of server maintenance and operation is relatively low in terms of manufacturing costs and standards, it is not negligible. The information traceability would provide safety and a foundation for the estimation of the remaining operational lifetime after repairs or the rebuilding process for second life BESS. Information traceability entails that the ones purchasing the battery will be able to acquire the amount of charge cycles that has been made. And the SOH of the battery along with when and why it was removed from its previous use. This information is vital to classify if the battery is useful in second-life applications.

Architecture standardization where the battery packs are standardized to specific voltages, sizes, and capacities. This level of design continuity simplifies the pack's end-of-life scenarios in regard to disassembling. However, the removal of full scalability in regard to power and size makes packs less optimizable unless a plethora of standards is made. Where by removing the opportunity to further develop the product no one stands to gain. However, there need to be incentives that include the echo design.

Manufacturer responsibility of design gives the manufacturers the freedom to use their own expertise to optimize the design. This allows for further research and development of the product. However, the goal is to optimize the entire life cycle of the pack. Subsequently, the less eco-friendly designs would need to be compensated for financially to achieve proper end product handling.

Manufacturer responsibility of waste additionally includes the collection of end-of-life batteries to the manufacturers. This will financially strain new and upcoming battery manufacturer's due to a more scattered and subsequently less profitable battery end-of-life collection.

Giving the manufacturer responsibility of design and responsibility of waste might provide sufficient incentive for change within the industrial norms. If parts of the cost of disassembly for remanufacturing and/or recycling is imposed upon the manufacturer.

Deposit refund for EVBs is the simplest method of end-of-life battery pack valorization. This shifts the responsibility of waste toward one of the consumer's economic benefits. The pickup and gathering of larger packs can in itself turn into a business endeavor potentially creating new jobs. Where the implementation of deposit refunds has in other products, similar or otherwise proven to increase the collection rate drastically. However, it is considered dangerous cargo in terms of transportation. In a battery replacement, this deposit refund will just become a net-zero equation. However, when the vehicle or pack reaches its end of life there is still value to be gained.

The use of a **certification/standard for conflict-free minerals** needs to be financially incentivized or mandatory to have the desired effect within the industry. And thus implemented equally for all manufacturers. Subsequently, not increase a specific manufacturer's cost. Securing the overall mass production, while the use of materials gathered from recycling becomes incentivized.

Maximising the separability of materials within a pack is in practical applications only beneficial to a module level. The battery cell's cathode and anode material as well as separator and current collecting metal sheets need to be arranged tightly with no risk of separation. Subsequently, the overall separability might include removing tabs screws, and auxiliary electronics. Without compromising cell design, for manufacturers, this might add additional complexity to the battery design.

Minimizing module weight or minimizing weight, in general, is one of the main objectives for EVs. However, the structural integrity of a module protects the cells from denting or other mechanical abuse.

Reduced pack complexity is a general recommendation.

Increased cell sizes makes for better space usage and further reduce auxiliary electronics. Increased cell size makes for a larger percentage of active material, whereof the cell increased volume makes it possible to have more anode and cathode material in relation to tabs and casing material. Further larger cells simplify the entire construct of a li-ion battery pack. This simplification in turn provides for less likelihood of battery pack failure due to fewer parts of parts integrated into the system. Additionally safer in regard to transport, dismantling, and general repairs.

7.6 Closing Thoughts

The author's ideal battery pack consists of large prismatic cells all series connected to increase the voltage for power performance. The cells are all connected by an interlocking clipping system. Where the thermal management system uses air channels between the cells equipped with heat sinks. The airflow is regulated by thermal sensors and can be increased using fans, air temperature can be regulated if needed. All cells are directly connected to the BMS where the offending cell can be circumvented if a failure occurs. Additionally, a measurement of the power received in the cell's lifetime in kWh and the battery SOH will be displayed at all times on a small screen located at the top of the battery pack. In the case of a failing cell or other issues, an error code will be displayed indicating the origin of the error. Visible on the pack will also be labeling containing chemistry, cell operating voltage, cell capacity, cell configuration, and max charge/discharge current.

Chapter 8

Conclusions

The handling of end-of-life lithium-ion batteries needs to be addressed considering that a massive number of lithium batteries will retire and enter the waste stream at the same rate just at a delay of 8-15 years. Whereof utilizing battery pack repair and second life can be extended to 20 years or more. The prolonged use time of the battery cells saves energy and resources compared to creating new battery packs. Furthermore, second life battery storage system can be used in low-demanding mobile or stationary applications. This thesis investigates the requirements for optimal battery pack design in regard to safety, repairability, second life, and mass production. By addressing issues that impede effective recycling and second life without impairing mass production capabilities or reducing safety measures. Where the investigation of recently published papers regarding developed countries is used to obtain barriers and access factors of economic, development, political, legal, social, and industrial nature.

It has been argued throughout this thesis that the design of lithium-ion battery pack needs to increase focus on end-of-life prospects for the battery pack. Where the state of the art have listed and discussed and the different requirements for improvement have been made. The work is based on available literature. It has been found that the highest-impact solutions can be addressed using incentives based on political and legal factors to change social and industrial norms. Where standards facilitating repairability cascade to second life and recycling due to tools and processes for dismantling can become more streamlined. Additionally, small implementations and changes in manufacturing have the potential to increase effectivity and value in regard to repairability, second life, and recycling. This project challenged the concept of production optimization and aims to increase product quality in a conventional way.

Previous large-scale production has shown that the valorization of the end product is essential to keep the material away from landfills. This circular business model reduces the footprint in an otherwise polluting production process, the climate change problem is perhaps the most important in our century. And by implementing a future-oriented design approach one might make a difference.

It would be interesting to research and test the dismantling and reuse possibilities presented by the newest generation battery packs, BYD blade, CATL Qilin, and Tesla 4680 where the use of simple design and larger cell sizes is implemented. It would further be interesting to find the extent of usefulness provided by full information traceability of battery packs to see if more precise estimates can be made for the full lifetime of the pack using primary and secondary applications. This is however left open for further work.

Bibliography

[1] C Annex and Viegand Maagøe. "Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot." In: (2019).

[2] John Houghton. "Global warming." In: *Reports on Progress in Physics* 68.6 (2005), pp. 1343–1403. DOI: `10.1088/0034-4885/68/6/r02`. URL: `https://doi.org/10.1088/0034-4885/68/6/r02`.

[3] Susan A. SHAHEEN and Timothy E. LIPMAN. "REDUCING GREENHOUSE EMISSIONS AND FUEL CONSUMPTION: Sustainable Approaches for Surface Transportation." In: *IATSS Research* 31.1 (2007), pp. 6–20. ISSN: 0386-1112. DOI: `https://doi.org/10.1016/S0386-1112(14)60179-5`. URL: `https://www.sciencedirect.com/science/article/pii/S0386111214601795`.

[4] Bernice Doyle and Guy Nicholson. *Grid Services: Innovative solutions to stabilise the power grid.* 2022. URL: `https://www.statkraft.com/newsroom/news-and-stories/archive/2021/grid-services-innovative-solutions-to-stabilise-the-power-grid/`.

[5] Dan Welsby et al. "Unextractable fossil fuels in a 1.5 C world." In: *Nature* 597.7875 (2021), pp. 230–234.

[6] Zhijie Jia and Boqiang Lin. "How to achieve the first step of the carbon-neutrality 2060 target in China: The coal substitution perspective." In: *Energy* 233 (2021), p. 121179. ISSN: 0360-5442. DOI: `https://doi.org/10.1016/j.energy.2021.121179`. URL: `https://www.sciencedirect.com/science/article/pii/S0360544221014274`.

[7] Mohammed Safiuddin and Robert Finton. "4 - Global Renewable Energy Grid Project—Integrating Renewables Via High-Voltage Direct Current and Centralized Storage." In: *Medium Voltage Direct Current Grid.* Ed. by M.M. Eissa. Academic Press, 2019, pp. 85–99. ISBN: 978-0-12-814560-9. DOI: `https://doi.org/10.1016/B978-0-12-814560-9.00004-5`. URL: `https://www.sciencedirect.com/science/article/pii/B9780128145609000045`.

[8] Yu Miao et al. "Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements." In: *Energies* 12.6 (2019). ISSN: 1996-1073. DOI: `10.3390/en12061074`. URL: `https://www.mdpi.com/1996-1073/12/6/1074`.

[9] Zhiwen Ma et al. *Grid Services: Innovative solutions to stabilise the power grid.* 2022. URL: https://www.frontiersin.org/research-topics/10251/long-duration-and-long-term-energy-storage-for-renewable-integration#research-topic-articles.

[10] Susan M Schoenung and William V Hassenzahl. *Long-vs. short-term energy storage technologies analysis: a life-cycle cost study: a study for the DOE energy storage systems program.* Tech. rep. Sandia National Laboratories (SNL), Albuquerque, NM, and Livermore, CA . . ., 2003.

[11] Runsen Zhang and Shinichiro Fujimori. "The role of transport electrification in global climate change mitigation scenarios." In: *Environmental Research Letters* 15.3 (2020), p. 034019.

[12] Willem Roper. *High Demand for Lithium-Ion Batteries.* 2020. URL: https://www.statista.com/chart/23808/lithium-ion-battery-demand/.

[13] Elena Mossali et al. "Methodology and Application of Electric Vehicles Battery Packs Redesign for Circular Economy." In: *Procedia CIRP* 91 (2020). Enhancing design through the 4th Industrial Revolution Thinking, pp. 747–751. ISSN: 2212-8271. DOI: https://doi.org/10.1016/j.procir.2020.01.139. URL: https://www.sciencedirect.com/science/article/pii/S2212827120308957.

[14] Ana CRESPO PARRONDO Tim McPHIE. *European Parliament agrees all new vehicles in EU to be zero emission by 2035.* 2022. URL: https://ec.europa.eu/commission/presscorner/detail/en/ip_22_6462.

[15] Colin McKerracher et al. *Electric Vehicle Outlook 2022.* 2022. URL: https://about.bnef.com/electric-vehicle-outlook/.

[16] Mahyar Mirzaei Omrani and Hamid Jannesari. "Economic and environmental assessment of reusing electric vehicle lithium-ion batteries for load leveling in the residential, industrial and photovoltaic power plants sectors." In: *Renewable and Sustainable Energy Reviews* 116 (2019), p. 109413. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2019.109413. URL: https://www.sciencedirect.com/science/article/pii/S1364032119306215.

[17] Fintan McLoughlin and Michael F. Conlon. "Secondary Re-Use of Batteries From Electric Vehicles for Building Integrated Photo-Voltaic (BIPV) applications." In: 2015.

[18] Tim Hettesheimer. "Strategische Produktionsplanung in jungen Märkten-Ein systemdynamischer Ansatz zur Konzeption und dynamischen Bewertung von Produktionsstrategien am Beispiel der Lithium-Ionen-Traktionsbatterie." PhD thesis. Dissertation, Karlsruhe, Karlsruher Institut für Technologie (KIT), 2017, 2017.

[19] John M. German. "Hybrid Electric Vehicles." In: *Encyclopedia of Energy.* Ed. by Cutler J. Cleveland. New York: Elsevier, 2004, pp. 197–213. ISBN: 978-0-12-176480-7. DOI: https://doi.org/10.1016/B0-12-176480-X/00180-7. URL: https://www.sciencedirect.com/science/article/pii/B012176480X001807.

[20] Andrea Vezzini. "15 - Lithium-Ion Battery Management." In: *Lithium-Ion Batteries*. Ed. by Gianfranco Pistoia. Amsterdam: Elsevier, 2014, pp. 345–360. ISBN: 978-0-444-59513-3. DOI: https://doi.org/10.1016/B978-0-444-59513-3.00015-7. URL: https://www.sciencedirect.com/science/article/pii/B9780444595133000157.

[21] E Jiaqiang et al. "Effects of the different air cooling strategies on cooling performance of a lithium-ion battery module with baffle." In: *Applied Thermal Engineering* 144 (2018), pp. 231–241.

[22] Vi Kie Soo et al. "Life Cycle Impact of Different Joining Decisions on Vehicle Recycling." In: (2018).

[23] Dana L Thompson et al. "The importance of design in lithium ion battery recycling–a critical review." In: *Green Chemistry* 22.22 (2020), pp. 7585–7603.

[24] Abhishek Das et al. "Joining technologies for automotive battery systems manufacturing." In: *World Electric Vehicle Journal* 9.2 (2018), p. 22.

[25] Heiner Heimes et al. *BATTERY MODULE AND PACK ASSEMBLY PROCESS*. Feb. 2019. ISBN: 978-3-947920-05-1.

[26] Malarvizhi Kaniappan Chinnathai et al. "Pilot To Full-Scale Production: A Battery Module Assembly Case Study." In: *Procedia CIRP* 72 (2018). 51st CIRP Conference on Manufacturing Systems, pp. 796–801. ISSN: 2212-8271. DOI: https://doi.org/10.1016/j.procir.2018.03.194. URL: https://www.sciencedirect.com/science/article/pii/S2212827118303536.

[27] Lorenzo Usai et al. "Analysis of the Li-ion battery industry in light of the global transition to electric passenger light duty vehicles until 2050." In: *Environmental Research: Infrastructure and Sustainability* 2.1 (2022), p. 011002. DOI: 10.1088/2634-4505/ac49a0. URL: https://dx.doi.org/10.1088/2634-4505/ac49a0.

[28] *In brief: Key components for a new era – the battery system*. Sept. 2020. URL: https://www.volkswagen-newsroom.com/en/press-releases/in-brief-key-components-for-a-new-era-the-battery-system-5645.

[29] PEDRO LIMA. *Volkswagen MEB details*. May 2020. URL: https://pushevs.com/2020/05/13/volkswagen-meb-details/.

[30] *ELECTRIC FOR ALL: Volkswagen viser for første gang understellet til den helelektriske ID. familien*. Sept. 2018. URL: https://kommunikasjon.ntb.no/pressemelding/electric-for-all-volkswagen-viser-for-forste-gang-understellet-til-den-helelektriske-id-familien?publisherId=16054789&releaseId=17853931.

[31] PEDRO LIMA. *Volkswagen MEB details*. May 2020. URL: https://pushevs.com/2020/04/12/simple-solution-for-safer-cheaper-more-energy-dense-batteries/.

[32] PEDRO LIMA. *Comparison of different EV batteries in 2020*. July 2021. URL: https://pushevs.com/2020/04/04/comparison-of-different-ev-batteries-in-2020/.

[33] Xiao-Guang Yang, Teng Liu, and Chao-Yang Wang. "Thermally modulated lithium iron phosphate batteries for mass-market electric vehicles." In: *Nature Energy* 6.2 (2021), pp. 176–185.

[34] Xinghua Meng and Eric Y. Zheng. "The Next-Generation Battery Pack Design: from the BYD Blade Cell to Module-Free Battery Pack." In: *BatteryBits* (2020). URL: https://medium.com/batterybits/the-next-generation-battery-pack-design-from-the-byd-blade-cell-to-module-free-battery-pack-2b507d4746d1#:~:text=In%20a%20conventional%20battery%20pack,also%20increases%20the%20manufacturing%20cost..

[35] Roeland Bisschop et al. "Fire Safety of Lithium-Ion Batteries in Road Vehicles." In: (May 2019). DOI: 10.13140/RG.2.2.18738.15049.

[36] Yuqing Chen et al. "A review of lithium-ion battery safety concerns: The issues, strategies, and testing standards." In: *Journal of Energy Chemistry* 59 (2021), pp. 83–99. ISSN: 2095-4956. DOI: https://doi.org/10.1016/j.jechem.2020.10.017. URL: https://www.sciencedirect.com/science/article/pii/S2095495620307075.

[37] Yang Hua et al. "Sustainable value chain of retired lithium-ion batteries for electric vehicles." In: *Journal of Power Sources* 478 (2020), p. 228753. ISSN: 0378-7753. DOI: https://doi.org/10.1016/j.jpowsour.2020.228753. URL: https://www.sciencedirect.com/science/article/pii/S0378775320310570.

[38] H. Rallo et al. "Economic analysis of the disassembling activities to the reuse of electric vehicles Li-ion batteries." In: *Resources, Conservation and Recycling* 159 (2020), p. 104785. ISSN: 0921-3449. DOI: https://doi.org/10.1016/j.resconrec.2020.104785. URL: https://www.sciencedirect.com/science/article/pii/S0921344920301063.

[39] Bernhard Faessler. "Stationary, Second Use Battery Energy Storage Systems and Their Applications: A Research Review." In: *Energies* 14.8 (2021). ISSN: 1996-1073. DOI: 10.3390/en14082335. URL: https://www.mdpi.com/1996-1073/14/8/2335.

[40] Benedikte Wrålsen et al. "Circular business models for lithium-ion batteries - Stakeholders, barriers, and drivers." In: *Journal of Cleaner Production* 317 (2021), p. 128393. ISSN: 0959-6526. DOI: https://doi.org/10.1016/j.jclepro.2021.128393. URL: https://www.sciencedirect.com/science/article/pii/S0959652621026068.

[41] J. Neubauer et al. "Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries." In: (Feb. 2015). URL: https://www.osti.gov/biblio/1171780.

[42] Lorenzo Usai et al. "Analysis of the Li-ion battery industry in light of the global transition to electric passenger light duty vehicles until 2050." In: *Environmental Research: Infrastructure and Sustainability* 2.1 (2022), p. 011002. DOI: 10.1088/2634-4505/ac49a0. URL: https://doi.org/10.1088/2634-4505/ac49a0.

[43] Yanqiu Tao et al. "Second life and recycling: Energy and environmental sustainability perspectives for high-performance lithium-ion batteries." In: *Science Advances* 7.45 (2021), eabi7633. DOI: 10.1126/sciadv.abi7633. eprint: https://www.science.org/doi/pdf/10.1126/sciadv.abi7633. URL: https://www.science.org/doi/abs/10.1126/sciadv.abi7633.

[44] Eklas Hossain et al. "A Comprehensive Review on Second-Life Batteries: Current State, Manufacturing Considerations, Applications, Impacts, Barriers and Potential Solutions, Business Strategies, and Policies." In: *IEEE Access* 7 (2019), pp. 73215–73252. DOI: 10.1109/ACCESS.2019.2917859.

[45] Hans Eric Melin. "State-of-the-art in reuse and recycling of lithium-ion batteries–A research review." In: *The Swedish Energy Agency: London, UK* (2019).

[46] Elena Mossali et al. "Lithium-ion batteries towards circular economy: A literature review of opportunities and issues of recycling treatments." In: *Journal of Environmental Management* 264 (2020), p. 110500. ISSN: 0301-4797. DOI: https://doi.org/10.1016/j.jenvman.2020.110500. URL: https://www.sciencedirect.com/science/article/pii/S0301479720304345.

[47] Kirti Richa. *Sustainable management of lithium-ion batteries after use in electric vehicles*. Rochester Institute of Technology, 2016.

[48] Yuqing Wang et al. "Recent progress on the recycling technology of Li-ion batteries." In: *Journal of Energy Chemistry* 55 (2021), pp. 391–419.

[49] Ahmad Mayyas, Darlene Steward, and Margaret Mann. "The Case for Recycling: Overview and Challenges in the Material Supply Chain for Automotive Li-Ion Batteries." In: *Sustainable Materials and Technologies* 19 (Dec. 2018). DOI: 10.1016/j.susmat.2018.e00087.

[50] Yangtao Liu et al. "Current and future lithium-ion battery manufacturing." In: *iScience* 24.4 (2021), p. 102332. ISSN: 2589-0042. DOI: https://doi.org/10.1016/j.isci.2021.102332. URL: https://www.sciencedirect.com/science/article/pii/S258900422100300X.

[51] Ahmad Mayyas, Darlene Steward, and Margaret Mann. "The case for recycling: Overview and challenges in the material supply chain for automotive li-ion batteries." In: *Sustainable Materials and Technologies* 19 (2019), e00087. ISSN: 2214-9937. DOI: https://doi.org/10.1016/j.susmat.2018.e00087. URL: https://www.sciencedirect.com/science/article/pii/S2214993718302926.

[52] Vivienne Halleux. "New EU regulatory framework for batteries." In: *EPRS | European Parliamentary Research Service* (2021), p. 6.

[53] Qian Wang et al. “A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles.” In: *Renewable and Sustainable Energy Reviews* 64 (2016), pp. 106–128. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2016.05.033. URL: https://www.sciencedirect.com/science/article/pii/S1364032116301435.

[54] Isidor Buchmann. *BU-205: Types of Lithium-ion*. Oct. 2021. URL: https://batteryuniversity.com/article/bu-205-types-of-lithium-ion.

[55] Dongjiang Li et al. “CHAPTER 9: Understanding battery aging mechanisms.” In: Mar. 2019, pp. 220–250. ISBN: 978-1-78801-418-2. DOI: 10.1039/9781788016124-00220.

[56] Xin Lai et al. “Electrical behavior of overdischarge-induced internal short circuit in lithium-ion cells.” In: *Electrochimica Acta* 278 (2018), pp. 245–254. ISSN: 0013-4686. DOI: https://doi.org/10.1016/j.electacta.2018.05.048. URL: https://www.sciencedirect.com/science/article/pii/S0013468618310727.

[57] Martin F Langøy. “Techno-economic assessment of future energy storage systems - ENE-503.” In: *UIA* (2021).

[58] E Peter Roth and Christopher J Orendorff. “How electrolytes influence battery safety.” In: *The Electrochemical Society Interface* 21.2 (2012), p. 45.

[59] Isidor Buchmann. *BU-306: What is the Function of the Separator?* Jan. 2019. URL: https://batteryuniversity.com/article/bu-306-what-is-the-function-of-the-separator.

[60] Xiaosong Huang. “Separator technologies for lithium-ion batteries.” In: *Journal of Solid State Electrochemistry* 15.4 (2011), pp. 649–662. DOI: 10.1007/s10008-010-1264-9. URL: https://doi.org/10.1007/s10008-010-1264-9.

[61] Isidor Buchmann. *BU-104b: Battery Building Blocks*. Dec. 2018. URL: https://batteryuniversity.com/article/bu-104b-battery-building-blocks.

[62] Jie Sheng et al. “Recent developments of cellulose materials for lithium-ion battery separators.” In: *Cellulose* 24.10 (2017), pp. 4103–4122.

[63] Isidor Buchmann. *BU-305: Building a Lithium-ion Pack*. Oct. 2021. URL: https://batteryuniversity.com/article/bu-305-building-a-lithium-ion-pack.

[64] Shashank Arora. “Selection of thermal management system for modular battery packs of electric vehicles: A review of existing and emerging technologies.” In: *Journal of Power Sources* 400 (2018), pp. 621–640.