Bacheloroppgave

SCM600 Logistikk

Lithium-Ion Battery Recycling Industry in Norway: Current state and future expectations

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Abstract

The objective of this thesis is to establish an overview of where the current and future state of Lithium-ion battery recycling is in Norway. As the demand for new lithium-ion batteries is increasing due to the rising use of electric vehicles, so will the demand for recycling used lithium-ion batteries. Therefore, actions have to be taken to make sure the influx of end-of-life batteries does not end up in a landfill.

As Norway is a leading country in adopting the use of electric vehicles, we wanted to see if they are on the right track when thinking about what to do with end-of-life batteries. A qualitative research method was chosen where we gathered secondary data and information to compare Norwegian companies to other Northern European actors, these actors being from Germany, Finland, and Sweden.

What we found was that Norway is heading in the right direction if they keep the same momentum up. What has been done up to now is not enough for what is coming in the future and the existing Norwegian companies have to expand even more to ensure that we have enough recycling capacity. There is also a lot of room for new actors to come in and help with tackling the incoming wave of lithium-ion batteries that needs recycling.

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1.0 Introduction

Since the 2000s there has been an ever-increasing focus on climate change. Governments around the world are always trying to find new ways of decreasing the growing crisis that the world is facing by implementing policies and researching innovative technologies that can help us on the path of becoming an increasingly greener world in the future.

In 2020 the European Union increased its goal of reducing greenhouse gas emissions to 55% by 2030. Previously this goal was only at 40%. This was to align the Paris agreement's goal of keeping the global temperature increase below 2 degrees Celsius, and to pursue efforts of keeping the temperature increase at 1.5 degrees. (European Comission, 2020) In line with this, Norway's government also strengthened its goals of reducing greenhouse emissions to 55% by 2030. (Regjeringen, 2022).

A key part in reaching these goals is the reduction of fossil fuel-based vehicles that are currently on the road everywhere around the world. The EU is looking towards the electrification of vehicles as a big part in reducing overall emissions. In 2023 the EU expects by 2035 that all new cars on the market will be carbon neutral and not emit any Co2 or other greenhouse gases. (European Parliament, 2022)

Electrification and moving away from fossil fuels are one of the most central talking points when it comes to moving towards net zero emissions. Battery electric technology is one of the best ways to implement zero-emission technology, Lithium-Ion Batteries are the primary battery type used to achieve the common goal. (Figenbaum, et al., 2020) All of this means that production, usage, and proper waste management of Lithium-Ion batteries should also align itself with the same goal, and that everything surrounding batteries should be as carbon neutral as possible.

With this the EU has plans for improving the number of batteries recycled in the coming years. Since this includes all types of batteries, Lithium-ion batteries are also a part of these new rules. As of 2023 the majority of recycled batteries come from the consumer sector. This means batteries that are in laptops, cellphones etc.

It will not be until after 2030 and onwards when the lifetime of EV batteries starts nearing its end, that it will take over as the more prominent type of battery to be recycled. (Schmaltz, 2023). This means that in the future, Norway and EU will need a greater recycling-capacity for the number of batteries (specifically LIB) they are capable of recycling.

This is where the topic of our thesis comes in, where we will look at how and where the battery recycling industry is at its current state and what it might look like in the future. With Norway as a primary focus point, due to its prominent use of Lithium-ion batteries in its already big and rapidly growing EV fleet.

1.1 Lithium-Ion Batteries

A LIB (Lithium-ion battery) is an advanced battery technology that employs lithium ions as a crucial element in their electrochemistry. (Clean Energy Institute, 2020) They are made up of a single or multiple lithium-ion cell along with a protective circuit board and the number of cells used determines its size and voltage, commonly referred to with the number of cells followed by the letter s, i.e., 1s, 2s and so on. (Battery University, 2021)They are made up of a single or multiple lithium-ion cell along with a protective circuit board and the number of cells used determines its size and voltage, commonly referred to with the number of cells followed by the letter s, i.e., 1s, 2s and so on. (Battery University, 2021)

Lithium-ion batteries are the most popular rechargeable battery chemistry to this day and are used to power different devices we use every day, from a cellphone to an electric vehicle. (Clean Energy Institute, 2020) The increased use of lib's due to the popularity of electrifying everything in an attempt to drastically reduce all carbon emissions has led to a continuously growing demand. The Lithium-ion battery has four critical raw materials used to manufacture them, lithium, graphite, cobalt, and manganese. An increase in lib demand directly means an increase in those raw materials. (Maisel, et al., 2023)

1.2 The Norwegian EV Fleet

One of the biggest impacts on the increasing demand for lithium-ion batteries in Norway, is the “Norwegian EV Fleet.” Which contests of, fully electric vehicles (EV’s), plug-in hybrids (Hybrids/PHEV’s), and non-plug-in hybrids (HEV’s). These types of vehicles have been gaining more interest from the public and have established their place in the overall vehicle market at a fast pace during the last few years.

Its rapid growth is due to a number of distinct factors, the main ones being: Environmental (Norway aiming for a greener future) and economic (Norway having multiple benefits associated with owning an electric vehicle). (Fridstrøm, 2019)
The total number of registered electric vehicles in Norway by the end of 2022 was around 600 000. This sums up to be 21% of all registered passenger vehicles in Norway, with another 12% being hybrids. (Statistisk sentralbyrå, 2023)

1.2.1 EV Market Share Norway and Europe

According to the Norwegian national transport plan (NTP) 2022-2023, where the policy targets from the NTP 2018-2029 remain unchanged, all new passenger cars, light vans and city buses shall be emission free by 2025. And by 2030, that will also include all new heavier vans, 75% of long-distance buses and 50% of lorries. (Ministry of transport, 2020-2021)

In 2018 the number of new passenger cars sold in Norway being fully electric was 31,2%, in 2019-42,4%, in 2020-54,3%, in 2021-64,5%, all the way up to 79,3% in 2022. (veitrafikken, 2023) If the NTP scenario is correct that number will be closer to 100% already by 2025.

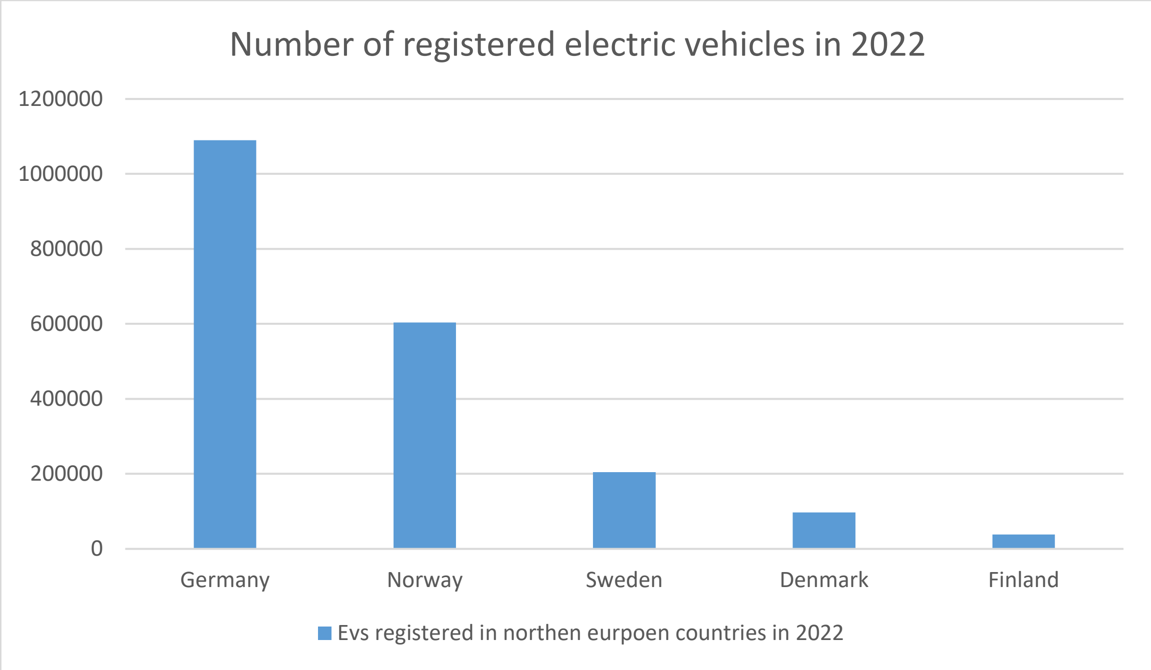

Figure 1 Number of fully electric vehicles 2022 Numbers acquired from *(European Automobile Manufacturers Association, 2022)*

Figure 1 Shows the number of registered electric vehicles in 2022 in Northern European countries. Germany (1.09million), Norway (604 000), Sweden (205 000), Denmark (97 000) and Finland (38 000).

The increase in sales and use of electric transportation is also significant in other parts of Europe. One of the reasons this increase is happening is thanks to European climate law. The Fit for 55 proposals, to revise and update EU legislation, has to a degree been adopted by the council. One of the proposals that has been implemented is on emissions from cars and vans. This proposal aims to reduce emissions from cars and vans by 55% by 2030 and 100% by 2035. (European council, 2023) This has encouraged countries in Europe to follow Norway's lead and sell more Emission-free vehicles i.e., electric vehicles.

Even though Norway and the rest of Scandinavia are the leading countries in Europe when it comes to the number of new registered electric vehicles, other countries such as Germany, Sweden, Finland, and more, have also had a significant increase in their EV market share. The number of registered EV's in Europe only accounted for a market share of 1,9% in 2018 but is rising rapidly and by 2021 it was already up to 17,8%. (European Environment Agency, 2022)

1.3 Growing demand for Lithium-Ion Batteries

Electric vehicles are becoming increasingly prominent in Norway and the rest of Europe, the demand for Lithium-ion batteries is also becoming increasingly higher in conjunction with the EV-market that continues to grow.

Since Lithium-ion batteries are the most common batteries found in EV’s and are also prominent in everyday devices, this battery type will continue to see a surge in demand throughout the 2020’s and likely more into the 2030’s. According to the European Council the number of electric road-vehicles on the road in Europe in 2019 was 1.8 million. This is estimated to rise to 30 million vehicles by 2030. That is an increase of 1567% in just 10 years.

At the same time, it is estimated that the global demand for batteries will increase by x14 by 2030 of what it was in 2019. It is also expected that the price for batteries will drop by an estimated 50% throughout the 2020’s. (European Council, 2019)

This is why it is essential for governments and companies to start making sure how to get the needed materials and how to do so in a manner that is healthy for the environment. As this is the case, recycling has been the number one talking point for used batteries.

1.4 Assumptions

There are a lot of distinct types of batteries being used that require recycling. We have decided to strictly focus on larger Lithium-Ion Batteries, with bigger emphasis on EV-batteries for this study. This is because of possible differences in how batteries are recycled and also because Lithium-Ion Batteries are as of today the most relevant and widely used battery type in electric vehicles.

We have also decided to restrict the geographic area to cover Norway and countries surrounding Norway if it becomes relevant to the study. Since policies and views on certain things can be different depending on where in the world you are. This is also the geographic area where electrification has become a much more central talking point compared to other parts of the world.

1.5 Research questions

As already stated, LIBs are becoming increasingly popular, and the demand is growing at a rapid pace. Because of this recycling is also becoming more important as the years go by. This thesis will predominantly look at the Norwegian LIB recycling industry, how it is and potentially will become, with comparison to some other European countries. As the title of the thesis says: *"Lithium-Ion Battery recycling industry in Norway: current state and future expectations."* With this in mind, we have formulated 5 individual research questions that will help us get closer to answering this issue and potential problems surrounding it:

1. Why is lithium-ion battery recycling important?
2. What is the current state of the lithium-ion battery recycling industry in Northern Europe?
3. What is the demand for lithium-ion battery recycling in Northern Europe in the coming years?
4. Is Norway in an advantageous position to become a leader in the lithium-ion battery recycling industry?

1.6 Structure

The thesis starts off with the introductory chapter where general knowledge of the subject is explained. This chapter is used to introduce the subject and gain relevant knowledge for the research questions after the introduction chapter.

After the introduction and the research questions are presented, we move onwards to the literature review in Chapter 2. Here all the valuable information and data needed for answering the research questions are gathered. The information gathered here is ultimately the most important and relevant part of the thesis. After the literature review, we go on to methodology. Here it is explained how we gathered the data and what methodology we used to try and find an answer. This then moves onto results and discussion where we discuss the data and information found to try and come to a satisfying conclusion. This conclusion is then presented in the final chapter of the thesis.

2.0 Literature and Theory Review

2.1 Lithium-Ion Battery Recycling

Recycling of materials can be defined as "*any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes*". (European Comission, 2023) As this definition falls under any recyclable materials, LIBs are also a part of this definition.

2.1.1 Why it is important

Battery recycling is steadily becoming a more and more important factor due to multiple reasons. The main factors being:

The continuously increasing demand for LIBs outgrowing and outweighing the current production capacity of batteries and the availability of raw materials needed in their production process. *"Recycling processes are the only options to re-introduce end-of-life batteries."* (Jonas, et al., 2022).

The danger on the environment and the risk to the public's health, that come with the pollution and dangerous chemicals deriving from LIBs that are being piled up and thrown in garbage landfills and stockpiled, instead of being correctly destroyed or recycled.

There is also an economy driven need to recycle batteries. Spent LIBs still contain valuable materials, those materials will eventually become more expensive to get as the raw or "virgin" material, then the cost of recycling, as the supply is not going to be able to meet the demand in the future. When that happens recycling will become the more viable option both environmentally and economically. By using a circular economy model which promotes recycling, we will extend the lifespan of battery materials and minimize waste generation.

Although recycling of LIBs has many environmental advantages, we have to remember that the recycling processes of lithium-ion batteries are still in their "infant" stage. This is due to many reasons such as economic barriers, science and technology gaps, collection and sorting issues, and logistic issues. In the EU, some battery directives have been implemented to fight against the growing environmental impact EoL (End-Of-Life) batteries are having by ending up on landfills or stockpiles that contaminated the land and become a waste of nonrenewable natural resources. (Zachary J., et al., 2022)

These present regulations or directives in the EU are the Battery Directive (Directive 2006/66/EC) and the Waste Electrical and Electronic Equipment (WEEE) Directive (Directive 2012/19/EU). Countries abiding by these regulations are required to set up collection schemes for EOL batteries by having collection points located in the close vicinity of end-users.

Revision from the 2006 Battery Directive shows that in 2012 most countries achieved the set collection target by only 25% and only 14 members reached the target of 45% by 2016, meaning that 56% or about 35 000 tons of portable batteries ended up in municipal waste streams. However new targets were proposed during the European Green Deal in 2020 and goals are 65% by 2025 and 70% by 2030. These targets do not include bigger batteries such as EV-batteries, but they do set a legal framework to establish collection of those as well.

As the demand for LIBs continues to grow so will the demand for the raw materials required to produce them. The most important and common raw materials we find in LIBs are lithium, graphite, cobalt, and manganese.

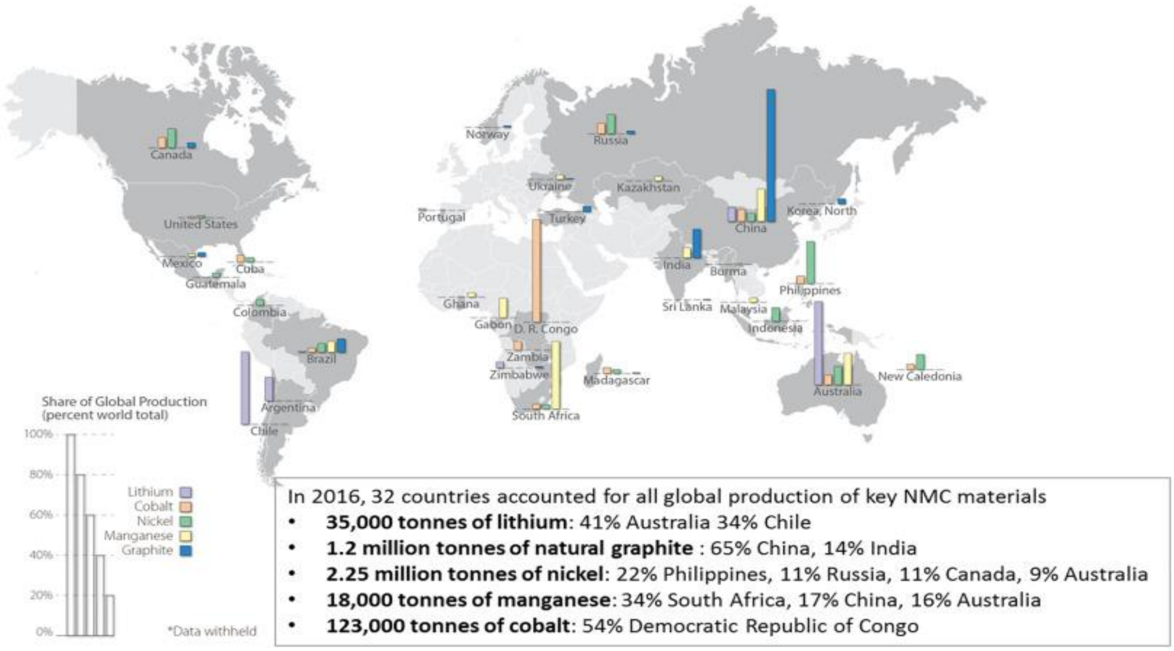

Figure 2 Production2 location of LIB raw materials (Mayyas, et al., 2019)

Figure 2 shows the location of where certain metals are produced and the respective production share between the producing countries. From this we see that 41% of lithium is produced in Australia, and 34% in Chile. China produces 65% of the worlds natural graphite and India produces 14%. South Africa produces 34% of the world’s manganese, China produces 17% and Australia 16%. Cobalt is mainly centered in Africa where the Democratic Republic of Congo produces 54%. (Mayyas, et al., 2019) As some of these metals are centered around unstable geopolitical areas/climates, the availability of the metals (for Europe) can be uncertain depending on how things develop in the future.

The main metals of concern where the demand is most likely going to exceed production are lithium and cobalt. Depending on future scenarios, the total production capacity for lithium will have to be increased by six times, while cobalt’s total production will need to be increased three times, to be able to meet the expected future demand. (Maisel, et al., 2023) It can be difficult to increase production by this much in a short amount of time. Therefore, mining operations either need to be expanded or develop innovative technology that would be able to increase efficiency enough to meet the demand.

Finally, the push for LIB recycling promotes the circular economy agenda. Circular economy can be explained as "*a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible*". (European Parliament, 2015) Basically meaning, extending the lifetime of all types of products as long as you possibly can. This push for the recycling of LIB will promote an environmentally friendly way of thinking and could possibly influence other industries if LIB recycling proves to be effective.

All the reasons mentioned above are some of the most important reasons for why LIB's recycling is so important. Making sure to preserve the environment best as possible, making sure we have enough resources easily available to make the change from fossil fuels easier, and at last being able to use the way of making the statement that a circular economy business model can be beneficial for everyone.

2.1.2 Recycling process from collection to final end results

There are currently three recycling processes for lithium-ion batteries in use today. These recycling methods are direct recycling, pyrometallurgical and hydrometallurgical.

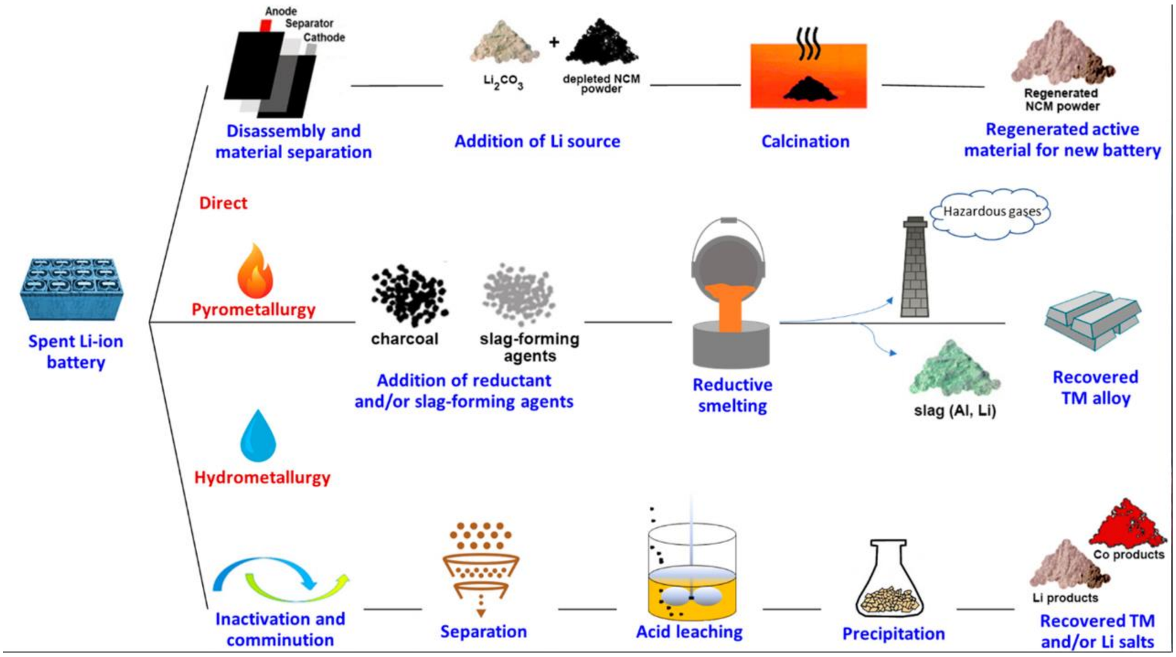

Figure 3 Different3 recycling processes for LIBs (Zachary J., et al., 2022)

Figure 3 shows a visual representation of the three current recycling processes of Lithium-ion batteries in use today.

The three methods listed and shown above in figure 2, all have the same first step which is the collection and sorting of the EOL LIBs based of type, size, and chemistry. Using the direct method, the collected and sorted batteries are then properly discharged, followed by the disassembly for access to internal components, then the battery cells or packs are crushed/shredded to expose the electrode materials and enables subsequent separation. Once the cells are shredded, the material is passed through sieves, separating the mix based on particle size, then with the help of magnets, remaining ferrous metals such as iron and steel are removed from the mix. This process alters based on the way the batteries are made and depending on what exactly is wanted to recover from said batteries.

Pyrometallurgy is the use of high temperatures to extract valuable metals that are used in LIBs. The process starts with the removal of non-metallic components or electrolyte residues if needed, then the preprocessed materials are fed into a smelting furnace/heated vacuum where different metals such as cobalt, nickel, copper and others depending on the battery composition, reach their melting point and separate from non-metallic materials. Once they are separated, they undergo refining and purification to reach high enough purity level for reuse, and are then solidified into ingots or other forms, to facilitate storage, transportation, and further processing in the manufacturing of new batteries.

Hydrometallurgy uses aqueous solutions and chemical processes to separate valuable metals from LIBs. The process starts like the one mentioned above, with the removal of any non-metal materials or remaining electrolyte residue and is then sent to leaching. That is the use of aqueous solutions containing acid or other chemical agents to dissolve and extract the valuable metals within the preprocessed batteries. The dissolved solution is then filtered to separate the dissolved metal from solid residue and other impurities. On to precipitation, which is when a chemical agent is added to the filtered solution to separate the metals in the solution into a form of solid compound or salts. The solids and liquids are then separated, and the metals are refined before being turned into solidified ingots or other forms.

It is worth to note that these different processes, also described in (Zachary J., et al., 2022) (Jonas, et al., 2022), are not a “only one” type of process but are often used in combination.

2.1.3 Repurposing of Lithium-Ion Batteries

Repurposing lithium-ion batteries is the process of finding new ways to use said batteries after they have reached the end-of-life cycle of their primary application. This is a process typically used in batteries that still have a lot of their remaining capacity but not enough to be used in their primary application, such as for example EV batteries.

EV batteries have been proven to retain upwards of 70-80% of their initial capacity. (Gur, et al., 2018) Some of the repurposing possibilities of used EV batteries are home energy storage, off-grid power solutions and portable power banks. However, these have not become very usable solutions in the private market as the investment to cost to saving ratio has not been very noteworthy.

Repurposing of LIBs is more attractive in the business side of the world, as for example BMW's new power station located in Hamburg. (Hossain, et al., 2019) It uses 2 600 used EV batteries with a total capacity of 2 800kWh to keep the electricity grid stable. Projects like this and finding secondary uses for batteries with at least 70-90% remaining total capacity, help expand a battery's life cycle by approximately 5-10 years. This is good due to multiple reasons, it mitigates the demand for virgin raw materials and by extending the battery's life, it delays the time before recycling, meaning there is more time to evolve and better the recycling process before the batteries are sent to be recycled.

As mentioned in Chapter 1.2.1 Norway has the goal all new passenger cars, light vans, and city buses to be emission free by 2025, and by 2030, that will also include all new heavier vans, 75% of long-distance buses and 50% of lorries. EV's already made up 79% of all new passenger vehicle sales in Norway in 2022 and will continue to grow, this growth will undoubtedly lead to a large amount of EoL by 2030 considering the average estimated primary lifecycle of an EV battery is around 8 years.

As a result, Norway will have a great opportunity to economize second-life batteries, as the supply will no longer be a challenge. The Norwegian company Eco Stor AS (Eco Stor, 2022) was established in 2018 and is already actively using second life batteries to provide multiple products, such as residential energy storage solutions, Grid Energy Storage, and Industrial Energy Storage.

2.1.4 Commercial and governmental reports, roadmaps

In 2021, on behalf of the European Commission, the European Technology and Innovation Platform published a roadmap titled "*Roadmap on raw materials and recycling*". This roadmap talked about recommendations for what Europe and European countries should do to improve everything from sourcing raw materials to improving circular business models and end-of-life batteries. Around 40+ people contributed to the published roadmap. (Batteries Europe, 2021) It specifically gave short to medium-term needs and requirements for staying/becoming competitive in the industry. Some of the key take-aways from the report mentioned were:

- Batteries used and produced by Europe should follow high sustainability standards throughout the full life cycle. They also recommend Europe to develop a full European value chain so that the risks surrounding the sourcing of valuable raw materials are minimized.
- Improving the processes of collecting used portable batteries and **guaranteeing** the collection of all EV and industrial batteries. This requires informing citizens about the usage of collection points so that more and more household/portable batteries go to where they should be. The guarantee of being able to collect all of the used EV and industrial batteries requires cooperation between governments and companies so that that actors using these types of batteries are able to dispose of them in a safe and efficient manner.
- Being able to automate the dismantling processes so that it can better keep up with the inevitable high demand in the future.
- Thinking about the state of a battery by developing a standard state-of-health diagnosis that determines where batteries should be sorted, whether they will be transported straight to a recycling facility or be used for repurposing. This is to ensure that every battery will be handled with care in safe environments.

These are just some of the important takeaways from the roadmap. It is important to mention that things can change in the future, as technologies and protocols are further developed upon. This roadmap includes short to medium term goals that span from 0-5 years into the future and 5-10 years into the future.

2.1.5 Industry players in Northern Europe

2.1.5.1 Hydrovolt

Hydrovolt is a new company established as a joint venture between the Norwegian energy- and aluminum company Hydro and the Swedish battery manufacturer company Northvolt. It was established in June of 2020 with a goal to deliver a sustainable solution for battery recycling in Europe to make sure that every battery is never wasted. Hydrovolt is also partnered with the Norwegian battery collection and recycling company Batteriretur. Batteriretur already collects all kinds of batteries throughout Norway, which makes it the perfect resource for Hydrovolt. (Hydrovolt, 2023)

In May 2022 Hydrovolt started its commercial recycling operations in Europe, it was EU's largest Lithium-ion battery recycling plant at the time, located in Fredrikstad, Norway. This facility has the capacity to process 12.000 tons of battery packs a year. (Hydrovolt, 2022) This was sufficient enough to recycle the entirety of Norway's end-of-life battery market in 2022.

The recycling process at the facility manages to recycle approximately 95% of battery materials. A lot of these materials are being sent back to Hydro and Northvolt to be used again in production as needed. Hydrovolt has a long-term plan of being able to recycle 70.000 tons of battery packs by 2025, and 300.000 tons by 2030. They are planning to do this by exploring the option of expanding more within Europe. (Hydrovolt, 2022)

2.1.5.2 Eco Stor AS

Eco Stor AS is a relatively new Norwegian company established in 2018. This is primarily a company specializing in energy storage systems that are provided with minimal to no carbon footprint. They have a vision of contributing to a circular economy where no material is wasted. This includes recycling and reusing LIB's.

At the start of 2022 Eco Stor AS announced that they will open a new recycling facility in Norway that is planned to have an annual capacity of 10.000 tons. This is in a partnership with Li-Cycle, a North American company that will provide the needed technology, equipment, and management for the facility. The facility plans to open sometime in 2023. (Eco Stor, 2022)

2.1.5.3 Fortum

Fortum is a Finnish energy company that has started to expand into battery recycling in the recent years. In April 2023 they started commercial operations at their facility in Harjavaltar, Finland and according to Fortum themselves, it is the largest facility in terms of recycling capacity in Europe at the time of their opening. Here they are using in-house technology that has the capability of recovering 95% of black mass from LIB's. The materials recovered will go back into the cycle and can be used to produce new LIBs as needed. (Fortum, 2023)

In March 2023 Fortum also gained a license to start battery recycling operations in Kirchardt, Germany. Here they have opened a recovery hub that will work closely with the recycling facility in Finland to bring more opportunities for people to recycle batteries in Europe. Fortum is also looking to expand into other European regions that might also need more options for recycling their LIBs. (Fortum, 2023)

2.1.5.4 Primobius

Primobius is another joint venture between the Australian company Neometals Ltd and the German plant manufacture company SMS group GmbH. The joint venture was established to "*commercialize an efficient, environmentally friendly recycling solution for end-of-life scrap lithium-ion battery cells*." (Primobius, 2023) With this they aim to reduce carbon emissions and waste by making the process as efficient as possible so you can get raw materials without worrying about mining operations.

In March 2022 Primobius officially opened its first recycling facility for commercial use in Hilchenbach, Germany. This facility has an operating capacity of 10 tons per day which equates to a yearly capacity of approximately 3650 tons. The technology used in the facility is able to recover 95% of the black mass found in a LIB. (Primobius, 2022)Even though the plant is commercial, it also serves as a demonstration of what is potentially possible with bigger facilities that have higher recycling capacities.

2.1.5.5 Stena Recycling

Stena Recycling is a Swedish company specializing in every form of recycling and they have a goal of being a part in the creation of a fully functional circular economy where no material will be wasted. As of 2023 they are operating in Sweden, Denmark, Norway, Finland, Germany, Poland, Italy, and the US. They have 178 recycling facilities and 3500 total employees spread across all of the above-mentioned countries. (Stena Recycling, n.d.) This makes them a strong candidate in the big push for the recycling of LIBs.

In 2021 Stena Recycling invested a quarter billion SEK in a LIB recycling facility that is located in Halmstad, Sweden and it opened in March 2023. This facility is able to recycle about 95% of the original material found in a battery and will have a yearly capacity of 10.000 tons with the availability of expanding in the future as needed. The batteries that will go to the recycling facility will be collected and sorted by the already existing infrastructure Stena Recycling has available. (Stena Recycling, 2021)

3.0 Methodology

A methodology can be described as a way in which you approach a problem, this can be further divided into quantitative methods and qualitative methods. A quantitative method is a method where the collected data is presented in the form of numbers and graphs. A qualitative method is expressed in words and where you gather already written data and interpret that data in your own way. (Streefkerk, 2023)

This thesis uses primarily a qualitative method where we have gathered different literature and already collected data from secondary sources. We then interpret the collected information and data where we try and come up with a satisfying conclusion based on what we have found in the literature and theory review.

3.1 Comparative Case Study: The Lithium-Ion Battery recycling industry

The primary aim of this thesis is to find out the current and future state of the LIB recycling industry in Norway and comparing it to other commercial agents in Germany, Sweden, and Finland. By doing this we find out what the current state of the LIB recycling industry is in Northern Europe as a whole, and how it might develop in the future based on the interest shown in what is being done. This will also allow us to find out what Norwegian companies are doing, and the potential Norway has as a country to establish itself as an industry leader.

3.1.1 Commercial agents

In the literature and theory review we went through some industry players in countries from Norway, Finland, Sweden, and Germany. These are the commercial agents that will be included in the comparative case study:

- Hydrovolt (Norway)
- Eco Stor (Norway)
- Fortum (Finland)
- Primobius (Germany)
- Stena Recycling (Sweden)

3.1.2 Factors

For a comparison to work, we must establish different factors that we can compare between the different commercial actors. These factors are based on what we see as the most important and relevant to what we are trying to figure out in the research questions stated in chapter 1.5:

- **Lithium-ion batteries in use** – An estimate of how many LIBs are currently in use in different markets/locations in tons, based on the EV-market shares.
- **Yearly recycling capacity** – The yearly recycling capacity in each of the company's facilities, in tons.
- **Recycling effectiveness** – Approximately how effective each company is at extracting the important materials from a LIB, in Percentage.
- **Ease of collecting** – How easy it might be for someone to dispose of their high-energy LIB based on existing infrastructure.
- **Geographical coverage** – The facility locations "sphere of influence".

4.0 Results and discussion

4.1 Results

Table 1 Tons of LIBs in the EV fleets of each country housing one of our chosen industry players by 2022

	Factor
Countries	LIBs in use 2022 (tons)
Norway	271 800 t
Finland	17 100 t
Germany	490 500 t
Sweden	92 250 t

In Table 1 we collected data from chapter 1.2.1, giving us the number of registered EVs in each country housing one or more of the industry players we chose for comparison with Norway. With these numbers, we multiplied the number of EVs in a country with the average weight of batteries per EV (454kg or 0,45Ton- (Hart, 2023)). This gave us the estimated total tons of EV-LIBs in each country.

The EV market share started its rapid growth after 2018 going from accumulating 1,9% to almost 18% in 2021(Chapter 1.2.1) This means that the majority of accounted for EVs were acquired between 2018 and 2021. With the average estimated primary lifecycle of an EV battery being around 8 years (Chapter 2.1.3), we can then assume that at least 80% of the total LIBs circulating in the different EV fleets of each country is going to reach its need for repurposing or recycling by 2030.

Table 2 Each company facilities yearly recycling capacity and its recycling effectiveness

	Factors	
Companies	Yearly recycling capacity (tons)	Recycling effectiveness (%)
Hydrovolt (Norwegian)	12 000 t	95%
Eco Stor (Norwegian)	10 000 t	95%
Fortum (Finnish)	12 000 t +	95%
Primobius (German)	3 650 t	95%
Stena Recycling (Swedish)	10 000 t	95%

In Table 2 the data collected is the yearly recycling capabilities and recycling effectiveness of each of the respective company facilities. With this data we figure out that the typical recycling capacity of newly built facilities is around 10 000 t per year.

Eco Stor's facility has yet to be built, but the planned yearly capacity is 10 000 t. Fortum has not explicitly given the yearly capacity of its facility, what they have stated however, is that at the time of its completion in March 2023, it became the facility with the largest recycling capacity in Europe. If this is correct, we can assume that it is at least equal to or slightly higher than Hydrovolt's 12 000 t yearly capacity.

We can also see that the effectiveness percentage of the recycling facilities is all equal, each facility being at 95% respectively. This is the percentage of collected black mass which consists of all the critical metals like lithium, graphite, manganese, and cobalt needed to produce a LIB.

Table 3 Collecting capabilities and geographic location

	Factors	
Companies	Collection capabilities	Geographical coverage
Hydrovolt (Norwegian)	Easy	Neutral
Eco Stor (Norwegian)	Easy	Neutral
Fortum (Finnish)	Moderate	Poor
Primobius (German)	Easy	Ideal
Stena Recycling (Swedish)	Easy	Neutral

In table 3 for collection capabilities the variables were from easy, moderate, and hard. Easy having good access to lithium-ion batteries without much struggle with things like transport. To hard being in a position where you need to invest more into the collection of batteries with harder transportation options etc. The geographical coverage was based on poor, neutral and ideal. Poor being a geographical area with small coverage of the existing LIB market. Ideal being in a position where you have a large area of options and sourcing capabilities.

We summarized the different companies' abilities to source their end-of-life LIBs and how good the geographical locations are for each of the respective recycling facilities. We based this on the existing infrastructure that each company uses and how well they market themselves to manufacturers who are required by EU law to make sure that their batteries are disposed of in a safe manner. Because of this law end-of-life companies like Eco Stor get a lot of their batteries through donations.

Hydrovolt is partnered with Batteriretur who has a long history of collecting and recycling batteries in Norway. Hydrovolt’s facility is also right next to Batteriretur and because of this Hydrovolt can take full advantage of the existing infrastructure and competence that Batteriretur offers in collecting LIBs. Stena Recycling is similar to Batteriretur with the fact that they also have a long history of recycling and collecting, where they can use their existing infrastructure as they move into the industry of LIB recycling.

Eco Stor specializes primarily in energy storage systems made up of repurposed LIBs. Because of this they have no problems in collecting LIBs for recycling. Eco Stor inspects incoming batteries to see if they are healthy enough for repurposing. They also collect their own batteries from their own energy storage systems whenever it needs to be changed out and recycled. Primobius is the most similar to Eco Stor. They specialize in recycling and the way they source their batteries is through other companies contacting Primobius and delivering their used or defective LIBs for disposal.

Out of the companies listed it is Fortum that has the most challenging time with collecting recyclable LIBs. This is because Finland itself is further behind when it comes to LIBs in circulation, compared to the other countries listed. This makes it so Fortum must look outside of Finland to source their batteries. However, Fortum already has a sorting facility in Germany that can do the dismantling process before sending it further to their recycling facility in Finland so Fortum are doing things that can counteract this weakness.

When it comes to the geographical coverage, we looked at how well placed a facility is. Primobius's recycling facility is located close to the center of Germany in Hilschenbach. Being closer to the center of Europe makes it much easier for them to source LIBs from a larger number of places compared to Hydrovolt in Norway and Stena Recycling in Sweden. Fortum being in Finland makes them much further away from everything else, this makes their influence smaller than the other facilities and it means Fortum has to use more resources to acquire their batteries because of their location. This is why Primobius's location is ideal since its influence can reach further than anyone else in this comparison.

4.2 Discussion

Here we will discuss our findings in chapter 4.1 derived from our introduction chapter 1 and literature review and theory chapter 2. The discussion will help us further build on our finds, which in return will give us a good basis towards the thesis conclusion.

To give an answer surrounding the current state and future expectations of the lithium-ion recycling industry in Norway, we implemented these underlaying research questions:

1. *Why is lithium-ion battery recycling important?*
2. *What is the current state of the lithium-ion battery recycling industry in Northern Europe?*
3. *What is the demand for lithium-ion battery recycling in Northern Europe in the coming years?*
4. *Is Norway in an advantageous position to become a leader in the lithium-ion battery recycling industry?*

4.2.1 Why is battery recycling important

The main factors around the importance of battery recycling mentioned more in depth in Chapter 2.1.1 were:
The increasing demand for lithium-ion batteries, which to a large degree is directly connected to the continuously growing EV market. As mentioned in chapter 1.2.1 the EV market share in Europe had already grown from accumulating 1,9% of all passenger vehicles in 2018 to 17,8% by 2021. The goals set by the European Fit for 55 proposals also expect to reduce road emissions by 55% by 2030, increasing the interests of using Battery powered vehicles. Coupled with the goal of a more circular economy approach to the LIB market, rather than using virgin materials, promotes the importance of battery recycling.

The danger on the environment spent LIBs are causing, and on the public health by being stockpiled or thrown into garbage landfills, releasing dangerous chemicals, and becoming a waste of nonrenewable natural resources, instead of being correctly destroyed/recycled.

The economy and circular economy goals connected to battery recycling. Spent LIBs still contain valuable nonrenewable materials that when becoming a scarce resource, will have a negative effect on the price of making new batteries. While a circular economy promotes the reusing/recycling of already acquired materials and existing products will have a positive effect on the price of new batteries.

4.2.2 What is the current state of LIB recycling in Northern Europe

The LIB recycling industry in Northern Europe is still very much in its infant stage. If we look at all of the companies we compared, every single facility that has been built was opened in 2022 and 2023, this also includes facilities by other companies not included in the comparison like Mercedes-Benz who built its own recycling facility that opened in March 2023. (Mercedes-benz, 2023).

Companies that are actively making internal changes by, for example, building their own recycling facility. Will inspire others to do the same or/and implement the importance of recycling into their internal channels, which is crucial if we are the meet the growing demand for recycling as at its current state, the total recycling capacity will not be enough for the future need.

The built facilities also already have good enough technology to recycle 95% of the valuable materials found in LIBs. These technologies use very little to no emissions as well and there is still room to improve on them in the future.

The current state is overall in a very good position to expand as needed and all of the companies mentioned have plans for expansion in the near future. If companies like Hydrovolt can stick to its plan of expanding its operations to be able to recycle 70.000 tons by 2025 and 300.000 tons by 2030 there will be little to worry about in regards of not having enough capacity to reach the demand, especially if other actors are able to do the same.

4.2.3 What is the demand for LIB recycling in Northern EU in the coming years

With the information acquired in table 1, we can see that the demand for recycling in northern European countries will grow exponentially in the coming decade. Between Norway, Finland, Germany, and Sweden only, there is an estimate of approximately 900 000 tons of LIBs circulating in current in-use EV vehicles that will be ready for repurposing or recycling by 2030.

The European EV-fleet consisted of a total of 1.8million vehicles in 2018 and is estimated to grow into 30million + vehicles by 2030 (European Council, 2019). This in conjunction with the increasing demand for batteries in other appliances, will make the demand for LIBs by 2030 well over 13.5 million tons (30million x Average weight of EV Battery).

To meet such high demand for new LIBs in the next decade, without draining the availability of natural resources/materials needed to produce new LIBs, recycling and repurposing is an absolute must.

4.2.4 Is Norway at an advantageous position to become industry leader in LIB recycling

Revising all literature and results acquired throughout this thesis, it does point towards Norway having a slightly higher chance of becoming a sort of Leader and/or significant role model in the industry that is LIB recycling, especially with focus on EV-batteries and their reuse/recycling. This is due to multiple factors:

Norway is already by 2022 the leading country in Europe when it comes to EV market share per capita. As stated in chapter 1.2 and 1.2.1, Norway already had an EV-market share of 21% by the end of 2022, and 79,3% of new passenger cars sold in 2022 were fully electric. Meaning the circulation of higher capacity LIBs is already well implemented and growing.

Norway's environmental focus and strong commitment to implementing a circular economy also makes them advantageous in claiming the industry leader status. Unlike the rest of Europe's goal of removing all emissions from cars and vans by 2035 (Chapter 1.2.1), Norway's goal is emission-free only new cars, vans, and city buses already by 2025.

Norway also has a well-established knowledge base in battery technology, several companies already implementing the reuse and recycling of batteries, well-structured and promising collection results of batteries, good governmental support of the research and development of battery recycling at home. Along with already implemented collaborative efforts with other countries and organizations to advance and better LIB recycling.

5.0 Conclusion

This thesis looked at the LIB recycling industry in Norway, its current state, and its future expectations. We did this by comparing Norwegian actors to other actors from countries like Finland, Sweden, and Germany.

What we found is that Norway is on good track if they keep the same momentum they have going right now. One of the challenging parts attached to LIB recycling is the collection ease and sorting, Norway has a slight advantage with the company Batteriretur actively working with already establish recycling facilities surrounding the supplying of EoL batteries.

Norway as a country still has a high need for existing and new companies to come forward and begin investing in LIB recycling, as the demand for reuse and recycling is only growing. So far two companies have taken the biggest initiative, Hydrovolt and Eco Stor AS. In the near future these two companies are actively planning to expand and help as much as possible, so that the growing demand Norway and Europe has for LIB recycling is met both today and tomorrow.

6.0 References

Batteries Europe, 2021. *Roadmap on raw materials and recycling.* [Online]

Available at: https://energy.ec.europa.eu/system/files/2021-12/vol-2-009.pdf

[Accessed May 2023].

Battery University, 2021. *Batteryuniversity.* [Online]

Available at: https://batteryuniversity.com/article/bu-302-series-and-parallel-battery-configurations

[Accessed May 2023].

Clean Energy Institute, U. o. W., 2020. *Washington.edu.* [Online]

Available at: https://www.cei.washington.edu/education/science-of-solar/battery-technology/

[Accessed May 2023].

Eco Stor, 2022. *Introducing: Lithium-ion Battery Recycling Facility in Norway.* [Online]

Available at: https://www.eco-stor.com/news/introducing-lithium-ion-battery-recycling-facility-in-norway

[Accessed May 2023].

European Automobile Manufacturers Association, 2022. *Euronews.* [Online]

Available at: https://www.euronews.com/green/2023/05/08/norway-germany-uk-which-european-countries-have-the-biggest-share-of-electric-cars

[Accessed May 2023].

European Comission, 2020. *2030 Climate Target Plan.* [Online]

Available at: https://climate.ec.europa.eu/eu-action/european-green-deal/2030-climate-target-plan_en

[Accessed May 2023].

European Comission, 2023. *Definition of recycling.* [Online]

Available at: https://joint-research-centre.ec.europa.eu/scientific-activities-z/less-waste-more-value/definition-recycling_en

[Accessed May 2023].

European Council, 2019. *Infographic - Towards a sustainable, circular, European battery supply chain.* [Online]

Available at: https://www.consilium.europa.eu/en/infographics/battery-supply-chain/

[Accessed May 2023].

European council, 2023. *Council of europen union, fit for 55.* [Online]
Available at: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/
[Accessed May 2023].
European Environment Agency, 2022. *European Environment Agency.* [Online]
Available at: https://www.eea.europa.eu/ims/new-registrations-of-electric-vehicles
[Accessed May 2023].
European Parliament, 2015. *Circular economy: definition, importance and benefits.* [Online]
Available at:
https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits
[Accessed May 2023].
European Parliament, 2022. *EU ban on the sale of new petrol and diesel cars from 2035 explained.* [Online]
Available at:
https://www.europarl.europa.eu/news/en/headlines/economy/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained
[Accessed May 2023].
Figenbaum, E. et al., 2020. *From Market Penetration to Vehicle Scrappage: The movement of Li-Ion Batteries through the Norwegian Transport Sector*, s.l.: Institute of Transport Economics 1756/2020.
Fortum, 2023. *Fortum Battery Recycling opens Europe's largest closed-loop hydrometal-lurgical battery recycling facility in Finland.* [Online]
Available at: https://www.fortum.com/media/2023/04/fortum-battery-recycling-opens-europes-largest-closed-loop-hydrometallurgical-battery-recycling-facility-finland
[Accessed May 2023].
Fortum, 2023. *Fortum Battery Recycling receives permit to start battery recycling operations in Germany.* [Online]
Available at: https://www.fortum.com/media/2023/03/fortum-battery-recycling-receives-permit-start-battery-recycling-operations-germany
[Accessed May 2023].
Fridstrøm, L., 2019. *Electrifying the vehicle fleet: Projections for norway 2018-2050*, s.l.: Institue of trasnport economics, https://www.toi.no/getfile.php/1350199-

1553693924/Publikasjoner/T%C3%98I%20rapporter/2019/1689-2019/1689-2019-sum.pdf.

Gur, K., Chatzikyriakou, D., Baschet, C. & Salomon, M., 2018. The reuse of electrified vehicle batteries as a means of integrating renewable energy into the European electricity grid: A policy and market analysis. *Energy policy,* Volume 113, pp. 535-545.

Hart, M., 2023. *Axelwise.* [Online]
Available at: https://axlewise.com/electric-car-battery-weight/
[Accessed May 2023].

Hossain, E. et al., 2019. A Comprehensive Review on Second-Life Batteries: Current State, Manufacturing Considerations, Applications, Impacts, Barriers & Potential Solutions, Business Strategies, and Policies. *Institue of electrical and electronics engineers,* Volume 7, pp. 73215-73252.

Hydrovolt, 2022. *Europe's largest electric vehicle battery recycling plant begins operations.* [Online]
Available at: https://hydrovolt.com/europes-largest-electric-vehicle-battery-recycling-plant-begins-operations/
[Accessed May 2023].

Hydrovolt, 2023. *About us.* [Online]
Available at: https://hydrovolt.com/about-us/
[Accessed May 2023].

Jonas, N. et al., 2022. Recycling of Lithium-Ion Batteries—Current State of the Art, Circular Economy, and Next Generation Recycling. *Advanced Energy Materials,* 12(17).

Maisel, F., Neef, C., Marcheider-Weinermann, F. & Nissen, N. F., 2023. A forecast on future raw material demand and recycling potential of lithium-ion batteries in electric vehicles. *Resources, Conservation and Recycling,* Volume 192.

Mayyas, A., Steward, D. & Mann, M., 2019. The case for recycling: Overview and challenges in the material supply chain for automotive li-ion batteries. *Sustainable Materials and Technologies,* 19(Recycling of Batteries and Electronics).

Mercedes-benz, 2023. *Groundbreaking for battery recycling factory.*. [Online]
Available at: https://group.mercedes-benz.com/company/news/recycling-factory-kuppenheim.html
[Accessed May 2023].

Ministry of transport, N., 2020-2021. *National transport plan 2022-2023,* s.l.: https://www.regjeringen.no/en/dokumenter/national-transport-plan-2022-2033/id2863430/?ch=1.

Primobius, 2022. *https://www.primobius.com/news-media/press-releases/detail/ready-for-commercial-operation-battery-recycling-plant-officially-opened.* [Online]
Available at: https://www.primobius.com/news-media/press-releases/detail/ready-for-commercial-operation-battery-recycling-plant-officially-opened
[Accessed May 2023].

Primobius, 2023. *Our setup.* [Online]
Available at: https://www.primobius.com/about-us/the-company
[Accessed May 2023].

Regjeringen, 2022. *Nytt norsk klimamål på minst 55 prosent.* [Online]
Available at: https://www.regjeringen.no/no/aktuelt/nytt-norsk-klimamal-pa-minst-55-prosent/id2944876/
[Accessed May 2023].

Schmaltz, T., 2023. *Recycling of lithium-ion batteries will increase strongly in Europe.* [Online]
Available at: https://www.isi.fraunhofer.de/en/blog/themen/batterie-update/recycling-lithium-ionen-batterien-europa-starke-zunahme-2030-2040.html
[Accessed May 2023].

Statistisk sentralbyrå, b., 2023. *Statistisk sentralbyrå.* [Online]
Available at: https://www.ssb.no/transport-og-reiseliv/landtransport/statistikk/bilparken/artikler/fire-av-fem-nye-biler-i-2022-var-elbiler
[Accessed May 2023].

Stena Recycling, 2021. *Stena Recycling invests heavily in new battery recycling plant.* [Online]
Available at: https://www.stenarecycling.com/news-insights/newsroom/2021/stena-recycling-invests-heavily-in-new-battery-recycling-plant/
[Accessed May 2023].

Stena Recycling, n.d. *About Stena Recycling.* [Online]
Available at: https://www.stenarecycling.com/about-us/about-stena-recycling/
[Accessed May 2023].

Streefkerk, R., 2023. *Qualitative vs. Quantitative Research | Differences, Examples & Methods.* [Online]

Available at: https://www.scribbr.com/methodology/qualitative-quantitative-research/
[Accessed May' 2023].
veitrafikken, O. f., 2023. *Norske elbilforening.* [Online]
Available at: https://elbil.no/om-elbil/elbilstatistikk/
[Accessed May 2023].
Yaocai, B. et al., 2020. Energy and environmental aspects in recycling lithium-ion batteries: Concept of Battery Identity Global Passport. *Materials Today*, Volume 41, pp. 304-315.
Zachary J., B., Robert E., B., Xiang, Y. & Jia, M., 2022. Lithium-Ion Battery Recycling─Overview of Techniques and Trends. *ACS Energy Letters*, 7(2), pp. 712-719.