Towards a circular economy for lithium-ion batteries stemming from electric vehicles

- Recycling directly or a preceding second-life? A qualitative study of market mechanisms and end-of-life strategies.

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Preface

This master thesis was written in the spring of 2021 and marked the completion of our master's programme in Industrial Economics and Technology Management at the University of Agder. The decision to work together was made in the summer of 2020 and was sparked through initial meetings. In November 2020, we attended a conference regarding second-life batteries, which gave us a head start and motivation for further work. The same month we chose to write our thesis about the end-of-life utilisation of electric vehicle batteries. Through our supervisor, we got in touch with a company within the electric vehicle battery value chain, and together we agreed on an adequate problem statement.

We would like to thank our supervisor Benedikte Wrålsen for her time and effort devoted to guiding this thesis. Furthermore, we want to express our gratitude and contentment to everyone who has contributed during the process, both the interviewees and others who have provided valuable information and input. Moreover, we would like to thank our partner company, which wishes to remain anonymous, for presenting us with relevant problem statements within their business and provide the resources needed to realise this thesis. We would also like to thank our external supervisor at the company for providing us with the necessary information and decisive feedback in the initial and final interviews. Lastly, we would like to express our gratitude toward each informant that has contributed to the research.

The master's programme has been an exciting journey with many unforgettable moments. Unfortunately, our studies ended during the Covid-19 pandemic, which brought with it particular challenges. However, we would like to think it has also contributed to the advancement of technology, and perhaps, it could contribute by making it easier to perform qualitative interviews digitally for researchers all over the world, enabling more global access to data.

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Abstract

In a linear economy, humankinds' endless demand for more is satiated by continuous extraction of new commodities, a system that does not offer the needed alignment to the established climate goals of the Paris agreement. Transitioning to a circular economy where recycling and repurposing potentially replace mining and disposal could displace our need for freshly mined metal as materials and products are preserved. Europe has ambitious plans for battery production to meet demand primarily from the expansion of electric vehicles, and recycled materials could become an essential element in sustainably realising these plans. Moreover, repurposing batteries in second-life applications can prolong their intrinsic value and support the expansion of a more renewable electricity grid. Whether directly recycling or a preceding second-life of the spent battery is the most sensible end-of-life strategy to make the circular economy prosper depends on various factors and market conditions.

The objective of this qualitative study is to investigate whether the growing volume of spent electric vehicle batteries will be available for second-life or prioritised for recycling directly to meet an increasing demand for battery materials. In this thesis, repurposing and recycling have been analysed in terms of what drives the demand for recycled battery materials and how this could influence the market for second-life batteries. The study's results are based on interviews with lithium-ion battery industry stakeholders, which are discussed in relation to state-of-the-art literature from scientific and business research. The study finds that mandatory levels of recycled content in new batteries will be a vital factor driving the demand for recycled battery materials. Economic drivers are also identified as essential, and above all, economies of scale and high-value cathode materials are important for the viability of recycling. Additionally, the low share of virgin materials within Europe makes recycling of spent batteries a compelling opportunity. The EU's goal of interdependency from other continents could support the demand for securing material supply and create a local value chain for LIB manufacturing and recycling. Social and environmental considerations seem to be less critical drivers. Still, a local supply of materials mandates recycling due to concerns with mining and the ambitions of creating supply resilience in Europe. Market developments, such as rapid advancement of technology and diversification of chemistries, are uncertainties that can affect future end-of-life strategies.

The general conception amongst the interviewees is that recycling will dominate the end-of-life strategies for spent electric vehicle batteries. Yet, there is significant uncertainty, and there are scenarios where repurposing could be the preferred option. Batteries that are less viable for recycling due to low-value material content should be repurposed to exploit their remaining value, especially if the residual capacity is sufficiently high. In regions with high and volatile power prices and applications of low criticality, second-life could thrive, especially if the supply of new batteries is completely absorbed by the rapidly expanding EV market. Recycling directly after first use goes against the waste management hierarchy and circular economy's principles of exploiting a product's inherent value. However, in markets experiencing a rapid expansion, the demand for materials is massive, and recycling could provide important secondary material supply. The implication on circular economy is, therefore, that one should be careful when presuming that repurposing is the preferred option in a circular economy, and thorough impact assessments can guide the most sensible pathway for spent electric vehicle batteries.

Terms and Abbreviations

Closed-loop	*The recycled material or product, or reused material or product, can still be used in the same product system.*
Electric vehicle	*A vehicle powered by electricity. Predominantly battery electric vehicles are regarded in this thesis, not hybrids.*
End-of-life	*End-of-life refers to the point in time when the battery gets removed from the vehicle regardless of its condition in which the product no longer satisfies the first user.*
Gate fee	*A gate fee is a charge levied upon a given quantity of spent batteries at the recycling facility.*
Lithium-ion battery	*Used to describe electric vehicle batteries of the lithium-ion technology. Covers multiple chemistries, such as: LFP, LMO, NCA, NMC.*
Proposed regulations (COM (2020) 798/3)	*Regulations on industrial and electric vehicle batteries proposed by the European Commission in late 2020.*
Recycling	*Spent lithium-ion batteries are recycled after being discharged and disassembled to recover their materials. "Recycling directly" is used to describe the recycling of batteries directly after first life.*
Repurpose	*Using a spent battery in another application than its original purpose.*
Reuse	*The battery is partly or entirely reused for its original purpose.*
Second-life	*Batteries that are repurposed to be utilised in an application that is different from the one for which they were originally designed. Examples include the use of batteries from electric vehicles in stationary energy storage systems.*
Sustainability	*Predominantly used to describe a property that avoids negative economic, social, and environmental impact (of the battery production, use, and disposal).*
Spent (retired) battery	*A battery after its first use. It has a reduced ability to store and deliver electricity.*
Sustainable Development Goal 12	*Ensure sustainable consumption and production patterns.*

BEV	Battery electric vehicle
BMS	Battery management system
CE	Circular economy
EOL	End-of-life
EV	Electric vehicle (referring to BEV unless stated otherwise)
EVB	Electric vehicle battery (lithium-ion battery)
LIB	Lithium-ion battery
OEM	Original equipment manufacturer
SDG	Sustainable development goal
Battery chemistries/technologies	
LCO	Lithium cobalt oxide
LFP	Lithium iron phosphate
LMO	Lithium manganese oxide
LTO	Lithium-titanate oxide
NCA	Lithium nickel cobalt aluminium oxide
NMC	Lithium nickel manganese cobalt oxide

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1 Introduction

Electric Vehicles (EVs) are considered one of the key technologies to mitigate climate change efforts in the transportation sector. With global sales of EVs continually growing driven by policy and business support, the batteries needed for this disruptive technology to prosper requires careful consideration in terms of natural resource challenges. Putting too much pressure on the extraction of materials can have negative societal, environmental, and economic consequences. International policy efforts to integrate Circular Economy (CE) strategies may be a way forward to foster sustainable use of global resources while meeting climate and Sustainable Development Goals (SDGs). This study seeks to identify opportunities and limitations of circular economy strategies for Electric Vehicle Batteries (EVBs) by investigating the demand for recycled battery materials and this demand's influence on second-life market opportunities.

A direct consequence of a larger number of EVs on the roads is the growth of spent Lithium-ion Batteries (LIBs) once they have reached the end of their useful life inside an EV. This increasing stockpile of LIBs raises the question of whether and how they optimally can be disposed of, reused, repurposed, and recycled, taken into consideration economic circularity. This master's thesis and its accompanying theme is an investigation of whether the growing volume of spent EVBs will be available for second-life or prioritised for recycling. In order to investigate this, a problem statement with two components was constructed.

> *What drives the demand for recycled battery materials, and how can this influence the market for second-life electric vehicle batteries?*

A selection of experts in relevant fields have been interviewed, sharing up-to-date knowledge and what they believe will be the most important drivers for the future of used lithium-ion batteries. The information from the interviews will then be compared to findings from the theoretical framework, which covers scientific and business research.

1.1 Research scope

The scope of the research has been limited to the circular economy strategies repurposing and recycling. The concept of circular economy includes several other strategies with different focuses such as reuse, redesign, sharing services, and so on. Some of these strategies are to various degrees mentioned, but the main focus of the research is centred around the end-of-life (EOL) strategies repurposing and recycling. Furthermore, the data collection has been limited to Norwegian stakeholders in the value chain for lithium-ion batteries, with observations from a conference and interviews being the main source of empirical data. Thus, a Norwegian context is the primary focus of this thesis. The research has been conducted within less than five months, during the spring semester at the University of Agder in 2021.

1.2 Background

The Paris Climate Agreement was adopted in 2015 as an important measure to combat climate change. It is an international climate agreement ensuring that the countries of the world are able to limit climate change (United Nations, n.d.). The deal aims to reduce global greenhouse gas emissions substantially and to limit the global temperature increase this century to 2 degrees Celsius while pursuing means to limit the increase even further to 1.5 degrees (United Nations, n.d.). As of current trends, the world is on course for 3 degrees C of warming, implying that a great shift is needed with a greater focus on efficiency, higher renewable electricity consumption, investment in low-carbon energy, innovation, and more widely adopting green technologies (Crooks, 2020).

The European Union has a strong ambition of meeting the climate targets set by the UN. In late 2020 the European Commission presented an updated plan on how to reduce their climate gas emissions by at least 55% within 2030, compared to 1990-levels (European Commission, 2020d). Achieving this includes strengthening the policy for energy efficiency and renewable energy and strengthening CO2 standards for cars (European Commission, 2020d). Norway's climate politics is closely interlinked with that of the European Union, and Norway has an explicit ambition of reaching the climate targets set by the Paris agreement (Klima- og Miljødepartementet, 2021). New technologies, principles from circular economy and a new mindset could potentially unlock the necessary means to realise such ambitions.

Mankind has greatly increased its wealth in recent decades but achieving this prosperity has had an enormous cost to nature. While globally produced and human capital per head has increased in the last decades, the value of the stock of natural capital per head has declined, demonstrating that our wealth has been achieved at the expense of nature's richness (Dasgupta, 2021, p. 114). The traditional economic system has viewed the material and energy flow linearly where resources are extracted, produced, used and then thrown away (Frosch & Gallopoulos, 1989). The consequence of this is overconsumption and that we cross planetary boundaries affecting climate change (Mhatre, Panchal, Singh, & Bibyan, 2021). We have for decades understood that it is unsustainable (Boulding, 1966; Frosch & Gallopoulos, 1989), yet humans continue to "make, use, dispose" (Stahel, 2016, p. 435). Pursuing the current linear system is projected to lead to resource use nearly doubling from 2011 to 2060, which will further exacerbate global challenges and lead to issues of supply chain fragility (Ellen MacArthur Foundation, 2021, p. 12). However, the linear economy is weakened by strong disruptive trends which favour the circular economy (Ellen MacArthur Foundation, 2013, p. 78). A circular economy would turn goods that are at the end of their life into resources for other purposes, closing the loops in industrial ecosystems and minimizing waste (Stahel, 2016, p. 435). It will require moving away from today's take-make-waste linear model towards an economy that is regenerative by design, energy is renewable, materials are safe, and waste is avoided (Ellen MacArthur Foundation, 2019).

Circular economy is experiencing increased popularity within political and economic fields (Schöggl, Stumpf, & Baumgartner, 2020). Governments have a vital role in helping to finance and coordinate the investment necessary to help shift to a sustainable future (Dasgupta, 2021, p. 489). Government policy and subsidy support for circular economy efforts will be key to catalyse investments (Mulvaney et al., 2021). For the European Union, CE represents the possibility to promote environmental benefits, continuous economic growth, and the creation of new workplaces (Schöggl et al., 2020), thus, functioning as a support for the triple objectives of sustainability encompassing people (society), planet (environment) and profit (economic). Furthermore, the transition towards a more circular economy will contribute to the delivery of many of the SDGs of the United Nations (Ellen MacArthur Foundation, 2021, p. 13), in particular: SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land) (Schroeder, Anggraeni, & Weber, 2019).

1.3 Electric vehicle batteries expansion

As the battery is a vital component in an EV, the battery industry must deliver supply growth to meet the anticipated demand for electric vehicles (WBCSD, 2020, p. 13). Consequently, there is a potential large-scale battery industry taking shape in the Nordics. Swedish Northvolt emerged in 2016 (Northvolt, n.d.-a), Freyr is planning a 40 GWh of battery cell production capacity by 2025 (Freyr Batteries, n.d.), Morrow Batteries are establishing a battery factory in Arendal (Morrow Batteries, n.d.), and a strategic partnership exploring possibilities for establishing a "sustainable and cost-competitive European battery business" is forming between Equinor, Hydro and Panasonic (Bloomberg, 2020). Furthermore, Beyonder has developed the "next generation eco-friendly and energy-efficient batteries" (Beyonder, n.d.). Additionally, Elkem sees a supply chain potential within batteries, as they are materialising their plans of a battery materials industrial plant focused on synthetic graphite production to meet expected demand from the battery industry (Elkem, n.d.). Evidently, many Nordic actors have ambitious plans for developing battery technology. There is a rationale for this as Norway’s cost position is on par with other European countries, with cheap Norwegian power and relatively productive labour offsetting higher logistics and construction costs (Valstad et al., 2020, p. 52). Moreover, the recycling of LIBs is one of many industries that benefit from the knock-on effect generated by EV expansion. Fortum already has multiple recycling facilities in Finland and are continuing to expand their recycling operations (Fortum, 2021b), and Norsk Hydro and Northvolt have recently launched a joint venture to establish an electric vehicle battery recycling facility in Norway in 2021 called Hydrovolt (Northvolt, n.d.-a).

Likewise, there are plans and a collective engagement towards this boom in all of Europe. The EU wants to reduce its reliance on EVBs from Asian producers, and consequently, the value of Europe’s battery market could reach 250 billion euros by 2025 (Krukowska, Patel, & Nicola, 2021). Batteries are among the key investments in the EU’s ambitions for a new “Green Deal”. Therefore, the European Commission has approved to deviate from state aid regulations for developing the battery industry in Europe through the scheme “Important Projects of Common European Interest” (Krukowska et al., 2021). The projects will cover the entire battery value chain, including the extraction of raw materials, design and manufacturing of battery cells and packs, and recycling and disposal (Krukowska et al., 2021). Since 2011 over 33 European research projects have been initiated where at least one work package in each has included recycling or repurposing of LIBs (Melin, 2019, p. 40).

We see an increasing growth of electric vehicles in Norway and Europe (Gersdorf, Schaufuss, Schenk, & Hertzke, 2020; Schmidt Automotive Research, 2021b; Statistisk Sentralbyrå, 2021). It is hard to predict what will happen when all these electric vehicles reach their end-of-life and how the market for second-life and recycling of electric vehicles will look like in the next few years. This inspired us to peruse several recent studies and consult with a broad range of experts from the metal industry, energy industry, the academic world, and the battery industry to get their take on how the market will likely develop.

2 Theoretical framework

2.1 A change in economic logic

Over 90% of the economy worldwide continues to treat natural resources unsustainably as the linear take-make-dispose approach still prevails over circular economy ideas in practice (Mulvaney et al., 2021). The production and consumption practices following this linear flow have negatively impacted the environment over time (Julianelli, Caiado, Scavarda, & Cruz, 2020). Concerns of negative impacts continuing propel our society to seek sustainable development possibilities such as a transition to a circular economy where take-make-dispose is replaced by take-make-recover (Frankenberger, Takacs, & Stechow, 2021).

Circular Economy would change economic logic because it replaces production with sufficiency (Stahel, 2016, p. 435). In contrary to the traditional method of extracting materials from the ground, using them once, and ultimately landfilling them, companies in a circular economy recapture resources at the end of their lifetime in order to use them over and over again (Frankenberger et al., 2021). The CE aims to maintain the value of products, components, materials and resources in the economy for the longest time possible (Alamerew & Brissaud, 2020). Performing such a shift would reduce greenhouse gas emissions and could even lead to an increased workforce (Stahel, 2016, p. 435). A circular economy can contribute towards tackling the remaining 45% of greenhouse gas emissions that cannot be resolved by solely transitioning to renewable energy (Ellen MacArthur Foundation, 2021, p. 12). Also, in Europe, the CE could yield annual benefits of up to EUR 1.8 trillion by 2030, double that of a linear development path, and represents additional 7% GDP growth (Ellen MacArthur Foundation, 2021, p. 12).

2.2 Circular economy

The concept of circular economy does not have any clear evidence of a single origin (Winans, Kendall, & Deng, 2017, p. 825). But the knowledge that the world’s resources are finite and that this has economic consequences has been around for decades: “Economists have failed to come to grips with the ultimate consequences of the transition from the open to the closed earth” (Boulding, 1966, p. 2). Kenneth Boulding published “The Economics of the Coming Spaceship Earth” over 50 years ago, describing the open economy of the past (“Cowboy economy”), with its seemingly unlimited resources, and contrasting it with the closed economy of the future (“Spaceship economy”) (Boulding, 1966, pp. 7-8). Boulding’s essay was influential as it highlighted how humankind needs to rethink its connection to nature to transform into a more sustainable economy.

Boulding recognised that the main impetus for change has to occur in the production and consumption relationships found in modern economies: “The closed earth of the future requires economic principles which are somewhat different from those of the open earth of the past” (Boulding, 1966, p. 7). A decade after Boulding’s essay, the concept of the circular economy grew out of the idea of substituting energy with manpower. This was described in a report to the European Commission by Stahel and Ready-Mulvey because of rising energy prices and high unemployment, e.g., refurbishing buildings took more labour and fewer resources than erecting new ones (Stahel, 2016, p. 435). In more recent times, the Ellen McArthur Foundation has strongly contributed to increasing the awareness of CE (Merli, Preziosi, & Acampora, 2018).

The report, “Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition”, evaluated economic opportunities for the transition to a circular model (Ellen MacArthur Foundation, 2013). It argued that the EU’s production industry could achieve massive cost savings and stimulate economic activities within product development and reproduction. The report claimed that principles from a circular economy could create short-term financial advantages and strong long-term strategic opportunities (Ellen MacArthur Foundation, 2013, p. 11). In a later report, a circular economy is described as “a systems-level approach to economic development designed to benefit businesses, society, and the environment” (Ellen MacArthur Foundation, 2019, p. 19). The main principle that the circular economy is built on is to design out waste and pollution, and thereby keep products and materials in use and regenerate natural systems (Ellen MacArthur Foundation, 2019, p. 19). The 2019 report further presents the circular economy’s aim of decoupling economic growth from the consumption of finite resources and creating economic, natural, and social capital. Kirchherr et al. (2017, p. 229) define circular economy more in-depth following an analysis of 114 definitions:

> *It is an economic system that replaces the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit*

> *of current and future generations. It is enabled by novel business models and responsible consumers.*

Kirchherr et al. (2017, p. 229) found in their analysis of the term that it has different meanings for various scholars, with some definitions showing that “some authors have no idea what circular economy is about”. Some authors define CE solely with recycling, although the most common conceptualisation of the term includes reduction, reuse and recycling. Their analysis shows that several scholars neglect reduction in their definition of CE, probably since it weakens the idea of the principles regarding consumption and economic growth. According to Potting, Hekkert, Worrell, and Hanemaaijer (2017), this is unfortunate as reduction strongly contributes to circularity. Furthermore, Kirchherr et al. (2017) state that many definitions of CE have a missing link to sustainability. Their study claim that several authors see CE as a path to economic prosperity, whereas early scholars believed that circular economy was primarily concerned with environmental goals. The study also showed that social considerations are often neglected.

In the context of circular economy, Merli et al. (2018) find that articles often investigate the environmental dimension of sustainability. In most cases, this environmental focus is associated with economic considerations, while in some cases, it is considered exclusively. The triple bottom line is more rarely adopted. Finally, social and economic aspects, jointly or exclusively, are only marginally considered (Merli et al., 2018). Systems thinking is essential to remain vigilant of rebound effects and the wider consequences of adopting each CE strategy, “not only from the environmental and economic perspective, but also from the social perspective” (Bocken, de Pauw, Bakker, & van der Grinten, 2016, p. 317). Fortunately, during recent years, a more comprehensive approach to CE has emerged, as more articles integrate the three dimensions of sustainability (Merli et al., 2018).

Natural extraction is synonymous with severe environmental degradation, emissions, and waste generation (Mulvaney et al., 2021). As stated in The Dasgupta Review, “it is less costly to conserve nature than it is to restore it” (Dasgupta, 2021, p. 487). Natural resource extraction impacts can be avoided where recovery and recycling efforts augment supplies (Mulvaney et al., 2021). The circular economy offers an approach that is not just powered by renewable energy sources but will also transform the method of how products are designed and used. Consequently, greenhouse gas emissions are cut across the economy through strategies that reduce emissions across value chains and retain embodied energy in products (Ellen MacArthur Foundation, 2019).

Reducing the finite resources consumed and wasted are what governments and policymakers intend to achieve by transitioning to a circular economy. Ursula von der Leyen, President of the European Commission, says that Europe will emerge stronger from the Covid-19 pandemic by investing in a resource-efficient circular economy, promoting innovation in clean technology and creating green jobs (European Commission, 2020d). Governments have the responsibility to avoid unintended consequences for the reliability or affordability of supply following Covid-19 (IEA, 2020). The Club of Rome (2020, p. 29) mentions that resilience has become the highest political priority as the experience of the Covid-19 pandemic has proved the fragility of our economic system. One of the most effective measures to increase resilience is to reduce strategic dependencies, for example, being reliant on a single supplier for a vital resource. The European green deal is generally strong on this point. Particularly the new Circular Economy Action Plan details how a transition to a circular economy could reduce dependencies on certain suppliers of raw materials (European Commission, 2020c). The idea is that circular economy strategies can present alternatives that provide a supply of materials and that products and materials are preserved through repurposing, recycling and recovery.

2.2.1 Circular economy strategies

As seen from the definition of CE by Kirchherr et al. (2017), reducing, reusing, recycling, and recovering materials are important CE strategies. However, the strategies can be further broken down as the CE concept can be expanded to include 10Rs (Morseletto, 2020): Recover (R9), recycling (R8), repurpose (R7), remanufacture (R6), refurbish (R5), repair (R4), re-use (R3), reduce (R2), rethink (R1), refuse (R0). This builds on the acknowledged framework introduced by Potting et al. (2017), where circularity strategies within the production chain are ordered based on their priority. The framework is highly regarded as it represents a complex phenomenon in an easily accessible manner, contains a comprehensive set of circular strategies, includes efficiency as well as effectiveness strategies, and points to value drivers that circular strategies can contribute to (Blomsma et al., 2019).

As per Potting et al. (2017), low R-number strategies have high circularity, whereas high R-numbers have low circularity. Thus, recovering and recycling are considered less valuable in a circular economy compared to repurpose, reuse, and reduce. This is in line with the rationale that extending a product's life fulfils circular economy principles as the price per year is minimised, and it contributes to environmental benefits as it slows down product replacement cycles (Bocken, Short, Rana, & Evans, 2014, p. 52). Recovery and recycling have limited benefits in terms of reclamation of materials and energy recovery, and therefore more powerful circular economy strategies should be prioritised (Morseletto, 2020). Closing resource cycles through recycling will not significantly contribute to shrinking, slowing, and redistributing resource cycles, argues Calisto Friant, Vermeulen, and Salomone (2021). Still, recycling is the most used CE strategy in the EU and worldwide (Mhatre et al., 2021; Morseletto, 2020).

Following the aforementioned circularity framework and the waste management hierarchy introduced in 1979, also known as Lansink's ladder, repurposing is considered environmentally preferable over recycling (Harper et al., 2019; Morseletto, 2020; Potting et al., 2017), see Figure 1. Even more so, prevention (i.e., reduction, rethink, or redesign) is considered the most environmentally beneficial strategy, as seen in Figure 1. This is in line with The Dasgupta Review, stating that avoiding degradation of nature should be the priority (Dasgupta, 2021).

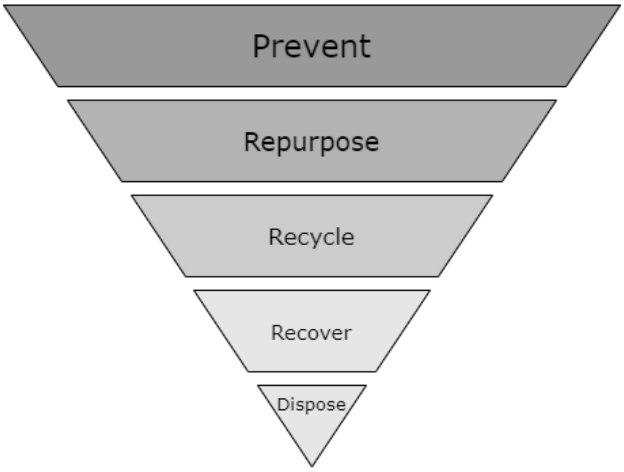

Figure 1: Waste management hierarchy, ranking waste management options from the most to least environmentally desirable options. Adapted from Harper et al. (2019).

The framework by Potting et al. (2017) orders the strategies in terms of their ability to achieve circularity and similar holds for the waste management hierarchy of Figure 1. However, as Morseletto (2020) points out, the hierarchy must only be considered a "rule of thumb" because the order is not always consistent. This underlines the existence of exceptions and rebound effects, which means that the R-order is not appropriate for all products and under all conditions (Morseletto, 2020). The framework of Potting et al. (2017) is macro level, meaning it describes the macro level of industrial systems or economies and is therefore generic and abstract, focusing on inspiring systems change (Blomsma et al., 2019). For these reasons, the hierarchy has to be thoroughly evaluated, but still, it can provide a helpful orientation when examining CE strategies (Morseletto, 2020).

2.2.2 Challenges regarding the circular economy

Lessons learned from Tran et al. (2018) show that all circular economy strategies should be applied carefully to ensure the transition toward sustainability and require thorough evaluations to define all the associated benefits and trade-offs as well as chances for improvement. To improve the loop, you need to look into both your own and your partners' production processes and customer activities to understand the ecological footprint along the entire loop (Frankenberger et al., 2021). Such a holistic view is resulting in trade-off decisions, which are often difficult to make. Frankenberger et al. (2021) explain that while the choice of a specific material might reduce the environmental footprint of a company, it might increase the technical complexity and costs of another company in the ecosystem. Hence, one will have to proactively highlight such trade-offs, learn how to manage them, and find solutions that are best for the environment, but still consider the needs of the individual companies as well (Frankenberger et al., 2021).

The influential paper of Zink and Geyer (2017) highlights the dangers of strategies that result in an increase in net environmental impact, resulting in circular economy backfiring through rebound effects. As illustrated in the waste management hierarchy and the framework of Potting et al. (2017), the core of the CE is prevention, i.e., “reduce”, “refuse”, and “rethink”. However, researchers question whether closing material and product loops do, in fact, prevent primary production. Circular economy activities can increase overall production, which can partially or fully offset their benefits. Circular economy rebound occurs when circular economy activities, which have lower per-unit-production impacts, also cause increased levels of production, reducing their benefit (Zink & Geyer, 2017).

It can be challenging to realise a circular economy for a business. The use of durable materials for production and enabling more repair and maintenance facilities are mentioned by Mhatre et al. (2021) as a potential key to the realization of circular business models. However, the decisive factor in the practical adoption and implementation of circular business models is the perception of the company management. As Casas-Arredondo et al. (2018) point out, final waste destinations are determined by the market prices, thus economic rather than environmental criteria. Resource recovery, being a very laborious job, requires sufficient infrastructure and technology to make the process economically viable (Mhatre et al., 2021, p. 198). Collecting and reusing waste is labour intensive and expensive but can be fostered through taxation changes and recouping costs through re-marketing rather than scrapping parts (Stahel, 2016, p. 437). Furthermore, a key CE challenge related to the use and reuse of materials in an application is the quality of these materials over time (Winans et al., 2017, p. 830).

A theoretical implementation of a circular economy (where all waste becomes secondary raw materials) may reduce the demand for primary raw materials and the associated environmental impacts. Yet, since a significant share of commodities is still used to build up our infrastructure and thus accumulates in societies' material stock, the overall potential for reducing primary raw material consumption and accompanying impacts is currently limited, even for a highly developed economy like the EU (Fellner, Lederer, Scharff, & Laner, 2017). Only in an economy where consumption of resources and generation of wastes are more balanced, and stocks are rebuilt and maintained at a constant level, the circular economy can evolve to its full potential (Fellner et al., 2017).

2.3 Electric vehicles and lithium-ion batteries

With the signing of the Paris Agreement, global carmakers are speeding up the pace of EVs powered by lithium-ion batteries (Y. Ding, Cano, Yu, Lu, & Chen, 2019). The worldwide number of battery electric vehicles (BEVs) in use has grown substantially in the last decade, with almost 4.8 million BEVs in use globally in 2019, growing from around 110 000 in 2012 (Statista, 2020). The market growth is especially evident in Europe. Nine of the top ten markets for EV penetration rate during 2019 and early 2020 were in Europe, with Norway, Iceland and Sweden having the highest rate (Gersdorf et al., 2020). In 2020 there were registered a total of 726 000 new electric vehicles in Western Europe (Schmidt Automotive Research, 2021b). The EV market expansion in Europe is driven by sales in Germany and the Netherlands (Gersdorf et al., 2020). However, big markets such as UK and France are also experiencing an increasing share of electric vehicles in their vehicle fleets, with both regions registering over 100 000 EVs each in 2020 (Kilbey, 2021; Torregrossa, 2021).

The increased electric car sales in Western Europe is likely sparked by the need to meet new European Union CO2 fleet average emissions targets (Schmidt Automotive Research, 2021b). In fact, the ambitions of the European Union means that 30 million or more zero-emission cars will have to be on its roads by 2030 as part of efforts to cut emissions by at least 55% (Abnett & Carey, 2021). In Wood Mackenzie's base-case forecast, there is massive worldwide growth in electric vehicles as the number of EVs on the road is projected to hit 323 million by 2040 (Crooks, 2020). BloombergNEF also expects a considerable increase in the global EV fleet as it is projected to reach 116 million by 2030, with BEVs accounting for a majority of these (BNEF, 2020). They expect that EV sales will reach 8.5 million in 2025, 26 million in 2030 and 54 million in 2040 (BNEF, 2020). The share of EVs is expected to continue as regions ban the sales of fossil vehicles. Norway is planning to ban new sales of internal combustion engine vehicles by 2025, and the Netherlands has similar plans for 2030 (Schmidt Automotive Research, 2021a). More European governments intend to ban the sales of internal combustion engine vehicles by 2030 or 2040 and some European cities plan to restrict diesel access in 2025 (Eddy, Pfeiffer, & van de Staaij, 2019; Kamran, Raugei, & Hutchinson, 2021).

Batteries make up a third of the cost of an electric vehicle, thus, as battery costs continue to fall, demand for EVs will rise (Bebat, 2020). Falling battery costs means that the total cost of ownership for a passenger EV will likely reach parity with internal combustion engine cars by the mid-2020s (Eddy et al., 2019). Accordingly, the real significant EV market penetration growth across the major share of European markets is expected between 2025 to 2030 (Schmidt Automotive Research, 2021b). After that, further EU CO2 cuts will help phase out internal combustion engines up to 2035, according to Schmidt Automotive Research (2021b).

Transitioning from private vehicle ownership to more transportation services has the potential to make much more intensive, hence, efficient use of individual vehicles (Kamran et al., 2021). Fewer, especially young people in larger cities, see a necessity in owning a car due to sharing platforms and other transportation systems, according to NAF, the Norwegian Association of Road Traffic Services (Pedersen, 2020). Sharing platforms enable increased utilisation rates of products by enabling shared access (Moreno, De los Rios, Rowe, & Charnley, 2016, p. 10). Car-sharing radically reduces material throughput as the asset avoids being under-utilised (Bocken et al., 2014, p. 50). This could influence the trend of sold vehicles, yet for now, it does not seem to be a widespread phenomenon (Pedersen, 2020). Perhaps because product ownership is one of the main characteristics of modern consumer culture, and the social norm of ownership is one of the main obstacles to access-based consumption, especially for cars due to high associated social status (Gullstrand Edbring, Lehner, & Mont, 2016).

2.3.1 Norwegian EV fleet

In Norway, there is a prominent share of electric vehicles, with the passenger car fleet existing of 340 002 electric vehicles by the end of 2020 (Statistisk Sentralbyrå, 2021), see Table 1.

54.3% of all new passenger cars registered in Norway in 2020 were BEVs (Fridstrøm & Østli, 2021). Norway has had an exponential expansion of electric passenger cars for several years, and by the end of 2020, EVs represented over 12% of the registered vehicles in total (Statistisk Sentralbyrå, 2021). From 2019 to 2020, the number of EVs increased by 30.4%, and in the last five years, it has almost quintupled, with an increase of 391.8%, as shown in the table.

Table 1: The total number of registered vehicles and electric vehicles in the Norwegian market by December 31st, 2020 and the percentage change for one and five years (Statistisk Sentralbyrå, 2021).

Registered Vehicles[1]

	2020	2019-2020	2015-2020
Private cars[2]	2 823 543	0.3%	7.1%
Electric cars	340 002	30.4%	391.8%

[1] The statistics count all registered vehicles by 31st of December

[2] Includes ambulances, combined vehicles and motor homes

If measured per capita, the Norwegian EV fleet is the largest in the world (Dale, 2019). This a result of multiple factors, such as politically initiated user incentives, tax reduction and cheap hydro power (Dale, 2019). Norway has strongly CO2-differentiated automobile purchase and ownership taxes, of which zero exhaust emission vehicles are entirely exempt, and BEVs are also exempt from the 25 percent value-added tax (Fridstrøm & Østli, 2021). Fridstrøm and Østli (2021) predict that subjecting BEVs to value-added tax again would halve the demand for BEVs, while the market for other vehicles would expand considerably, resulting in a 60% increase in the average CO2 emission rate of new passenger cars. This demonstrates the importance of incentives for EVs to achieve the shift towards zero-emission vehicles.

2.3.2 Lithium-ion battery

With the world trending toward vehicle electrification, LIBs are the energy storage technology of choice over the next half-century (Or, Gourley, Kaliyappan, Yu, & Chen, 2020). LIBs are the most suitable technology to satisfy the supply and demand of EVs due to their flexibility, higher energy and power densities, lower costs, relatively low pollution, smaller and lighter cell designs, and reliability (Y. Ding et al., 2019; Meng, McNeice, Zadeh, & Ghahreman, 2021). EV battery packs can be relatively complex but generally consist of LIB cells assembled into modules with heating and cooling components, a battery management unit (safety electronics to prevent over-charge/discharge) and other control electronics housed in an insulated casing (Or et al., 2020). For a fully electric vehicle, the energy content of a LIB is usually between 50-100 kWh (Duffner et al., 2021; Turcheniuk, Bondarev, Singhal, & Yushin, 2018). The energy content can also be lower, and this is especially the case for older EVBs. The battery pack of the original VW E-up was 18.7 kWh, whereas Tesla Model S and X Long Range editions are 100 kWh (Figenbaum, Jayne Thorne, Amundsen, Pinchasik, & Fridstrøm, 2020, pp. 28-29). Regarding economics, the price per lithium-ion cell has declined by around 97% since their commercial introduction 30 years ago (Ziegler & Trancik, 2021).

2.3.2.1 Composition

The lithium-ion battery cell is predominantly composed of a cathode, anode, electrolyte, and separator (Zheng et al., 2018). In commercial batteries the active anode is typically a carbon graphite material (Garole et al., 2020; Olivetti, Ceder, Gaustad, & Fu, 2017; Pagliaro & Meneguzzo, 2019; Zeng, Li, & Singh, 2014). New anode chemistries using silicon could displace a certain amount of carbon (Olivetti et al., 2017; Steward, Mayyas, & Mann, 2019). In addition to silicon, lithium is a widely researched anode material, and both are capable of meeting future energy targets better than carbon (Masias, Marcicki, & Paxton, 2021). Furthermore, lithium titanate (LTO) is a promising candidate for replacing graphite in lithium-ion battery anodes because of its unique advantages for EV applications (Y. Ding et al., 2019). For instance, electric buses need to have batteries that have a long life and allow fast charge, which is why LTO is used (Reid & Julve, 2016, p. 12).

Compared to the anode, the active material of the cathode has far greater variability. The cathode conductor plate is made of aluminium, however, the type of cathode materials in commercial LIBs varies. It is always a lithium-containing material, usually an oxide, but there is a diversity in the composition (Zeng et al., 2014). Regarding cathodes, the lithium metal oxides are generally comprised of lithium-iron phosphate (LFP), lithium-nickel manganese cobalt (NMC), lithium nickel cobalt aluminium oxide (NCA), or lithium-manganese oxide (LMO) (Pagliaro & Meneguzzo, 2019). As seen in Figure 2, some active cathode materials are more prevalent than others, specifically NMC and LFP.

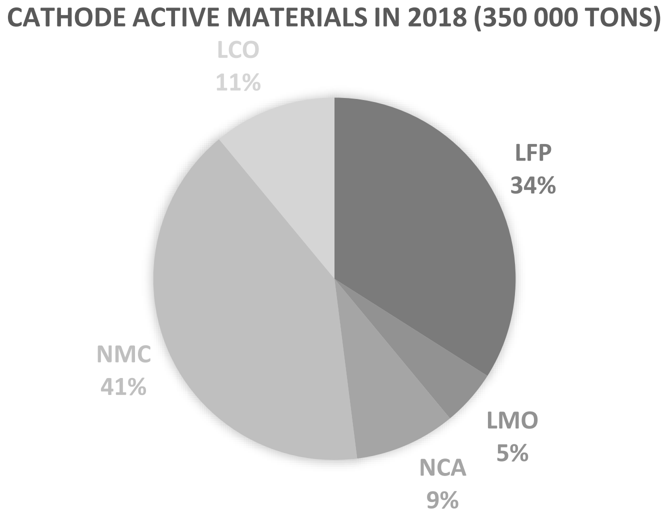

Figure 2: Share of cathode active materials in lithium-ion batteries in 2018. Adapted from Pillot (2019).

Performance trade-offs among these chemistries mean that they are expected to coexist for some time as technologies evolve (Reid & Julve, 2016, p. 10). Lithium cobalt oxide (LCO) is mainly used for electronic devices, including smartphones, tablets and laptops (Y. Ding et al., 2019; Pillot, 2019). NCA technology is principally used by Tesla (Y. Ding et al., 2019). NMC is used in other electronic devices and EVs, and LMO is mainly used as a blend with NMC in EVs (Pillot, 2019, p. 16). LFP can be used in electric buses (Liu et al., 2021), as well as in electric trucks, vessels and low speed-EVs (Pelegov & Pontes, 2018). Bar Tesla, most other carmakers use LFP, NMC, LMO or blended NMC and LMO technology (Y. Ding et al., 2019), with various versions of NMC dominating (Olivetti et al., 2017). Figure 3 shows the battery capacity in the Norwegian EV fleet from 2011 to 2018, divided into pillars representing the most common LIB chemistries found in BEVs.

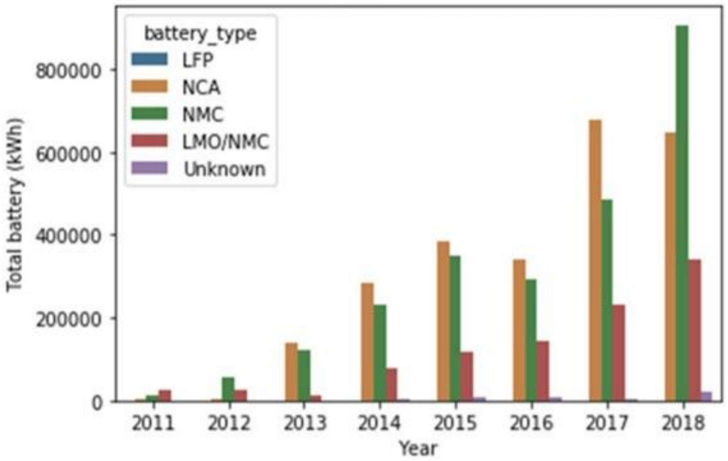

Figure 3: The estimated total amount of batteries (kWh) introduced to the Norwegian EV fleet, divided by different battery technologies (Figenbaum et al., 2020, p. 148).

As the graph shows, NCA and NMC have been the most common battery types. NMC is estimated to dominate as active cathode material for EVs and could account for around 80% of the global market (Kamran et al., 2021; The Faraday Institution, 2020). Its dominance could even reach up to 90% in 2030, as LFP and NCA cathode chemistries decline (Pillot, 2019, p. 17; The Faraday Institution, 2020), see Figure 4. It must be noted that NMC batteries can have different material shares with various content of nickel, cobalt, and manganese. As battery makers are attempting to improve both capacity and costs, LIBs could contain more nickel and less cobalt (S. Wang & Yu, 2020).

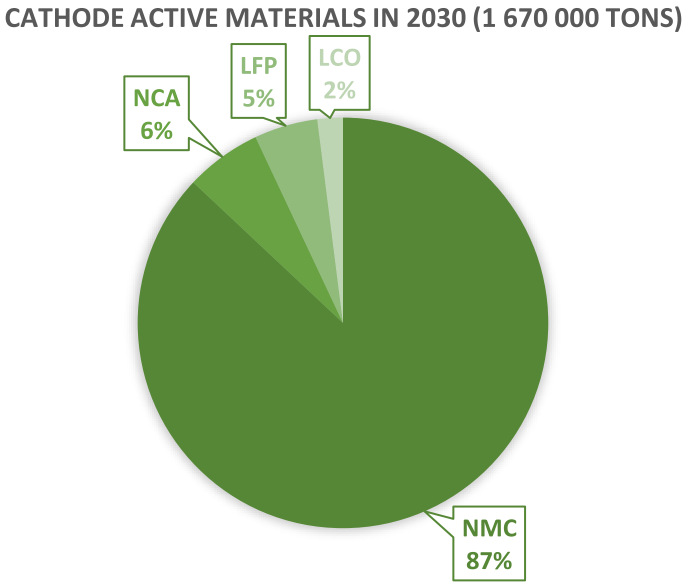

Figure 4: Share of cathode active materials in 2030. Adapted from Pillot (2019).

The resource-use per cell and its chemistry are constantly changing due to supply disruption or sharply rising costs of certain raw materials, along with higher performance expectations from EVBs (Karabelli et al., 2020). Battery technologies with different material compositions, particularly less cobalt, are increasingly expected due to material supply concerns (AE, 2021; Di Persio et al., 2020, p. 19; Steward et al., 2019). Based on their recent announcements, Volkswagen plans to employ manganese-rich nickel-manganese chemistry in volume models and nickel-rich NMC in high-end models (Ribeiro, 2021). In addition, Volkswagen intends to use LFP batteries for their low range EVs (Ribeiro, 2021). LFP has not seen much use in Europe, as the technology has been mainly found in Chinese-produced EVs, such as BYD (Y. Ding et al., 2019). By 2018, these had not yet penetrated the Norwegian market, as shown in Figure 3. However, Chinese EVs are making an entrance, and the entry of Chinese brands such as BYD and SAIC in the European market will likely continue (Scheel, 2020; Valle, 2021). There are recent prospects of more widespread use of LFPs in light-duty EVs, e.g., Tesla has recently announced to equip the Chinese version of its Model 3 with LFP batteries (C. Xu et al., 2020). And recently, Tesla's CEO Elon Musk has communicated that they could increase their LFP employment in more vehicles (Ribeiro, 2021). Hence, the share of LFP could become more significant than previously expected.

There are also expectations of new chemistries prospering in the next decade. Beyond 2030, estimations of future battery chemistries are subject to high uncertainty due to the potential market penetration of innovative technologies currently researched (Karabelli et al., 2020). New chemistries will be needed to have a disruptive improvement in performance and cost in batteries. One such promising technology which could become a market leader is lithium-sulphur (Reid & Julve, 2016). Lithium-sulphur may use twice the amount of lithium per kWh compared with lithium-ion, thus increasing the need for lithium (Olivetti et al., 2017). However, lithium-sulphur and similar technologies are not expected to achieve significant market penetration in the 2025 time frame (Olivetti et al., 2017). Research and development in the battery industry are time-consuming, and it can take 10-20 years to commercialize a new material (Pillot, 2019, p. 25). This is because the industrialization of such technologies requires intensive research and development activities focusing on establishing new manufacturing competencies and developing new machinery (Duffner et al., 2021).

Hence, EVs will still depend on mature battery technologies to develop new battery chemistries with high specific energy and lower costs, such as nickel-rich NMC (S. Ding & Zhang, 2020). With estimations of 323 million EVs hitting the road by 2040, the annual demand for batteries for EVs soars from 142 GWh in 2020 to 1594 GWh in 2030 and 4750 GWh in 2040 (Crooks, 2020). This implies that there will be massive pressure on the metals required to produce batteries. In a scenario dominated by NMC, metal demand is estimated to increase by factors of 18–20 for lithium, 17–19 for cobalt, 28–31 for nickel, and 15–20 for most other materials from 2020 to 2050, thus requiring a drastic expansion of lithium, cobalt, and nickel supply chains and likely additional resource discovery (C. Xu et al., 2020).

2.3.3 LIB raw materials

Raw materials account for 60-70% of LIB cells business, thus the cost impact from raw materials is drastic on battery producers' profit (Pillot, 2019). Driven by the construction of massive capacities for battery manufacturing facilities for electric mobility, prices have fallen significantly, especially for battery modules (Hiesl, Ajanovic, & Haas, 2020). However, there are limited regions worldwide producing LIB materials which could potentially create availability and price issues (Steward et al., 2019). Over half of the cobalt in use is from

Congo; Australia and Chile control around 80% of lithium production, while China controls around 70% of graphite production (Chen et al., 2019). This chapter will present the most relevant LIB materials, namely lithium, nickel, cobalt, manganese, and graphite.

2.3.3.1 Lithium

Following the high demand for lithium for LIBs, both production and consumption have increased rapidly over recent years due to extensive LIB use in portable electronic devices, electric tools, electric vehicles, and grid storage applications (Gil-Alana & Monge, 2019). Despite it being used in multiple applications, EVs dominate and will continue to dominate global lithium demand (Crooks, 2020; Y. Ding et al., 2019). The annual lithium inflow into EVBs is predicted to show a continuous and robust increase in the following decades before eventually levelling out (Ziemann, Müller, Schebek, & Weil, 2018). The inflow into EVBs is expected to develop in the same way regardless of whether low (NMC) or high (lithium-sulphur) lithium content is employed (Ziemann et al., 2018).

Being a critical element in LIBs, lithium might encounter potential supply problems in the future. The irregular distribution of lithium mineral resources in countries and the unequal concentration in brine reserves causes lithium extraction to be of critical importance (Meng et al., 2021). However, a recent study of lithium supply shows expected demand growth could be matched by the projected production scale-up for almost all scenarios over the next two decades (Greim, Solomon, & Breyer, 2020). The small deficit between now and 2050 can be managed with a minor adjustment for almost all scenarios, except for the scenario corresponding to low recycling, for which an early supply deficit that continues until the end of the century occurs due to the early depletion of fresh lithium supply (Greim et al., 2020). In other words, maintaining a good balance of supply and demand in the first half of the century requires the development of an efficient recycling system.

2.3.3.2 Nickel

Nickel is the 24th most abundant metal in the earth’s crust and the 5th most abundant element by weight, constituting almost 3% of the earth composition (Meshram, Abhilash, & Pandey, 2019). The annual production of EVs will significantly increase high pure demand from 33kt in 2017 to 570kt in 2025 (Meshram et al., 2019). Karabelli et al. (2020) argue that it is vital to explore nickel-rich cathodes further, as they promise to overcome resource and cost problems. Thus, the nickel content of EVBs is likely to increase in the future (Mayyas, Steward, & Mann, 2019). However, recently proposed plans from Volkswagen and Tesla goes against the popular belief that nickel-rich chemistries will dominate the EV market in the future (Ribeiro, 2021). Hence, there is some uncertainty regarding how much nickel will dominate as materials in LIBs. Nickel has a potential for SOx emissions, but this is an issue for Russian-produced nickel and does not represent a general inherent hindrance of nickel (Kelly, Dai, & Wang, 2020). Nickel provides high energy/power density in cathode materials and is cheaper than cobalt but may block lithium diffusion pathways (Mayyas et al., 2019).

2.3.3.3 Cobalt

Due to the projected increase in demand over the coming decade, LIBs will continue to be the largest end-use sector of cobalt (Beatty et al., 2019, p. 356). Rising battery production almost quadrupled wholesale prices of cobalt between 2016 and 2018, from $22 to $81 per kilogram (Turcheniuk et al., 2018). All commercial, high-energy-density cathodes as of today contain a certain amount of cobalt due to their high cathode density and advantageous electron configuration, enhancing the cathode’s ability to maintain a layered structure (Olivetti et al., 2017). This is highly beneficial for lithium motion and, thus, for power density and effective capacity as well (Olivetti et al., 2017). However, the future deployment of optimised battery chemistries could result in the partial replacement of cobalt in batteries, potentially causing reduced demand (Di Persio et al., 2020, p. 19). For instance, Morrow intends to commercialize a cathode technology that replaces cobalt with manganese reducing costs by 20% (AE, 2021). On the other hand, Freyr intends to use cobalt, as evident by their supply deal with Glencore (Glencore, 2021).

The market of cobalt is prone to three significant supply risks (Baars, Domenech, Bleischwitz, Melin, & Heidrich, 2021): First, cobalt is primarily mined as a by-product of copper (70%) and nickel (20%) and therefore relies on both markets for the expansion of new mines (Baars et al., 2021; van den Brink, Kleijn, Sprecher, & Tukker, 2020). Second, the cobalt market has a high centralisation of mine production and reserves located in the Democratic Republic of Congo (Baars et al., 2021). In this region, geopolitical instability and unethical working conditions can halt cobalt exports. This was apparent in 1978 where civil conflict generated a drastic price spike known as the Cobalt Crisis (Gourley, Or, & Chen, 2020). Third, substituting cobalt while maintaining product performance is challenging and time-consuming in LIBs (Baars et al., 2021). Moreover, China dominates the supply chain as the world largest producer, supplier, and consumer and has heavily acquired foreign cobalt mining operations primarily in the Democratic Republic of Congo, reducing their net import reliance on raw cobalt (Gourley et al., 2020). Considering the fact that China itself may experience cobalt supply deficits by 2030, their cobalt production will likely be prioritised for domestic battery manufacturers (Gourley et al., 2020).

There is growing public pressure that materials such as cobalt are sourced in a responsible manner and that their supply chains are transparent, ethical and compatible with international standards (Petavratzi, Gunn, & Kresse, 2019, p. 52). A traceability system includes both forward tracking and backward tracing within the value chain and is realisable in both current and future battery production systems (Riexinger et al., 2020). Blockchain technology could be used as a supporting tool to guarantee traceability in sourcing raw minerals, ensuring value chain responsible business practices (Bonsu, 2020). However, tackling raw minerals origin issues via blockchain will do little to address structural and practical system issues (Bonsu, 2020). Profoundly understanding social structures, unemployment and livelihood challenges within resource-rich mining communities will remain key. This will ensure responsible and ethical sourcing of raw minerals, which will help fulfil UN's SDGs such as SDG 8, Decent Work and SDG 12, Responsible Production (Bonsu, 2020). Companies within the material and EV supply chain, such as Glencore and Tesla, support the Fair Cobalt Alliance working towards child labour free communities focusing on the societal impacts of the supply chain through responsible sourcing (The Impact Facility, n.d).

2.3.3.4 Manganese

Manganese is incorporated into LIB cathode's active material to improve thermal stability and is lower cost than nickel and cobalt (Mayyas et al., 2019). However, high manganese content batteries have a relatively low specific capacity and poor cycling performance in part because of manganese leaching during cycling. Although manganese plays an essential role in many LIB chemistries and is low cost, it is not likely to replace other more expensive LIB materials according to previous trends (Mayyas et al., 2019). However, Volkswagen explicitly announced that their nickel-manganese chemistry for their volume EV models would be manganese-rich, not nickel-rich (Ribeiro, 2021). And Morrow Batteries intend to commercialize cathode technology where manganese replaces cobalt (AE, 2021). Hence, this could imply that manganese will play a more central role than what has been previously predicted.

2.3.3.5 Graphite

Graphite is used in the anodes of LIBs (Mayyas et al., 2019). Natural graphite is prevalent in the earth's crust and has a diverse set of end uses, of which battery use constitutes a small percentage of consumption (Olivetti et al., 2017). Today, most of the graphite production takes place in Asia (Elkem, n.d.). This is a concern as the developments in the industry are currently focused on in China (Olivetti et al., 2017). However, crustal abundance for graphite is quite high with the potential for increased production in India, Brazil, and throughout Africa, as well as further exploration and development in the United States, thus the geographical supply concentration is likely only of short-term concern (Olivetti et al., 2017). Furthermore, synthetic graphite can be mixed with natural graphite (Olivetti et al., 2017). Elkem plans to produce synthetic graphite and composites and claims that with their technology and renewable hydropower, CO2 emissions can be reduced by more than 90% compared to conventional production while potentially reducing energy consumption by around 50% (Elkem, n.d.). Synthetic graphite is about twice as expensive, so the trade-off between cost and supply concentration will continue to influence the use of both (Olivetti et al., 2017). Although various combinations of lithium and other materials (including graphite and silicon) are being investigated as anode materials, it is likely that graphite will continue to play a key role in LIBs (Mayyas et al., 2019).

2.3.3.6 Supply of LIB materials

There is potential for bottlenecks in the supply of some virgin raw materials in the mid-term, i.e. 5 to 15 years (Mayyas et al., 2019). EVs dominate global lithium and cobalt demand (Crooks, 2020). Consequently, the main potential concerns from a supply concentration perspective are cobalt and lithium (Olivetti et al., 2017). Yan et al. (2020) find that lithium and cobalt indicate potential supply risk and shortages in the 2030 time frame. According to Olivetti et al. (2017), nickel and manganese have no detectable supply concerns, with their utilisation in LIBs representing a small portion of their end-use demand. Furthermore, both nickel and manganese are well distributed among the countries from which they are mined (Olivetti et al., 2017).

However, according to Crooks (2020), there could be supply constraints even for nickel in the next few years, depending on the recovery of Covid-19 effects. Pelegov and Pontes (2018) point out that since the most popular cell chemistries utilise NMC/NCA cathodes, the most significant critical risk, besides lithium, is associated with cobalt and nickel supply. Wood Mackenzie expect "supply gaps", i.e., tighter markets that put upward pressure on prices to incentivise additional production, for nickel in 2026 and cobalt in 2029. If EV adoption accelerates at the same pace required to limit global warming to 2 °C, the supply gaps could emerge even earlier in 2025 for cobalt and 2024 for nickel (Crooks, 2020). Similarly, as per

Turcheniuk et al. (2018), cobalt and nickel are scarce and expensive, and the reserves of cobalt and nickel used in EV cells will probably not meet future demand.

A review by Y. Ding et al. (2019) shows that there are no demand and supply risks of lithium and cobalt in the short term. But in the long term, lithium demand outpaces its production while cobalt demand exceeds its reserves when facing a high growth rate for LIB production capacity. Thus, improving lithium and cobalt extracting technology is highly desirable for fulfilling the rapid increase in LIB demands for transportation and grid energy systems in the future (Y. Ding et al., 2019). Regarding cobalt, the study of van den Brink et al. (2020) concludes that the risk of supply chain disruption is high due to strongly concentrated supply with weak governance performance in the mining countries and, to some extent, weak governance performance in the refining countries. Exploiting both cobalt-free and cobalt-less battery chemistries is an effective solution to mitigate the consumption problems of cobalt (Y. Ding et al., 2019). In the case of raw material price fluctuations, many firms end up implementing reactive strategies to material price shocks. These are less optimal than proactive strategies such as the circularity strategies recycling, remanufacturing and reuse, and may also exacerbate the situation, driving prices higher and for a more extended period of time (Gaustad, Krystofik, Bustamante, & Badami, 2018).

To summarise, there are some opposing opinions regarding shortages and supply gaps among scholars and business researchers. Yet, there seems to be a unison belief that lithium, cobalt and nickel are the most likely to reach constraints, especially cobalt due to potential supply chain disruption. Nonetheless, without a timely, reliable and sustainable metal supply, the pace of the electric mobility transition could be inhibited as it would hinder the expansion of LIBs. As sustainable batteries and vehicles underpin the future of mobility (European Commission, 2020c), the European Union and its car manufacturers have realised the importance of LIB supply to secure the growth of electric vehicles. Therefore, they are currently turning their focus on the production of lithium-ion batteries.

2.3.4 Production of batteries in Europe

Previously, the EVB market has been dominated by China, Japan, and Korea. In 2018, over 97% of the total global demand for EVBs was supplied by companies from these three countries, and only approximately one percent was supplied by European companies (Eddy et al., 2019). The expected increase in EVs means that the potential battery market is huge. McKinsey project that by 2040 battery demand from EVs produced in Europe will reach a total of 1,200 GWh per year, which is enough for 80 gigafactories with an average capacity of 15 GWh per year (Eddy et al., 2019).

There is consensus in Europe that there is a great need for sustainable battery production, making Europe less dependent on external supply. To catch up with the fierce competition from mainly Asia, Europe has to strengthen all steps of the battery value-chain, starting from ensuring a secure and sustainable supply of battery raw materials to the battery manufacturing industry (European Commission, 2018). Getting the proper demand is a challenge as economic, and sector growth makes implementation pressing and essential but difficult for manufacturers (WBCSD, 2020, p. 13). The EU claim they have all the necessary means to address the challenges by resorting to sustainable sourcing of raw materials from global markets, sustainable domestic raw materials production, and resource efficiency and supply of secondary raw materials (European Commission, 2018, p. 2).

Regardless of rapidly growing output from new factories in China, the demand for LIBs currently overcomes supply, especially in Europe, where there is limited LIB manufacturing (Pagliaro & Meneguzzo, 2019). Manufacturers will need access to strategic or critical materials to produce batteries. But, current prices for raw materials used in batteries are providing little incentive to develop much of the necessary capacity and may not support the development of new capacity (WBCSD, 2020). However, recycling spent EVBs may ensure a constant supply of these materials, thereby closing the material cycle in the context of a circular economy (Karabelli et al., 2020). This is supported by the fact that the EU aims to boost the circular economy of the battery value chains and promote more efficient use of resources with the aim of minimising the environmental impact of batteries (European Commission, 2020b).

There are environmental rationales for producing batteries in Europe, above all with a local supply chain. NMC batteries produced in Europe with a European-dominant supply chain would reduce greenhouse gas emissions and water consumption compared to both a US-dominant supply chain for LIB production and batteries produced in China with a Chinese-dominant supply chain (Kelly et al., 2020). Furthermore, The European Commission proposes mandatory requirements for all batteries, including EVBs, which will be essential for the development of a more sustainable and competitive battery industry across Europe and around the world (European Commission, 2020b). Requirements include the use of responsibly sourced materials with restricted use of hazardous substances, the minimum content of recycled materials, carbon footprint, performance and durability and labelling, as well as meeting collection and recycling targets.

The correlation between the cost of a battery and the commodity price is far lower than the correlation between the cost of a battery and the production volume (Philippot, Alvarez, Ayerbe, Van Mierlo, & Messagie, 2019). The mix of electricity that is used to power the battery factory is a key parameter for the total impact of battery manufacturing on climate change, whereas the effect of mining and refining of materials on the carbon footprint is relatively small (Costa et al., 2021). To enhance battery manufacturing eco-efficiency, a high production capacity and an electricity mix with low carbon intensity are therefore suggested (Philippot et al., 2019). Yet, to ensure sustainable battery production, a satisfactory collection, treatment, recycle, and reuse of those batteries in the downstream stage is required considering various aspects such as security, legal, environmental and economic (Sato & Nakata, 2021). For those aspects, planning the future production/supply and the respective collection and recycling of the batteries is described by Sato and Nakata (2021) as essential for creating a sustainable EV market and achieve a circular supply chain. The rapidly growing EV market is not believed to decline any time soon. Therefore, it is crucial to prepare for the return of spent EVBs as they eventually reach end-of-life.

2.3.5 End-of-life electric vehicle batteries

Due to internal chemical reactions occurring in the anode, cathode and electrolyte, LIBs lose capacity with time and use (Casals, Amante Garcia, & Canal, 2019). When an EVB's capacity decays to below 80% of the rated capacity, it fails to meet the requirements of EVs (Pagliaro & Meneguzzo, 2019; Xu et al., 2021). However, determining when the battery has lost 20 percent or more of its original capacity is not easy (Tadaros, Migdalas, Samuelsson, & Segerstedt, 2020). In real-world use conditions, most combinations of lithium-ion chemistries, battery architectures, and recharge strategies retain a capacity above 80% in over five years for 1000 km/month driving profiles (De Gennaro et al., 2020). However, most researchers estimate a longer lifespan than that.

Usually, the warranties of cars often last for over eight years (Ahmadi, Yip, Fowler, Young, & Fraser, 2014), after which batteries typically still have a capacity of 80% (Casals et al., 2019). Richa, Babbitt, and Gaustad (2017) consider an average of 9 years as the "design life span" of EVBs, whereas Akram and Abdul-Kader (2021) use 12.5 years as a lifespan of EVBs. Baars et al. (2021) use a similar estimate stating that all battery chemistries are expected to reach 80% of their initial capacity within 12 years. Tadaros et al. (2020) assume that each battery will be functional within the vehicle for 15 years as technological development is contributing to prolonging the expected life span of LIBs. LIB development is characterised by rapid technological advancements which could influence the lifetime of future EVBs (Yükseltürk, Wewer, Bilge, & Dietrich, 2021).

Furthermore, EVBs in a state of health of 80% that would typically mark their EOL might still be used by consumers who accept a shorter range over the expense of battery replacement (C. Xu et al., 2020). EVs with a residual battery capacity of 80%, could still meet daily travel requirements in 85% of cases (C. Xu et al., 2020), and as per Hossain et al. (2019), EVBs that have 60 % of their original capacity can continue to meet the daily travel of over 75% of drivers. Using EVs with lower than 80% battery capacity could be further supported by widespread charging infrastructure (C. Xu et al., 2020). Nonetheless, once EVBs reach the end of their first life, the spent battery can be further utilised following disassembly.

2.3.5.1 Disassembly

Disassembly of spent LIBs is hazardous, and improperly handling a spent battery could lead to an explosion (Alamerew & Brissaud, 2020). The high amounts of residual power also make them vulnerable to fire and toxic gaseous emissions, especially if damaged (Ahuja, Dawson, & Lee, 2020). Damaged batteries must be disposed of immediately without making any attempt to extract materials through recycling (Hossain et al., 2019). During transportation, LIB cells can self-ignite, leading to safety hazards which means that transportation must be handled carefully (Richa, Babbitt, & Gaustad, 2017). There are specific shipping, packaging, and labelling guidelines when transporting LIBs domestically or internationally, and additional safety requirements are expected for transporting spent EVBs due to their large size (Richa, Babbitt, & Gaustad, 2017).

In the case of large assemblies of battery cells such as an EV pack, cells are often discharged to render them safer for handling and to recover unused energy (Sommerville et al., 2021). One challenge, particularly for EVB packs, is the lack of automation infrastructure and design standardisation to feasibly disassemble the packs (Or et al., 2020). Currently, most cells are hand disassembled, which may bring multiple health and safety issues due to chemical constituents (Sommerville et al., 2021). To avoid health and safety issues when automation is not an option, disassembly of EVBs must be performed in well-ventilated areas to prevent any potential exposure to toxic gases (Alamerew & Brissaud, 2020). However, manually dismantling battery components is not applicable at an industrial level which pushes the need to develop automatic or semi-automatic processes for treating the batteries (Forte, Pietrantonio, Pucciarmati, Puzone, & Fontana, 2020).

Automation could revolutionise the industry as automated battery sorting, integrated automated transport of batteries around the recycling facilities, and increased control and automatic optimisation of chemical processes could lead to significant savings (Baltac & Slater, 2019, p. 39). Consequently, allowing higher recycling productivity, increased recovery of materials, and lower recycling fees (Baltac & Slater, 2019, p. 39). While manual disassembly requires little initial investments, it has a much higher operating cost due to the specially trained staff that is needed for the disassembly operation (Thies, Kieckhäfer, Hoyer, & Spengler, 2018). Establishing automation in the disassembly of EVB packs has the potential to reduce processing costs and also reduce safety concerns owing to the high operating voltages of the packs (Or et al., 2020).

2.3.5.2 The circular value chain for LIBs

With electric mobility still at its implementation phase, there is a great opportunity to form circular economy value chains for EVBs (Yükseltürk et al., 2021). Circular economy goals demand that the residual electric energy and valuable material components remaining in spent EVBs are used to the fullest possible extent before being disposed of (Ahuja et al., 2020). In fact, “capturing the value that is left in a product after use is the cornerstone of circular economy” (Olsson, Fallahi, Schnurr, Diener, & Loon, 2018, p. 1). With their retaining capacity, EVBs could turn useful in second-life, or they could be directly recycled to recover materials. Consequently, spent EVBs become part of the circular economy instead of becoming waste (Olsson et al., 2018). Figure 5 illustrates the circular value chain of EVBs entailing design and manufacturing, first life in EV, diagnostics and refurbishment, reuse in EV and repurposing, and finally recycling. Product design is an essential part of the circular value chain in developing systems easy to be repurposed and recycled to minimize landfilled materials (Mossali et al., 2020). Recovering materials through recycling and repurposing are vital links in the circular industry chain, which can increase the life cycle value of batteries (Liu et al., 2021). It is a vital step in realising a CE, changing from a take-make-use-dispose linear value chain to a take-make-use-recover circular value chain (Frankenberger et al., 2021).

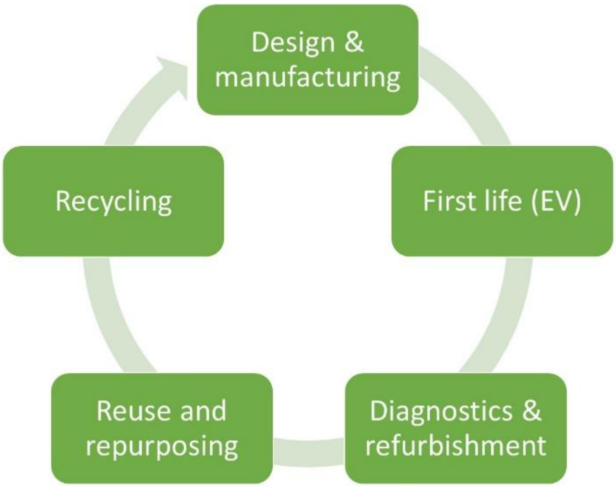

Figure 5: The circular value chain of electric vehicle batteries. Adapted from Olsson et al. (2018).

The EOL options depend upon the batteries’ design, quality, and state of health (Chen et al., 2019). The circular value chain starts with battery screening, which determines the value and usability of the retired EVBs and their suitable applications according to the battery’s performance (Hua, Zhou, et al., 2020; Z. Xu et al., 2020). The state of health, i.e., the remaining capacity of the battery after its first life, determines the EOL route (Baars et al., 2021). As per L. Wang, Wang, and Yang (2020), cell capacity higher than 80% could be transported to the remanufacturing plant and reassembled into new EVBs, whereas 60%-80% capacity cells could be repurposed or recycled (L. Wang et al., 2020). Baars et al. (2021) assume that batteries with a capacity below 80% are directly recycled, and those between 85% and 80% are repurposed in less-demanding energy storage systems. Wu, Lin, Xie, Elliott, and Radcliffe (2020) propose that the ideal remaining capacity for battery retirement is 77% since it enables the maximum total surplus of economic welfare from reutilising EVBs for energy storage. Batteries with a state of health higher than 85% might be reused in smaller EVBs, where the range is less of an issue, or used to replace damaged battery cells (Baars et al., 2021).

Advanced technologies such as big data, block chain and cloud-based services, as well as the improvement of regulation and standardisation processes, are required to solve present issues in the circular value chain of EVBs (Hua, Zhou, et al., 2020). Enabling an effective recovery of end-of-life EVBs will depend on standardisation of battery components, modules, and cells; design of batteries for ease of disassembly; access for the usage history of the battery; new timely policies following the advancement of EVB recovery; and development of advanced technologies for recycling and remanufacturing of EVBs (Alamerew & Brissaud, 2020). For businesses to achieve a resilient circular value chain, Carraresi and Bröring (2021) conclude that cross-industry relationships are fundamental. Actors along the battery value chain should create novel collaborations with other actors to successfully create new business opportunities and develop new business models together (Olsson et al., 2018).

2.4 Repurposing of EVBs

Following disassembly, an EVB would either be directly recycled or repurposed in less demanding stationary energy storage applications (Abdelbaky, Peeters, Duflou, & Dewulf, 2020). Seeing as recycling is the final step, repurposing could potentially add an extra stage to the circular value chain before material recovery takes place. Repurposing of EVBs in electricity grid applications is a potential dual solution for extending the value of these high-quality batteries beyond EV service while reducing the capital cost of grid-scale energy storage (White, Thompson, & Swan, 2020). Additionally, delaying the entry of LIBs into the waste stream through an expanded life span creates ancillary benefits by allowing additional time for capacity building in the nascent LIB recycling sector (Richa, Babbitt, Nenadic, & Gaustad, 2017).

2.4.1 Current and future state

The rapidly increasing use of renewable energy sources for electricity generation will require a growing number of battery energy storage systems to enhance the reliability of the electricity supply. The increasing number of spent EVBs can match this demand as they can be used as energy storage (Cusenza, Guarino, Longo, Mistretta, & Cellura, 2019). As long as a spent battery does not suffer from any defects or damages, it can be repurposed in second-life stationary applications that demand lower current density from the battery pack (Pagliaro & Meneguzzo, 2019). Battery modules found to have similar power and life are sorted and re-assembled in new repurposed battery packs ready for stationary usages, such as utility-scale grid and building storage (Pagliaro & Meneguzzo, 2019). Spent batteries can also be repurposed for communication base stations (Yang, Gu, & Guo, 2020), residential photovoltaic energy storage (Assunção, Moura, & de Almeida, 2016), mobile use such as commercial idle management and public transportation (Gu, Zhou, Huang, Shi, & Ieromonachou, 2021), or electric delivery vehicles (Hua, Zhou, et al., 2020), fresh food distribution centres (Hossain et al., 2019), or even providing cheap 24/7 monitoring of water cables (Torgersen & Morsund, 2021). Since there are several second-life applications, choosing the right application at optimal time interventions becomes necessary for efficient use of the batteries throughout their life cycle (Basia, Simeu-Abazi, Gascard, & Zwolinski, 2021).

The ageing of the battery determines the economic viability of any energy storage solution (Rallo et al., 2020). Depending on the application and the residual capacity, repurposing LIBs for second-life applications could increase the lifetime of the battery by up to 30 years. Results from Casals et al. (2019) show that second-life EVBs could provide support to fast EV charging stations for over 30 years. Moreover, their results show that second-life EVBs can endure up to 12 years in other stationary energy storage applications such as self-consumption (Casals et al., 2019). For other applications related to the grid, such as area regulation and transmission deferral, battery lifespan estimations are about 6 and 12 years, respectively (Casals et al., 2019). Other scholars usually estimate a lifespan of around 10 years for second-life (Ahmadi et al., 2014; Akram & Abdul-Kader, 2021; Reid & Julve, 2016, p. 26). Hence, depending on the exact application, the lifespan will vary but is typically around 10 years.

Battery types have different potential in second-life depending on their characteristics. The feasibility of using second-life batteries depends on the battery chemistry and in-vehicle use of the EVB (Kamath, Arsenault, Kim, & Anctil, 2020). A battery coupled with a photovoltaic installation can have a lower energy density, but it needs a longer cycle life as it needs to be able to be charged and discharged many more times than, for instance, an NCA battery (Reid & Julve, 2016, p. 12). Most manufactures, therefore, choose the LMO chemistry (Reid & Julve, 2016, p. 12). Battery chemistries such as LFP have slower capacity degradation compared to LMO and NMC, still, with moderate cycling, LMO/NMC can be used for second-life applications (Kamath et al., 2020). Owing to the low cost, high safety, and long service life of LFP batteries, they are widely used in energy storage systems (Liu et al., 2021).

Besides the lifetime and chemistry, the value of second-life batteries is determined by several factors, namely battery design, their condition after first life, the intended use for the battery in second-life and the profitability of recycling (Costa et al., 2021). Repurposing can provide the most value in markets where there is demand for batteries for stationary energy-storage applications that require less-frequent battery cycling, i.e., 100 to 300 cycles per year (Engel, Hertzke, & Siccardo, 2019). Based on these cycling requirements, three applications are most suitable for second-life EVBs: providing reserve energy capacity to maintain a utility’s power reliability at lower cost by displacing more expensive and less efficient assets; deferring transmission and distribution investments; and taking advantage of power-arbitrage opportunities by storing renewable power for use during periods of scarcity (Engel et al., 2019).

2.4.1.1 Energy storage

In order to meet the 2030 targets set by the EU, renewable electricity sources play an essential role. Many European countries have already initiated their transition to a higher share of renewable electricity sources by increasing their capacity (IRENA, 2020b; Sinn, 2017). 2021 will potentially become a record-breaking year with up to 45GW of capacity put up for grabs across Europe, with wind and photovoltaics representing the majority (Wood Mackenzie, 2021). This trend should continue as wind and solar generation growth must nearly triple to reach Europe’s 2030 green deal targets, meaning over 100 TWh added annually by 2030 (Agora Energiewende & Ember, 2021, p. 9). Implementing variable renewable energy sources such as solar and wind production means that volatility poses a severe threat, and flexible energy storage systems reliably providing electricity may be required (Doughty, Butler, Akhil, Clark, & Boyes, 2010; J. Zhang, Guerra, Eichman, & Pellow, 2020). Attempting to control the volatility of wind and photovoltaics production without using storage while replacing fossil power production would lead to most electricity being wasted (Sinn, 2017). The consequence of a high share of photovoltaics and wind power is shown in Figure 6, showing high levels of electricity generation from wind, solar, and run-of-river hydro plants during a summer week (Ajanovic & Haas, 2019).

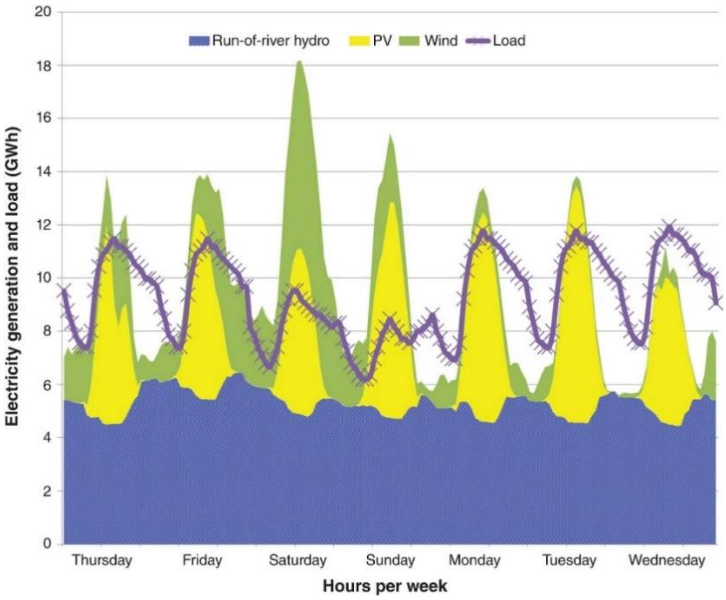

Figure 6: Electricity generation from variable renewables (wind, photovoltaic, and run-of-river hydro) over a summer week in Austria on an hourly basis in comparison to demand. From Ajanovic & Haas (2019).

Both solar and wind are unpredictable sources of power being weather dependant. Consequently, in some periods, there is an excess generation, in others, there is undercoverage, as seen in Figure 6. An increasingly renewable-integrated utility grid needs battery storage to improve stability in short-term regulatory actions such as voltage stability, frequency regulation, and demand response (Tong, Fung, Klein, Weisbach, & Park, 2017). It is also valuable for long term bulk managements such as peak shaving, energy time-shifting, and demand charge (Tong et al., 2017). Energy storage is particularly sought-after in areas where weak grids require reinforcement, where high penetration of renewables requires balancing supply with demand, and where there is an opportunity for trading energy with the grid and in off-grid applications (Harper et al., 2019).

From an economist's perspective, the economic value of stationary energy storage results from an opportunity for arbitrage (Hiesl et al., 2020; Rallo et al., 2020). The idea of energy arbitrage is to store low-price energy during periods of low demand and subsequently use it during high-price periods (Rallo et al., 2020). Yet, despite considerable battery costs reductions, from around 1,000 $/kWh in 2010 to around 150–200 $/kWh, storage can still not be considered fully competitive across all geographies and applications (Elshurafa, 2020). Hiesl et al. (2020) conclude that the economic prospects of storage are not very bright since, for all market-based storage technologies, it will become hard to compete in the wholesale electricity markets, and for decentralised battery systems, it will be hard to compete with the end users' electricity price. The core problem of nearly all categories of storage is low full-load hours for market-based systems (Ajanovic, Hiesl, & Haas, 2020) and low full charge/discharge cycles for decentralised batteries (Hiesl et al., 2020). Furthermore, the size of the energy storage market is uncertain. Sinn (2017) argues that electrical storage requirements may become excessive, whereas Zerrahn, Schill, and Kemfert (2018) argue for considerably lower storage needs, even for high shares of variable renewables, owing to renewable capacity expansion being combined with renewable curtailment.

The needs for electrical storage could decrease if the electricity sector is broadened to also include flexible additional demand, for example, related to heating, mobility or hydrogen production (Zerrahn et al., 2018). For hydrogen and methane, there are prospects for their use in the transport sector (Ajanovic et al., 2020). Such indirect use of clean electricity via synthetic fuels and feedstocks could be a key to reaching zero emissions in the road freight transport sector (IRENA, 2020a, p. 131). A widely accepted conclusion is that there is no storage option that outperforms all others (Cebulla, Haas, Eichman, Nowak, & Mancarella, 2018). Energy storage devices receive a significant fraction of the benefit from a diurnal operation and only a tiny fraction from seasonal operation (J. Zhang et al., 2020). Yet, looking at Figure 7, the variability of renewable electricity generation fluctuates over a year, with excess from photovoltaics in the summer creating the need for long-term storage options to cover demand at times of undercoverage (Ajanovic & Haas, 2019).

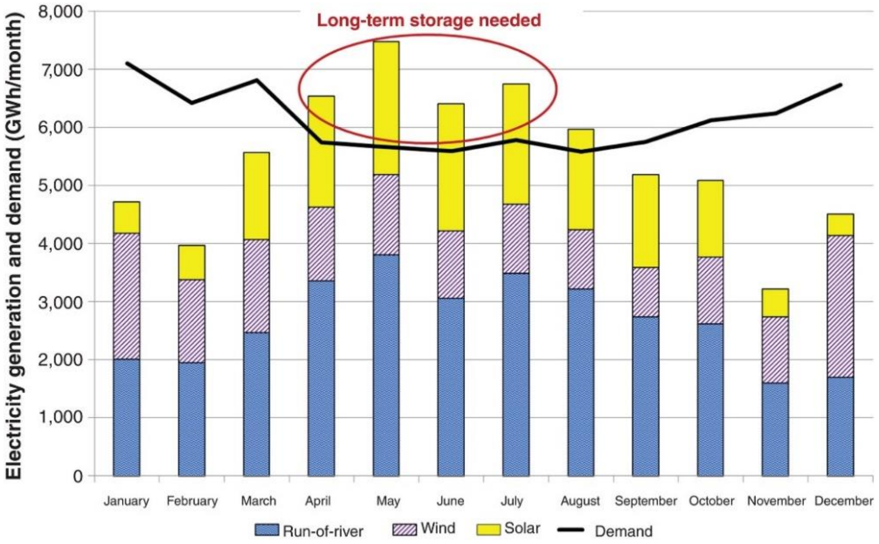

Figure 7: Electricity generation from renewable energy source over a year compared to the demand, highlighting the need for long-term energy storage. From Ajanovic & Haas (2019).

In smart and sustainable energy systems of the future, there will be more opportunities to place storage since the one-way system of the past will be replaced by kind of a bidirectional system where more flexibility options in the whole electricity system will be used (Hiesl et al., 2020). Service buildings can, for instance, provide a flexibility potential, but for optimal viability, it is dependent on large investments and increased smartness level in buildings (Krekling Lien, Ahang, Byskov Lindberg, & Fjellheim, 2020). Moreover, natural gas as storage and natural gas-fired turbines for short-term generation are flexible alternatives but not fully carbon-free (Hiesl et al., 2020). Additionally, EVs can supply energy to the grid during their idle time, countering peak power demand (Hossain et al., 2019). Vehicle-to-grid technology charges EVs using off-peak electricity then feeds it back into the grid at times of peak demand (Bonsu, 2020). Seeing as the charging window of EVs is relatively long, 8–12 hours, and the charging duration relatively short, around 90 minutes, it can offer considerable flexibility (Lund, Lindgren, Mikkola, & Salpakari, 2015).

2.4.1.2 Viability of second-life

Second-life batteries tie up less capital per cycle in stationary energy storage applications compared to new batteries (Engel et al., 2019). Assunção et al. (2016) conclude that repurposing EVBs as storage systems for residential appliances coupled with a photovoltaic system is a cost-effective option in comparison with brand new batteries, even considering its decaying costs. The study of Kamath et al. (2020) looked at energy storage for EV fast-charging systems and found that second-life batteries reduced the cost of electricity by 12–41% compared to new batteries, with the greatest cost reductions seen in off-grid configurations (Kamath et al., 2020). Still, despite lower costs when compared to new batteries, the economic payback time would be too high to justify the investment (Kamath et al., 2020). In fact, there is a concern to assert the economic feasibility of using repurposed batteries for second-life applications (Alamerew & Brissaud, 2020). The current price of battery second-life does not guarantee the economic viability of the energy storage (Rallo et al., 2020). Xu et al. (2021) investigate the economic benefits of applying spent EVBs in the day-ahead market and regulation market. In both markets, they find that retired EVBs cannot presently obtain profit due to the relatively low electricity price and high investment cost of the spent EVB. The cost of battery acquisition (including transportation), labour, administration, and packaging material are the major contributors to total second-life costs (Zhao et al., 2021).

Following the logic that the current market price for new EVBs presents an upper limit for spent LIBs (Wu et al., 2020), falling costs for new batteries could represent a challenge for second-life. According to Kotak et al. (2021), the most crucial factor for evaluating and comparing the benefits of repurposing is the cost development of new batteries. As new batteries become more affordable, the cost differential between used and new diminishes (Engel et al., 2019). Second-life batteries may be 30-70% less expensive than new ones by 2025 in stationary energy storage applications that require less-frequent battery cycling, and this could drop to 25% by 2040 (Engel et al., 2019). The cost gap needs to remain sufficiently large to warrant the limitations in performance of second-life batteries relative to new alternatives (Engel et al., 2019). In relation to this, Ziegler and Trancik (2021) suggest that battery technologies specifically developed for stationary applications might achieve faster cost declines owing to the less restricting volume and mass requirements. Furthermore, LIBs are likely to become the most competitive of electricity storage technologies in the majority of applications from 2030, being the most cost-efficient for nearly all stationary applications (Schmidt, Melchior, Hawkes, & Staffell, 2019).

Knowing that second-life currently would probably be insufficient to produce any significant discount on EVB upfront costs, one of the most important reasons to consider the repurpose of EVBs could be its environmental benefits (Martinez-Laserna et al., 2018). The environmental performance of secondary life depends mainly on the applications (Yang et al., 2020). Under certain circumstances, repurposing LIBs for household energy storage does not reduce the environmental impacts due to battery efficiency loss in the repurposing stage (Yang et al., 2020). Ahmadi et al. (2014) demonstrated that a 56% reduction in CO2 life cycle emissions could be achieved by repurposing LIBs for peak shaving compared to natural gas. Casals et al. (2019) analysed several possible applications of repurposed EVBs, including grid-oriented services and self-consumption; it was found that if environmental benefits are to be reached, second-life applications should go by the hand of renewable power sources; otherwise, they should not be used for grid services. Moreover, substituting high polluting portable power generators (diesel/fuel generators) in emergency shutdowns or temporary events could provide environmental benefits (Casals et al., 2019). The study of Kamath et al. (2020) found that second-life batteries used instead of new batteries as energy storage for EV fast-charging systems reduce global warming impacts.

Evidently, the environmental performance of these scenarios depends on the operating conditions, such as daily power delivery and use frequency (Yang et al., 2020). Thus, the environmental performance of the same application may also differ due to various configurations. Consequently, it is necessary to conduct specific environmental evaluations for any potential applications of repurposed EVBs (Yang et al., 2020). Yet, generally speaking, second-life energy storage applications show promise of reducing environmental impacts. Such reductions would be primarily due to avoiding the life cycle of an equivalent lead-acid battery-based system (Richa, Babbitt, Nenadic, et al., 2017).

2.4.2 Challenges regarding second-life

Spent LIBs have potential in repurposing scenarios, but there are still some technical challenges that must be faced, including safety issues, assessment methods, screening and regroup technologies, and comprehensive management during the repurposing process (Hua, Liu, et al., 2020). Fast and accurate evaluation methods with high generalisation ability remains a challenge. Screening and regroup technologies are key processes for EVB repurposing, ensuring homogeneity of the second-life pack, extending service life and improving safety performance (Hua, Liu, et al., 2020). Another challenge can be that the lack of sufficient information about the performance of spent batteries (Alamerew & Brissaud, 2020). By 2022 there could be 500 different EV models globally (BNEF, 2020). Such a wide variety of EV models poses a serious challenge as each battery is designed to match each EV model (Engel et al., 2019). This increases the complexity of refurbishing due to lack of standardisation and fragmentation of volume as a large number of battery-pack designs on the market vary in size, chemistry, and format (Engel et al., 2019).

Spent batteries have very different operating histories meaning that the residual capacities and battery efficiencies may differ quite a lot (Z. Xu et al., 2020). There could even be inconsistencies between the cells within a single battery pack (Han et al., 2019). Variations in cell properties are unavoidable and can be caused by manufacturing tolerances and usage conditions (Bruen & Marco, 2016). Different states within battery cells and modules causes problems (Hu, Jiang, Cao, & Egardt, 2016), such as lower efficiency, accelerated ageing and heat generation (Bruen & Marco, 2016). Therefore, using retired batteries with different states together could be problematic, and it is of great importance to assess and screen retired LIBs so that batteries with similar properties are regrouped (Z. Xu et al., 2020). When assembling cells with various capacities, the increased likelihood of a battery pack's capacity imbalance increases the risk of overvoltage or over current within a battery pack, and therefore requires well-integrated battery management (Tong et al., 2017). In fact, the function of the Battery Management System (BMS), equalization management, and thermal management are undoubtedly crucial in the second life of EVBs (Hua, Liu, et al., 2020).

Appropriately assessing the moment for battery retirement from automotive use will probably depend on the battery owner (Martinez-Laserna et al., 2018). When the EV owner is the battery owner, the battery would only be changed when it is unable to satisfy the customer's need and therefore is expected to have much less capacity than the recommended 80% threshold (Zhao et al., 2021). Instead, an EV battery leasing system would be beneficial for the subsequent repurpose of second-life batteries to ensure that the batteries are retired after a certain period of time or after reaching a particular state of health threshold (Martinez-Laserna et al., 2018; Zhao et al., 2021). If the EV manufacturer or a third party is the battery owner and the EV owner has a leasing agreement for the batteries, it is likely that battery retirement would obey predefined rules, based on either battery performance or warranty periods (Martinez-Laserna et al., 2018). On the contrary, if the EV owner is the battery owner, it is likely that the whole EV would be retired without any battery change or that the batteries would be changed when they are unable to satisfy the customer's needs (Martinez-Laserna et al., 2018).

One challenge can be vague policies and misalignment between Original Equipment Manufacturers (OEMs) and repurposers. Policies and regulations covering the entire lifecycle can help realise large-scale industrial development of battery repurposing (Hua, Liu, et al., 2020). Additional improvements can be gained via engagement and partnerships by stakeholder groups (Richa, Babbitt, Nenadic, et al., 2017). One promising approach may be to directly engage vehicle battery OEMs in rebuilding the packs for the secondary application. This approach leverages historical knowledge of the cells’ usage, which may minimise or even prevent the expensive process of refurbishing (Richa, Babbitt, Nenadic, et al., 2017). If OEMs were to collaborate with battery refurbishers and second-life users from the start, it might be possible to find ways to simplify the path to second-life, make the transfer through the value chain less costly, and learn how and when second-life adds value (Olsson et al., 2018). With new regulations proposed by the European Commission, a battery passport would mitigate some responsibility dilemmas as according to article 65: “When the change in the status is due to repairing or repurposing activities, the responsibility for the battery record in the battery passport shall be transferred to the economic operator that is considered to place the industrial battery or the electric vehicle battery on the market or that puts it into service” (European Commission, 2020a).

2.5 Recycling of EVBs

Recycling is seen as an end-of-life process returning as much material as possible into a circular economy (Thompson et al., 2020). Recycling can provide a domestic source of critical material from used products (Gaustad et al., 2018). Hence, establishing a closed recycling loop could be a major competitive advantage for European countries to implement a sustainable battery life cycle (Eddy et al., 2019). Besides diversifying LIBs with diverse chemistries, developing LIB recycling has been identified as a very needful strategy to alleviate potential supply risks of raw materials (Y. Ding et al., 2019). Yan et al. (2020) see recycling as a key approach among the three mitigation strategies, “production”, “substitution”, and “recycling”, as it can improve resilience and help cope with supply risks of lithium and cobalt. They state that “recycling is proved to be the most effective measure to alleviate potential supply risk of material shortages (Yan et al., 2020).

2.5.1 Current and future state

After being discharged, EV packs may then be disassembled to the module or cell level for recycling (Sommerville et al., 2021). The process after discharging consists of dismantling the LIBs, in some cases separating the cathode and anode materials, leaching of shredded material, and separation and recovery of metals (Meng et al., 2021). Usually, spent LIBs are treated by the hydrometallurgical process and in combination with pyrometallurgical treatment (Meshram et al., 2019). For instance, Umicore performs hydrometallurgy after pyrometallurgy to further extract metals (Sommerville et al., 2021). Copper, nickel and cobalt are recovered as an alloy from the pyrometallurgical recycling process, which is then separated through hydrometallurgy (Sommerville et al., 2021). Aluminium, lithium, and manganese are not generally recovered as metals and will be found in the slag, which is commonly used as an aggregate, though research into lithium extraction from slag is ongoing (Sommerville et al., 2021).

A depiction of current metal-recycling processes is shown in Figure 8. The pre-treatments enables the segregation of the fraction containing valuable metals (Mossali et al., 2020, p. 10). These valuable cathode materials are further extracted through pyrometallurgy or hydrometallurgy before the products are prepared through separation and recovery or synthesis, as seen in the figure below. Some recyclers only produce a “black mass” of active material, which is sold to a third party for further hydrometallurgical or pyrometallurgical recovery (Sommerville et al., 2021).

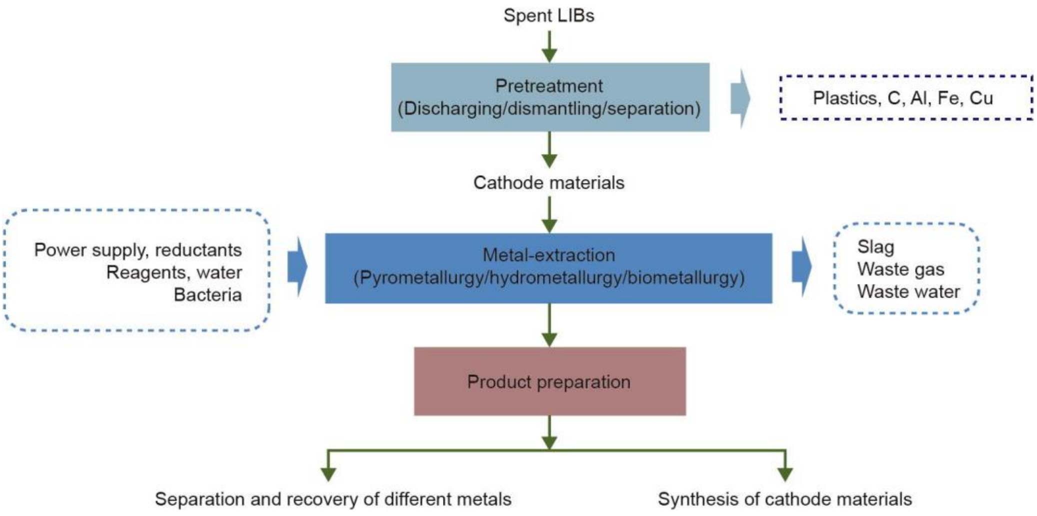

Figure 8: General schematic of the methods and processes for recycling spent LIBs. From Zheng et al. (2018).

The black mass contains the electrode materials with high-value materials and is therefore vital for the profitability of recycling (Thies et al., 2018). These materials include cobalt, nickel, manganese, and lithium and represents the main focus of pyro- and hydrometallurgical processes (Mossali et al., 2020, p. 10). Spent LIBs contain valuable metals such as lithium, manganese, nickel, and cobalt (Ordoñez, Gago, & Girard, 2016; Zeng et al., 2014), but also iron, aluminium, phosphorus and other elements with low recovery values (Zheng et al., 2018). Table 2 displays the value of cobalt, lithium, copper, graphite, nickel, aluminium, and manganese. These seven materials can comprise up to 90% of the economic value of a spent lithium-ion battery, with cobalt being the most valuable (Pagliaro & Meneguzzo, 2019, p. 4).

Table 2: Value of LIB materials from 2019 in USD per ton (Mossali et al., 2020).

	Aluminium	**Lithium**	**Cobalt**	**Nickel**	**Manganese**	**Copper**	**Graphite**
USD/ton	1 800	10 000	35 500	13 200	2 000	5 800	800

Recycling LIBs could provide a source of high-value materials at potentially lower cost (Mayyas et al., 2019). Commercially, recycling is focused on the recovery of cobalt and nickel rather than lithium due to superior value (Meng et al., 2021; Or et al., 2020; Reid & Julve, 2016, p. 26). Despite lithium and nickel having a similar value (see Table 2), recycling lithium is currently not viable as it is hard to recover and costly (Bonsu, 2020). Recycled lithium cost as much as five times the price of lithium produced from the least costly brine-based process (Reid & Julve, 2016, p. 26). Some cathode materials such as LFP and LMO, which have low material values, can only be treated profitably in very efficient processes when the lithium price is high (Melin, 2019, p. 48), making recycling inconvenient for the lower-value LMO and LFP (Mossali et al., 2020). Hence, at an industrial level, most of the recycling processes are set explicitly for LCO and NMC chemistries as they are incredibly profitable due to the high cobalt content (Mossali et al., 2020). The trend to reduce cobalt in spent LIBs will subtract the primary current profit source of recyclers (Mossali et al., 2020). Consequently, recycling facilities must adapt to handle mixed-type cathodes and comingled LIB scrap comprising diverse chemistries (Or et al., 2020).

Profitable recycling of lithium becomes more critical, and it will be necessary to implement innovative recycling processes able to value all the set of materials available in next-generation LIBs (Mossali et al., 2020). Since the pyrometallurgical process is not suitable to recover lithium, the hydrometallurgical process is more likely to be the mainstream option (Tang et al., 2019), as it seems to be more beneficial for lithium recovery (Ziemann et al., 2018). Recirculation of secondary lithium into new products will rely on the quality of the recovered lithium and the cost of producing it from primary sources (Ziemann et al., 2018). Abdelbaky, Peeters, and Dewulf (2021) argue that the potential lithium content of the EVB waste stream in 2040 is projected to substantially exceed the total European demand for lithium from other sectors. Consequently, recycling operators need to ensure that lithium is recovered with suitable purity for battery applications in order to avoid a surplus of secondary supply (Abdelbaky et al., 2021).

2.5.1.1 Regulations and policies

The widespread realisation of LIB recycling will require legislation and political pressure in the form of economic incentives, landfill disposal regulations, and defined responsibilities on the collection and disposal of LIBs for consumers, retailers, and EV and battery manufacturers (Or et al., 2020). Much of the legislation and rules related to batteries and end-of-life vehicles need updates to be in line with the ambitions of the circular economy. The European Commission’s new Circular Economy Action Plan (2020c) proposes a new regulatory framework for batteries, to build on the battery directive of 2006 (EUR-lex, 2006) and the work of Batteries Alliance, and to revise the rules on end-of-life vehicles from 2000 (EUR-lex, 2000).

The Batteries Directive of 2006 has been the main piece of EU legislation devoted to batteries so far (Malinauskaite, Anguilano, & Rivera, 2021). Within this directive, the battery manufacturer or car manufacturer bears the total cost for collecting and recycling batteries based on the concept of extended producer responsibility (Baltac & Slater, 2019, p. 41; Bebat, 2020). This responsibility obligates producers of batteries to take back spent batteries and secure an adequate treatment (Scheller, Schmidt, Herrmann, & Spengler, 2020). In the current industry’s practice, the OEM of an EV is responsible for ensuring the legal requirements. Still, it usually transfers the take-back and treatment to companies in the reverse supply chain. Hence, production and recycling are widely uncoupled (Scheller et al., 2020). If OEMs collaborate with battery recyclers from the start, informal standardisations could develop, and it could make it easier for recyclers to predict future volumes of batteries and their chemistries, reducing the risk of investments in recycling processes (Olsson et al., 2018). Such cooperation between the forward and reverse supply chain can help recycling reach its full potential (Scheller et al., 2020).

Following the 2006 Directive, it is illegal to landfill, incinerate or improperly dispose of spent batteries; and all spent batteries collected must undergo treatment and recycling. These considerations are all reinforced in the new proposed regulations (Malinauskaite et al., 2021). Additionally, the legislative proposal will consider the following elements (European Commission, 2020c): Rules on recycled content and measures to improve the collection and recycling rates of all batteries, ensure the recovery of valuable materials and provide guidance to consumers; sustainability and transparency requirements for batteries taking account of, for instance, the carbon footprint of battery manufacturing, ethical sourcing of raw materials and security of supply, and facilitating reuse, repurposing and recycling.

The proposal for a regulation concerning batteries and waste batteries (COM (2020) 798/3), repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020, introduces requirements of recovered cobalt, lithium and nickel content (European Commission, 2020a). As of January 1 2030, EVBs shall contain the following minimum share of recovered cobalt, lithium or nickel from waste in active materials in those batteries: 12% cobalt; 4% lithium and 4% nickel. As of 1 January 2035, the minimum share of recovered cobalt, lithium or nickel shall increase to 20% cobalt, 10% lithium and 12% nickel. However, as communicated in Article 8.4, “where justified and appropriate due to the availability of cobalt, lithium or nickel recovered from waste, or the lack thereof, the Commission shall be empowered to adopt a delegated act to amend the targets” (European Commission, 2020a). Thus, the targets can be altered depending on market conditions.

As the European Commission proposes recycling rates for LIBs and demanding recycled content in new batteries, European battery producers would have to comply. When revising the websites of present and future European LIB producers, only Northvolt mentions a target for recycled content with 50% in 2030 (Northvolt, n.d.-b). Still, when giving feedback on the proposal of mandatory levels of recycled content, Northvolt fears mandatory targets risk slowing market development if recovered volumes are insufficient to meet the demand in Europe (Northvolt, 2021). In addition to Northvolt, over a hundred stakeholders have given their feedback in response to the proposed EU battery regulations. The summary of the most central comments from key battery stakeholders regarding mandatory levels of recycled content in batteries can be seen in Table 3.

Table 3: Overview of central feedback from industry stakeholders regarding the proposed EU regulations, with emphasis on recycled content. Comments marked in green represent a positive stance towards mandatory levels of recycled materials in battery production, whereas comments marked in grey represent an opposing stance. The colour coding and table are the authors' own elaborations.

	Comments on recycled content
BMW Group (2021) Automotive manufacturer	The use of recycled materials in the production of new batteries will be an efficient and sustainable way to decrease the CO2 footprint in the life cycle of batteries significantly. Thus, we consider the recycled content requirements as set out in the new battery regulation as required and achievable. The revision clause in the proposed regulation is a sensible approach to potentially amend the targets based on the market situation. In order to maintain fair competition and an even playing field, it is essential that imported batteries have to meet the requirements set out in the new battery regulation.

EUROBAT (2021) Association of European Automotive and Industrial Battery Manufacturers	Mandatory levels of recycled content will have several negative effects: The actual administrative costs are 2-3 orders of magnitude higher than those assumed in the impact assessment. The availability of secondary raw materials will remain low for several years. The environmental and economic benefits of mandatory targets have not been appropriately assessed. Only having mandatory targets at the EU level could result in a split of materials, with secondary materials used only in batteries sold in the EU and zero net global effect. Overall, incentives and governmental support on setting up and reinforcing the recycling supply chain would have more positive effects on recycling than mandatory targets that have a whole host of unintended consequences.
Equinor ASA (2021) Energy company and battery producer (w/ Norsk Hydro and Panasonic)	With a rapidly growing market for batteries and considering their ever-increasing lifespan, including repurposing, there might not be enough recovered materials to meet both the production demand and the minimum required share of recovered materials. Setting targets could pressure EV batteries to become waste so that their materials can be recycled instead of trying to give those batteries a second life.
Eurometaux (2021) An organisation representing the European metal industry	Recycled content is very sector-specific and needs to be supported by a mature market. The market is constantly growing, and EVBs will only come to their end of life in 10-15 years. Not enough secondary materials will be available up to 2035 to specify relevant shares of recycled content in batteries placed on the market. EU mandatory minimum recycled content can also create a split of materials with manufacturers using available secondary material for the batteries sold in the EU and more primary materials for those sold to non-EU markets. Similarly, the material available for recycling could be redirected to the battery sector to increase recycled content in batteries and at the same time lowering recycled content elsewhere. The implementation of mandatory recycled content would result in a significant challenge for compliance verification of imported batteries. A large number of certificates would be required to be verified while it is not technically possible to undertake testing to distinguish between primary and recycled metals used in batteries.
Fortum (2021a) Battery recycler, energy company	We welcome the targets on recycled content in industrial batteries, electric vehicle batteries and automotive batteries. This is a crucial measure to increase the demand for recycled raw materials and speed up investments in battery recycling. We urge the EU to consider setting targets for the uptake of recycled raw materials in the manufacturing of portable Li-Ion batteries.

FREYR AS (2021) Battery producer	FREYR supports the ambition of increased use of recycled raw materials in the production of battery cells and supports the introduction of a harmonized calculation method for recycled materials. The target levels for such use need to consider the potentially limiting effect of such requirements for battery production output in a market with increasing demand. Further, the targets should be considered in light of the high material quality requirements in modern battery production and the impact the quality of such input materials has on battery production, efficiency, quality and safety. Therefore, FREYR is of the view that one should be careful introducing mandatory levels of recycled materials in new batteries as this may result in the recycling requirements impeding the producers' ability to meet market demand for batteries. A better approach is to focus on continuously updated target levels and introduce the labelling requirement earlier, e.g. in 2022 rather than 2027.
Nissan Motor Corporation (2021) Automotive manufacturer	Nissan would like to ask for a clarification of the justification of the basis for setting recycling targets, such as the content of recovered materials, recycling efficiency and material recovery rates. When setting targets, it is necessary that economic rationality and competitiveness are sufficiently secured from the viewpoint of consumers, to whom the price may be downstreamed.
Norsk Hydro (2021) Metal producer and battery producer (w/ Equinor and Panasonic)	Targets must be based on the certainty that enough secondary materials will be available in Europe to avoid market distortions and must include sufficient and credible verification of imported batteries. A robust timeline for the development of the methodology to calculate recycled content should be adapted, involving all relevant stakeholders in the process. Recycled content is very sector-specific, and it needs to be supported by a mature market.
Northvolt (2021) Battery producer	Mandatory levels for recycled content risks hampering the growth of battery production as the threshold levels risk exceeding the total supply of secondary recovered materials on the European market. Setting mandatory levels of recycled content risks slowing market development if recovered volumes are insufficient to meet the demand in Europe. Northvolt opposes mandatory levels of recycled content being introduced. Alternately, we propose that target levels can be easily updated and that the timeline for such thresholds are not introduced until the battery market reaches a steady state.

Saft (2021) Battery producer	Saft prefers voluntary initiatives to increase the recycled content. Avoid setting constraints with a 10 or 15-year horizon in an industry that is undergoing accelerated transformations. Furthermore, the Commission is pursuing competing goals an increase of recycled content in batteries on the one hand, and a longer battery first life, preferably followed by a second life on the other hand. These are structurally incompatible and should not be pursued concurrently for sound policy making. Impossible to distinguish recycled material from virgin material renders the tracking of the recycled content difficult. No consideration has been given to manufacturers of technologies that use little rare and critical materials. They will therefore be penalized by a significantly more elevated recycling cost with little environmental value.
Umicore (2021) Recycler	For metals that are mainly used in high-end applications, recycling ‘leakage’ to lower-end applications is a real risk. For cobalt, nickel (with the right quality) and lithium, batteries are the main application, and for these metals, quality recycling is not guaranteed. Consequently, it is recommended to create the proper boundary conditions to avoid leakage of these critical materials towards other applications through ‘downcycling’. Recycled content is a way to guarantee quality recycling. It will be crucial that all battery producers contribute their fair share in the recycling costs to protect the competitive position of European battery manufacturers.

The feedbacks on COM (2020) 798/3 shows that many companies and organisations within the battery and EV industry are opposed to the proposed mandatory targets arguing that the market will not be ready. In particular, the battery producers are opposed to the targets as they fear it can restrict their production. Conversely, recyclers are in favour of setting such targets claiming it will support the quality of recycling.

A labelling system to help identify cathode type and other data are also presented in the proposed regulations. This is important as the lack of a proper labelling system affects the entire value chain since it makes it impossible to identify the type of cathode that enters the treatment plant, thus hampering the recycling efficiency and the purity of the obtained products (Forte et al., 2020). Article 8 of COM (2020) 798/3 requires that by 1 January 2027, the technical documentation for EVBs with internal storage containing cobalt, lithium, or nickel in active materials shall contain information about the amount of the materials that have been recovered are present in each battery model and batch per manufacturing plant

(European Commission, 2020a). Such labelling is welcomed by battery producers; in fact, they want these rules implemented already by 2022 (FREYR AS, 2021; Northvolt, 2021). Furthermore, in the proposed battery regulation, the European Commission aims to impose the responsible sourcing of raw materials, addressing the social and environmental risks related to raw material extraction and processing (Malinauskaite et al., 2021).

2.5.1.2 Viability of recycling LIBs

Current estimates put approximately 60% of all mined cobalt production in the Democratic Republic of Congo (Kamran et al., 2021). This value is expected to reach 65% before 2030 (Beatty et al., 2019, p. 356). Cobalt mining attracts significant concerns because of associated ecological toxicity (Kamran et al., 2021). Additionally, the Congo region is historically characterized by conflict, labour impacts, and political instability (Althaf & Babbitt, 2020). Recovering materials through recycling can alleviate these concerns as it can help reduce dependency on foreign primary resources, with additional social impacts on reducing the risk of child labour and conflict (Malinauskaite et al., 2021). In addition to understanding the social structures and active engagement through legislations and alliances, recycling materials such as cobalt can relieve pressure on mining and alleviate demand and supply. Recycling and recovery ease the pressure on resources and the environmental burden caused by LIBs (Liu et al., 2021). Furthermore, a market for secondary materials can create new job opportunities along the supply chain, improve environmental and health conditions, facilitate further collaboration among different stakeholders and authorities, and build cooperative supply chains, and therefore brings positive societal impacts (Malinauskaite et al., 2021).

The development of an efficient process to recycle spent LIBs is essential for both economic aspects and environmental protection (Zheng et al., 2018). Ordoñez et al. (2016) conclude that the recycling and recuperation of these batteries are highly advantageous from an economical as well as an environmental perspective. Recycling LIBs has a lower environmental impact compared to mining virgin materials (Steward et al., 2019). LIB recycling reduces energy consumption and CO2 emissions and saves natural resources avoiding virgin materials mining and imports (Mossali et al., 2020). According to a real case study from a Chinese EV manufacturer, one can achieve a 21.8% reduction in CO2 emission through an EVB recycling network (L. Wang et al., 2020). The study of Tran et al. (2018) shows that battery collection and recycling systems do not provide benefits in terms of energy and land resource efficiency. However, they show considerable net benefit in terms of metal and mineral savings. Therefore, Tran et al. (2018) concluded that the implementation of resource management practices based on the circular economy is environmentally beneficial from a resource perspective.

The economics of recycling is complicated due to issues related to battery chemistry, preprocessing, and recovery techniques (Y. Zhang, Nguyen, & Liaw, 2021). Transportation costs, processing costs, carbon tax, and spent battery returns are significant factors dictating the profitability of recycling networks (Li, Dababneh, & Zhao, 2018; L. Wang et al., 2020). From the total cost perspective, processing cost has the most obvious impact, while carbon tax has the most negligible impact (L. Wang et al., 2020). Xiong, Ji, and Ma (2020) claim that potential cost savings from manufacturing batteries with recycled batteries is approximately $1.87 kg−1 cell produced compared to using virgin materials. The profitability of battery remanufacturing has also been claimed by Li et al. (2018) and L. Wang et al. (2020). Despite these indications of profitability, the viability is uncertain as it depends on numerous factors.

The total amount of returned batteries is an essential factor since it determines the recycling capacities to be installed (Li et al., 2018). Currently, battery recycling businesses might sustain economic losses when only spent batteries are used as material input because of the low utilisation rates of waste batteries (Xiong et al., 2020). However, this will change as the waste stream is increasing, and therefore recyclers need to invest in adequate battery recycling capacity to prepare for the exponential growth of returned EVBs (Abdelbaky et al., 2021). Steward et al. (2019) found that all studied recycling methods are economical with current raw material prices and battery composition if the volume is high. In addition to volumes of returned batteries, the battery type needs to be considered when assessing the economic viability of recycling. As previously mentioned, some cell chemistries like NMC contain a higher share of valuable metals compared to other cell chemistries like LFP (Thies et al., 2018). Hence, there is a cost-benefit of recycling if the waste stream is composed of NMC batteries and if the value of recovered materials approximates the virgin material price (Philippot et al., 2019).

The recycling fee is expected to decrease from about $1,700-2,000/tonne to around $480/tonne in 2030 (Baltac & Slater, 2019, p. 46). In an optimistic scenario, the value of recovered materials could rise significantly and subject to regulation and industry consensus, and recyclers may be paying back up to $260/tonne in 2030 for received batteries (Baltac & Slater, 2019, p. 46). Delayed policy implementation on recovery efficiency, increased labour costs, or an economic downturn characterised by steady metal prices, could keep the recycling fees at current levels. In addition, a dramatic decrease in the cobalt content of batteries via a switch towards LFP cathodes could almost double the recycling fees (Baltac & Slater, 2019, p. 46). Increased technological efficiency and volumes are likely to keep recycling fees under control despite a minor decrease in cobalt content and switch to LFP technology (Baltac & Slater, 2019, p. 47). For example, recycling fees would only increase by $10/tonne between 2030 and 2040, caused mainly by a decline in cobalt content (Baltac & Slater, 2019, p. 47). In addition, by 2040, improvements in battery recycling efficiency will have been fully implemented under the pessimistic scenario, allowing a higher recovery of valuable metals and leading to a 30% reduction in recycling fees compared to 2030 (Baltac & Slater, 2019, p. 47).

Future investments in battery recycling are subject to substantial risks from the changing battery technologies used in EVs (Abdelbaky et al., 2021). According to S. Wang and Yu (2020), the profitability of recycling will decrease along with battery evolution as less cobalt will be available in LIBs. Subsequently, the value of nickel could determine future profitability as producers shift to batteries with higher nickel content (Niese, Pieper, Arora, & Xie, 2020). S. Wang and Yu (2020) call for recycling businesses to figure out how to reduce recycling costs, such as installing new and more efficient recycling technology or facilities. Larger recycling machinery usually benefits from economies of scale, but there is also a higher risk of poor utilisation if the amount of returned batteries is overestimated (Thies et al., 2018). Accordingly, it is critical to develop reliable methods for collecting spent LIBs from consumers to ensure significant battery returns and better leverage remanufacturing (Li et al., 2018). For low-cost batteries, recycling becomes economically unattractive, so legal stipulations become important (Doose, Mayer, Michalowski, & Kwade, 2021). Subsidy and reward-penalty mechanisms can help improve the recycling rate of spent EVBs in comparison to a policy without any incentives (Tang et al., 2019).

2.5.2 Challenges regarding recycling

The benefit of recycling depends on the generation of secondary materials that can be substituted for raw materials when manufacturing new products (Accorsi, Manzini, Pini, & Penazzi, 2015, p. 131). To achieve closed-loop recycling, the intrinsic properties of materials must not undergo any changes so that they can be used in the same product system and thus replace primary materials (Ziemann et al., 2018). Yet, the viability of this for each material is not proven. Experimental research should be conducted to test whether the quality of remanufactured LIBs is able to reach the same quality as LIBs with virgin materials (Xiong et al., 2020). There are some positive notes regarding the anode as utilisation of carbonaceous materials from used LIBs as a negative electrode has demonstrated high cathode energy density (Garole et al., 2020). Yet, it is the cathode that is the most precious part of LIBs, and researchers have taken maximum efforts to recycle them due to the high value of metals. However, very few reports are available on the actual remanufacturing of recycled metals from spent LIBs (Garole et al., 2020, p. 3095).

More of the LIB can be recycled with hydrometallurgy compared to pyrometallurgy increasing its popularity (Sommerville et al., 2021). Through the hydrometallurgy process, the recovery rates could be up to 98% for cobalt and nickel (Xiong et al., 2020). However, hydrometallurgy is complex and strongly dependent on cathode chemistry, leading to unsustainable industrial treatments (Mossali et al., 2020, p. 10). Driven by economic interests, the recovery of spent LIBs mainly focuses on recycling precious metals from cathode materials, while the recovery of anode materials and the electrolyte is rarely reported (Sommerville et al., 2021; Zheng et al., 2018, p. 362). For hydrometallurgy to be effective, it is necessary to ensure that a minimum of extraneous material is subjected to this process. Yet, materials such as electrolyte, plastics, casings, current collectors, and graphite will not be recycled by hydrometallurgical processing (Sommerville et al., 2021). This represents a challenge for the circular economy as not all waste is recovered. The solvent, in particular, is a large proportion of the components of the cell and needs to be considered if we are moving towards 100% recycling of batteries (Sommerville et al., 2021). Besides, the quantity of high-value metals is expected to be reduced in future batteries, requiring us to pay attention to the recycling of more components other than metals (Sommerville et al., 2021). The fact that there will be many different battery types presents an issue as the diversity makes it very hard to come up with a valid “universal” recycling process (Costa et al., 2021).

New battery technologies, such as solid-state and lithium-sulphur batteries, could dominate the future EV market, which presents another challenge for recycling (Baltac & Slater, 2019, p. 39). Solid-state batteries have the advantage of using a solid-state electrolyte, which is not flammable, unlike the liquid electrolyte used in current batteries. Following this transition, physical processes would require a different cathode separation procedure, whilst hydrometallurgical and pyrometallurgical processes would remain largely unaffected. On the other hand, lithium-sulphur batteries would render pyrometallurgical recycling unfeasible as sulphur would poison the process (Baltac & Slater, 2019, p. 39). Varying compositions of batteries for different applications require the development of a suitable and sustainable recycling process to recover metals from all types of LIBs (Meng et al., 2021). Furthermore, the notoriously high costs of transporting waste batteries will complicate cross-European transportation and incentivise local recycling facilities (Baltac & Slater, 2019, p. 39).

As per Yun et al. (2018), a higher degree of automation and intelligence in the mechanical dismantling process is observed as the main challenge for the recycling of EVB packs. Although research on optimizing the disassembly of complex products is well established, little work has been explicitly dedicated to EVB packs (Or et al., 2020). Yet, there is ongoing research to create a process where mechanical dismantling to a certain extent can be replaced by a system based on artificial intelligence and robots. One example of this is the LIBRES research project initiated by Norsk Hydro (Eyde Cluster, 2021). Automated disassembly is expected to have high efficiency and meet industrial-scale requirements (Sommerville et al., 2021). However, the design of LIBs varies significantly with different models and manufacturers, which increases the difficulty of automated disassembly. Therefore, standardisation of cells is necessary to allow ease of access to the LIB cells and separation of electronic components (Or et al., 2020; Sommerville et al., 2021). Achieving this will likely require political pressure due to the proprietary nature of EV pack designs (Or et al., 2020).

2.6 Recycling directly or a preceding second-life

Overall, there exists a trade-off among social, economic, and environmental impacts, and there are advantages and limitations for both repurposing and recycling. Of all reviewed articles and reports, very few highlights the quandary between repurposing and recycling. One of few articles mentioning this “dilemma”, Ahuja et al. (2020), states that further data is still needed to decide whether circular economy benefits are best derived through directly recycling the critical materials contained within LIBs. Kamran et al. (2021) also discuss this dilemma, and while they see that recycling will eventually dominate, they conclude that repurposing is preferred and will be especially important at the beginning of the 2030s. Correspondingly, repurposing useful EVBs that would otherwise be recycled gains greater utilisation of the active materials, claims White et al. (2020). However, the relative sustainability merits of repurposing versus recycling are not so clear where EVBs are concerned. It is crucial to remember that despite the benefits, repurposing EVBs would interrupt the type of supply loop envisioned by the circular economy objectives and delay recycling (Ahuja et al., 2020).

Directly recycling, instead of repurposing, would bring high-demand critical materials back into the value chain faster. A sophisticated approach to understanding the value in a circular economy is to consider the optimal lifetime and “value” of each component, as opposed to treating the device as a single object (Bridgens et al., 2019). The benefits derived from repurposing an entire battery must therefore be balanced against the impact of the delay in the availability of the materials contained in the battery (Ahuja et al., 2020). With the growing number of EVs entering the market in the future and in the case of a significant supply crunch, it is expected that recycling will be an essential factor for consideration in an effective material supply for battery production (Reid & Julve, 2016, p. 26).

Naturally, the generated demand for LIBs recycling depends on the proportion of batteries repurposed in other applications. However, the extent of repurposing is, for various reasons, not possible to determine (Tadaros et al., 2020). One study assumes that 75-100% of EOL batteries will be used for second-life after 2020, basing it on being economically and environmentally beneficial (C. Xu et al., 2020). However, as the same paper mentions, this will delay the potential for recycling and is a figure used for the sake of simplicity. A Boston Consulting Group analysis found that the economics of EVB recycling at scale is attractive, whereas generating profits from second-life applications will be much more challenging (Niese et al., 2020). They believe that recycling directly is likely to be the favoured route in the circular economy. Despite the availability of used EVBs and the demand for energy storage solutions, second-life batteries are unlikely to represent a significant share of the power supply market for the foreseeable future (Niese et al., 2020). Based on this, they predict that only 20% of spent LIBs will be repurposed before recycling.

Some argue that second-life applications should be preferred as considerable recycling process advancements are still needed for a sustainable economy. “Suitable second-life uses for EV batteries can extract maximum value from manufacturing input and also delay the inevitable battery recycling to allow for continued improvements in recycling technology” (White et al., 2020, p. 2). Similarly, Kotak et al. (2021) claim that due to the high initial investment costs, the recycling option for low volumes cannot be considered economically beneficial. Thus, the argument for repurposing is to move the recycling or disposal into the future when recycling technologies have further developed and cost reductions are achieved (Kotak et al., 2021; White et al., 2020). Richa, Babbitt, and Gaustad (2017) suggest that recycling should be considered after repurposing. The authors stated that metal recovery would require policy and technology development to create collection programs, improve recovery efficiencies, and add economic incentives (Richa, Babbitt, & Gaustad, 2017). However, by extending the life of an EVB through second-life, issues of material resource availability might arise. If implemented on a large scale, additional lithium and other metals would need to be mined to satisfy demand resulting from a delay in material recycling (Ahmadi et al., 2014). This was described as “an interesting consideration for energy sustainability and technology assessment” by Ahmadi et al. (2014).

2.7 Theoretical summary

The theoretical framework presents theories and relevant data that are found to be of particular interest to answer the problem statement. A circular economy is presented as a concept that enables a more sustainable LIB industry as compared to the classical take-make-use-dispose pattern of the linear economy. With the circular economy concept, the value of EVBs can be prolonged through reuse, repurpose, and recycling. Figure 9 summarises the concept of a circular value chain where the product and its intrinsic materials are recovered instead of disposed of.

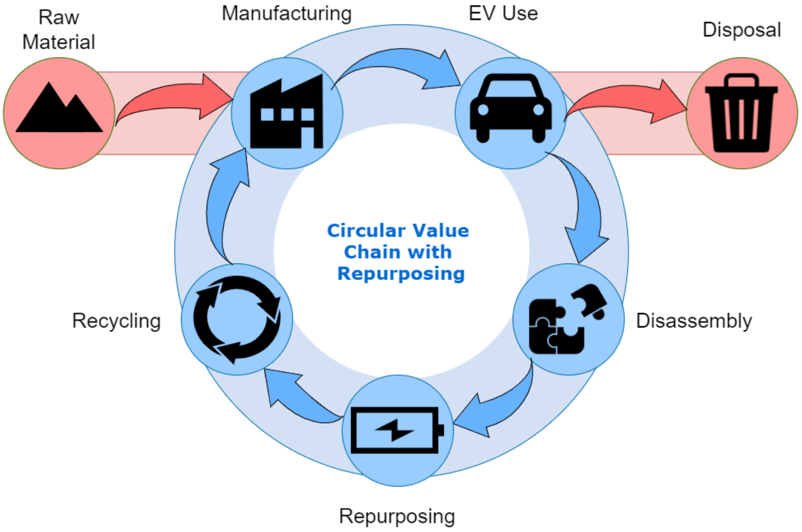

Figure 9: A theoretical circular value chain of EVBs illustrating how the product remains in the value chain instead of being disposed of. The figure is inspired by other EVB circular value chain figures such as those of Olsson et al. (2018) and Hua et al. (2020), in combination with the take-make-dispose approach of the linear economy.

The figure depicts the circular value chain focusing on repurposing and recycling. Instead of being disposed of, repurposing and recycling contribute to a circularity where materials are not wasted. To better understand the potential for repurposing and recycling LIBs, the market for energy storage, raw material market, second-life applications, recycling technologies and sustainable aspects have been covered in the theoretical chapter to create a holistic understanding of the subject. Table 4 presents a summary of the most central findings from the theoretical framework.

Table 4: Summary of the literature covering some of the most relevant theories and findings applicable to this study (own elaboration).

Topic	Literature	Source
Circular Economy	A central principle within the circular economy is to keep products and materials in use. It is an economic system that replaces the end-of-life concept with reducing, alternatively reusing, repurposing, recycling and recovering materials in production/distribution and consumption processes. Hence, take-make-use-dispose is replaced with take-make-use-recover.	(Ellen MacArthur Foundation, 2019; Frankenberger et al., 2021; Kirchherr et al., 2017)
	A circular economy aims to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity, and social equity. Often, the research focus is mainly on the environmental dimension. It is vital that circularity objectives integrate all the triple objectives of positively impacting people, planet, and profit.	(Bonsu, 2020; Kirchherr et al., 2017; Merli et al., 2018)
	In a circular economy, production is replaced by sufficiency, as a circular economy aims to maintain the value of products, components, materials and resources in the economy for the longest time possible. Thus, by optimising resource consumption, we reduce the quantity of "wasted" resources which need to be looped or adapted.	(Alamerew & Brissaud, 2020; Stahel, 2016; Williams, 2019)
	The waste management hierarchy (Lansink's ladder) was introduced in 1979 and is often quoted in relation to circular economy. Following the waste management hierarchy, prevention/reduction is preferred over repurposing; which is preferred over recycling; which is preferred over recovery; which is preferred over disposal.	(Harper et al., 2019; Morseletto, 2020; Potting et al., 2017)
Electric vehicles	The number of electric vehicles is continuously increasing, and within 2020, there were 340 002 electric vehicles in Norway. Europe is also experiencing an increase in the EV fleet.	(Gersdorf et al., 2020; Statistisk Sentralbyrå, 2021)
	The number of EVs is expected to increase significantly, driven by ambitions of cutting greenhouse gas emissions.	(Abnett & Carey, 2021; BNEF, 2020; Crooks, 2020)
	Shifting focus towards circular economy could see a transition from private vehicles ownership to car-sharing services to increase utilisation of vehicles.	(Kamran et al., 2021)
Electric vehicle batteries	NMC, LFP, LMO and NCA are the most dominant lithium-ion battery technologies for electric vehicles as of now. NMC will likely dominate the market in the future.	(Y. Ding et al., 2019; Kamran et al., 2021; Pillot, 2019; The Faraday Institution, 2020)

	Battery technologies with different material compositions, especially less cobalt, is increasingly expected.	(Di Persio et al., 2020; Steward et al., 2019)
	New chemistries with a disruptive improvement in performance and cost in batteries such as lithium-sulphur, solid-state li-ion and sodium-based batteries are expected. But such technologies are not expected to achieve significant market penetration for many years and are subject to great uncertainty.	(Duffner et al., 2021; Karabelli et al., 2020; Olivetti et al., 2017)
Raw materials for LIBs	The production of the primary materials used in LIBs is dominated by a small number of countries, few of which are in Europe. More than half of the cobalt used comes from Congo; Australia and Chile control ~80% of lithium production; China controls ~70% of graphite production.	(Chen et al., 2019)
	The annual lithium inflow into the EVB sector is predicted to show a continuous and strong increase in the following decades before levelling out. Lithium might encounter a potential supply crisis in the future if an efficient recycling system is not developed.	(Greim et al., 2020; Ziemann et al., 2018)
	The nickel content of EV batteries is likely to increase in the future as they promise to overcome resource and cost problems. The value of nickel will determine the attractiveness of the battery business case in coming years, as manufacturers shift to batteries with higher nickel content.	(Karabelli et al., 2020; Mayyas et al., 2019) (Niese et al., 2020)
	Lithium-ion batteries are and will continue to be the largest end-use sector of cobalt. Yet, cobalt is prone to various supply risks. Consequently, cobalt might be less used. New LIB technologies provide the most promising strategies to reduce the reliance on cobalt substantially but could result in burden shifting, such as an increase in nickel demand.	(Abdelbaky et al., 2020; Baars et al., 2021; Beatty et al., 2019; Gourley et al., 2020) (Baars et al., 2021)
End-of-life	Most scholars use the warranty period and 80% capacity as a reference point to define end-of-life. Around a 10 year lifetime is often assumed, yet the lifetime of future EVBs is uncertain and hard to predict. LIB development is characterised by rapid technological advancements influencing the lifetime of future batteries.	(Tadaros et al., 2020; Xu et al., 2021; Yükseltürk et al., 2021)
	Batteries in a state of health that would typically be considered to mark their EOL (80% capacity) may still be used by consumers who prefer to accept a shorter range over the expense of a battery replacement. EVs with 60-	(Hossain et al., 2019; C. Xu et al., 2020)

	80% residual battery capacity could still meet the daily travel needs of most drivers.	
	LIBs are hazardous and must therefore be handled and transported safely. Safety requirements for transporting retired EVBs may increase the cost.	(Richa, Babbitt, & Gaustad, 2017)
	One challenge, particularly with respect to processing EVB packs, is the lack of automation infrastructure and design standardisation to feasibly disassemble the packs. As of now, most cells are thought to be currently hand disassembled, which may bring safety issues due to the chemical constituents. Automation of disassembly is thought to improve the processing of batteries in terms of safety and cost savings.	(Abdelbaky et al., 2020; Or et al., 2020; Sommerville et al., 2021)
Circular value chain of EVBs	A satisfactory collection, treatment, recycling, and repurpose of LIBs in the downstream stage is required to consider security, legal, environmental, and economic aspects.	(Sato & Nakata, 2021)
	The circular value chain of spent LIBs is proposed to entail, reduce, redesign, remanufacture, repurpose, and recycle in the circular value chain process.	(Hua, Zhou, et al., 2020)
Repurposing	If retired LIBs do not suffer from any defects or damages, they can be repurposed in various second-life stationary applications that demand lower current density from the battery pack.	(Pagliaro & Meneguzzo, 2019; Z. Xu et al., 2020)
	There is a great potential from employing spent EVBs in second-life applications, but this will delay the return of EVBs to recycling significantly.	(Abdelbaky et al., 2020)
	Repurposing offsets initial manufacturing impacts by extending the battery life span. Hence it can hinder the production of purposed electricity storage batteries.	(Kamran et al., 2021; Richa, Babbitt, Nenadic, et al., 2017)
	Repurposing LFP battery types seems most beneficial due to the long lifespan and the reduced chance of cascading failure. In addition, recycling of LFP is not viable, which mandates its repurposing.	(C. Xu et al., 2020) (Mossali et al., 2020)
Recycling	Producing batteries with material from spent batteries would prevent possible price surges and supply disruptions of battery materials, mainly as material supplies are highly dependent on imports.	(Xiong et al., 2020)
	Legislations would incentivise manufacturers to recycle their end-of-life lithium-ion batteries and could help the widespread adoption of LIB recycling.	(Or et al., 2020; Thompson et al., 2020)

	Spent LIBs are treated mainly by the hydrometallurgical process in combination with pyrometallurgical treatment. For instance, performing hydrometallurgy after pyrometallurgy to further extract transition metals.	(Meshram et al., 2019; Sommerville et al., 2021)
	The focus of recycling is on the recovery of cobalt and nickel rather than lithium due to superior value. Lithium is hard to recover and costly in comparison to virgin material extraction.	(Meng et al., 2021; Or et al., 2020; Reid & Julve, 2016, p. 26) (Bonsu, 2020)
	As of 1 January 2030, batteries shall contain the following minimum share of recovered material: 12% cobalt, 4% lithium and 4% nickel. Increasing to 20% cobalt, 10% lithium and 12% nickel by 1 January 2035.	(European Commission, 2020a)

3 Method

Performing a study is dependent on a precise methodological process regarding its problem statement, research questions, literature review, data collection, analysis, and interpretation. This chapter justifies the methodological choices that have been made and explains why the chosen approaches were considered appropriate for the study. Moreover, the method chapter seeks to explain how the study can be performed similarly by others. In addition, it will account for challenges that have occurred along the way, as well as a reflection of the quality and limitations of the study. The steps of analysing documents, performing qualitative interviews and using the gathered data to construct discussions and predictions are inspired by the abductive approach. Lastly, we examine how the quality of this study can be related to reliability, validity and the potential of generalisation. An overview of this study's method can be found in Table 5.

Table 5: Overview of the method used in this thesis.

Research question	What drives the demand for recycled battery materials, and how can this influence the market for second-life electric vehicle batteries?
Research design	Qualitative study
Data collection	Qualitative data collection through semi-structured interviews with ten respondents
Data sample	Researchers, managers, and engineers working for various companies in the battery value chain
Data analysis	Abductive analysis with the decoding of interviews supported by findings in the existing literature

3.1 Research design

Research design is an essential step for a researcher as it is the primary bridge between the conceptual research problem and the relevant empirical research (Aboujaoude, Feghali, & Kfouri, 2018, p. 39). The aim is to make an overall plan of the study that describes how the problem will be clarified and answered. The work of this thesis, being business research, is derived from a social science perspective. As we were studying a relatively new and rapidly developing field, we identified the appropriate type of research to be qualitative. The nature of this study leads to a research question being proposed instead of a hypothesis. The research question is broadly scoped to give flexibility and is justified by the phenomenon's importance and the lack of viable theory and empirical evidence.

This study is affected by our personal ontological and epistemological perspectives and methodological choices. Ontology is considered philosophical assumptions about the nature of reality, epistemology concerns the theory of knowledge (Davidavičienė, 2018), whereas methodology describes the method used in conducting the study (Antwi & Kasim, 2015). A research inquiry should be based on these concepts, and answers to questions regarding these elements provide the interpretative framework guiding the research process, including methods and analysis (Antwi & Kasim, 2015). We believe in the pragmatic approach to the ontology that an external, diversified view of the nature of reality best enables answering a research question (Davidavičienė, 2018, p. 19). On an epistemological level, we believe that sufficient knowledge is constituted by both observable phenomena and subjective meanings depending on the research question, aligned with pragmatism (Davidavičienė, 2018, p. 19). Furthermore, we believe integrating different perspectives helps interpret data which is also in line with a pragmatic epistemology (Davidavičienė, 2018, p. 19). The pragmatic paradigm is interlinked with a data collection that most optimally fits the subject matter and could be both quantitative and qualitative (Davidavičienė, 2018, p. 19). This corresponds with our data collection, as we deem the qualitative data collection technique the most suitable for this subject.

Considering our pragmatic epistemology and ontology and a lack of existing empirical data, we firmly believe that qualitative interviews are a suitable method for our research. The qualitative method is helpful to get a deep understanding and focuses on gathering considerable information from few subjects (Dalland, 2017). Qualitative research has an approach to empirical research that mainly relies on the collection of qualitative data, i.e., non-numeric data such as words (Azoury, Kaissi, & Attieh, 2018, p. 117). Researchers using qualitative methodology can immerse themselves through interviewing key people and analysing existing documents (Antwi & Kasim, 2015). For this thesis, it is crucial to have up to date information about the market and technology as it is constantly shifting, and articles, documents, key figures, and statistics may already be outdated. Therefore, by using a qualitative methodology, we ensure that we get an updated understanding of today’s situation by using empirical data from interviews with key people from relevant businesses.

Researchers use qualitative research methods in an attempt to advance a theory based on the quality of the data collected. Two methods for theory advancement are the deductive and the inductive (Azoury et al., 2018, p. 118). Whereas deduction covers theory falsification or verification, induction covers theory generation and building (Davidavičienė, 2018, p. 20).

The abductive method combines both of these approaches back and forth, which often happens in business, management, and economic research (Davidavičienė, 2018, p. 21). This was also the case for this study. Abduction covers theory generation or modification, incorporating existing theory where appropriate to construct new theory or alter existing theory (Davidavičienė, 2018, p. 20). The literature review was updated during the data collection process and the empirical and theoretical collection of data influenced each other. An initial literature review paved the way for the initial qualitative interviews, where findings contributed to new insights and the need to gather more literature. Feedback on EU's regulations and recent business trends regarding battery types from Volkswagen and Tesla further contributed to the necessity to collect literature simultaneously with the empirical data collection and brought new knowledge and questions for the remaining interviews.

3.2 Literature review

Building research on and relating it to existing knowledge is vital in all academic research activities (Snyder, 2019, p. 339). A thorough literature review is an imperative step for the researcher since it helps delimit the research problem and enlighten the concepts that will be studied by considering past research (Aboujaoude et al., 2018, p. 36). For this study, a minor systematic literature review has been performed to gain an in-depth interpretation and assessment of previous research relevant to the topic being studied.

The following criteria for literature to be included was that it described (1) Circular economy, (2) Circular value chain, (3) EV lithium-ion batteries which cover (A) Lithium-ion batteries, (B) Lithium-ion battery raw materials and (C) Electric vehicles, (4) End-of-life of EVBs, (5) Repurposing of EVBs, and (6) Recycling of EVBs. When looking for studies regarding end-of-life LIBs, the tags "second-life", "second use", "repurposing", and "reuse" were included. Regarding literature on lithium-ion batteries for electric vehicles, various tags were used, e.g., "lithium-ion battery", "LIB", "EV battery", "li-ion battery", "electric vehicle battery". The literature search consisted of combinations of these and other relevant tags. For instance, "electric vehicle battery" plus "recycling". The literature was chosen to a large extent based on recency and citations in other articles.

The criteria for the literature search were not all set, to begin with, as some topics appeared during the data collection phase, such as feedback from companies and organisations on the proposed regulations for EV batteries. For the literature search, the Google Scholar search tool has been used to find relevant articles together with the University's database AURA.

Also, a snowballing method was used, where the work of relevant references and authors from the literature were further investigated. This also helped to explore and confirm research findings from the literature review. Besides, we have briefly investigated articles and books from other themes not directly related to our problem statement, e.g., linear economy, to gather a more holistic understanding of the subject. This acted as a way of evading bias by exploring different and opposing ideas and research fields.

We acknowledge that a limitation of the literature review is that additional literature could have been found by more extensively using alternative synonyms. For instance, “closed-loop” or “cyclic” for “circular economy” or “traction batteries” for lithium-ion batteries. Moreover, the CE concept is closely interlinked with various other concepts, some of which predate it, like industrial symbiosis (Winans et al., 2017, p. 826). In fact, industrial ecology (including industrial symbiosis and eco-industrial parks) are some of the categories most interlinked with CE by scholars (Merli et al., 2018). Yet, these terms were not used during the literature search of this study.

Peer-reviewed articles from journals and conference publishing were preferred in addition to reports written by well-known scientists or organisations such as the Ellen Macarthur Foundation, The Faraday Institute, the European Commission, and the Club of Rome. Moreover, to gain access to updated market data and trends, business research from the likes of Wood Mackenzie, Avicenne Energy and Boston Consulting Group was also reviewed and added. It was essential to include both “state of the art” studies and primary sources for existing theory. Yet, in regard to LIBs and end-of-life of EVBs, state of the art was preferred as this subject is rapidly evolving. An overview of some of the most relevant literature and their findings was presented in section 2.7. In order to ensure quality in this study, the background and context of articles and authors have been briefly controlled.

Non-scientific data such as the number of recycling processes, prices, volumes, and collection rates are changing every day. What is factually correct one year is not necessarily correct the year thereafter. This is especially important in a rapidly growing market, where both technology and the commercial context is changing fast. Several papers use data that is often more than ten years old; hence, it is vital that researchers, as well as all users of research, are critically reviewing references to be able to ensure the factual quality of the work they are using (Melin, 2019, p. 49). We have tried to use state of the art research because of this, as the subject under focus is rapidly evolving and using old data would seriously undermine the technological advancements and market expansion. Therefore, in addition to updated data and prognosis from respected organisations and firms, news on relevant subjects and information from company websites have been used to give us much needed up-to-date data.

A challenge of literature reviews within the circular economy is the diverse use of terms with a lack of alignment amongst scholars and businesses. Unfortunately, various terms are used to describe similar concepts. Reuse, for instance, is used by some to describe both reuse in the same application (for instance, LIB in EV), as well as second-life in a different application (for instance, LIB as stationary energy storage). This can complicate discussions and lead to misunderstandings among scholars, business research, and misinterpretations of policies. In fact, it even created challenges in the data collection process of this study as the terms had to be clarified in many of the interviews. It was also challenging when reviewing literature as scholars use the terms differently, and even though the terms are often described or understood through their context, it may not always be the case. Consequently, researchers might inaccurately quote other scholars leading to untruthful findings.

3.3 Data collection

This paper mainly builds on data gathered from interviews with EVB experts from Norwegian stakeholders in the battery value chain. The interviews were semi-structured, with a tailored interview guide for each stakeholder. Common topics were barriers and opportunities for recycling and second-life EVBs, material prices and supply, sustainability factors related to recycling and repurposing, battery design, and perspectives on regulations on recycled content. All the interviews were performed through Teams or Zoom due to the Covid-19 pandemic. They lasted between 25 and 75 min and were instantly transcribed to the best ability of the authors. All interviews had one respondent. The interviews were done in Norwegian, English and Italian. Quotes from interviews in Norwegian or Italian have been translated with the aim of capturing the essence of the respondent’s statement.

There is no universal answer on the ideal sample size for qualitative research (Mouselli & Massoud, 2018, p. 102). Increasing the sample size may result in including observations from a different population and consequently lead to misleading conclusions (Mouselli & Massoud, 2018, p. 102). A sample size of ten respondents was considered ideal for this research as we managed to cover the problem statement through data from battery experts from the entire value chain. When generalisability is not the ultimate goal for qualitative research, it could be useful to study in detail small samples. In such cases, it is up to the researchers to justify and amend their sample size to meet their research goals (Mouselli & Massoud, 2018). We believe a sample size of ten respondents is neither too big, which could have led to misleading conclusions or too small, limiting the study's generalisability.

The interviews were performed with different actors with special competence in this study's relevant field, shown in Table 6. The table shows the different categories of stakeholders represented in the study. All respondents are kept anonymous, as it would not add value to the paper to specify the interviewed companies or agencies. To prepare for the interviews and make them efficient, an interview guide was established. This guide was used during the planning of each individual meeting to ensure that the questions were relevant both for the interviewee and for the thesis. By doing so, the interviews could be kept short while still covering all the relevant topics.

The interview guide was formed by first identifying which topics were relevant. The topics chosen were, e.g., the raw material market, LIB technology, LIB second-life, or LIB recycling, depending on the respondent's expertise. Although most of the interviews touched on each subject, the main subject of each conducted interview was guided by the respondent's expertise. To give the interview structure, themes were divided into sections with an estimated time limit for each segment. The interview guide was based on the literature findings and especially inspired by the findings regarding LIB production and recycling, second-life, market developments, et cetera. Moreover, the initial interviews gave insights that altered our literature findings, and in turn, gave us new subjects to investigate in the following interviews.

In the theoretical framework, several potential factors that could drive the demand for recycled battery materials were found. Raw material supply and prices, together with regulation for recycled content, were identified as important drivers for the demand for recycled content in LIB production. Additionally, lifetime, technological advancements, various economic considerations, distribution of LIB chemistries, and transition to transportation-as-a-service, which could affect the vehicle fleet, were identified as potential factors, or at least essential elements to consider. These became the subjects of the interviews through detailed questions or through open questions where the respondents themselves brought the subject up.

When selecting the respondents we wanted to interview, we started by looking at the value chain for EVBs. We tried to include stakeholders from as many sectors of the value chain as possible to get an understanding of the entire lifecycle of the batteries. Additionally, a presentation was made for each of the interviews to help explain the thesis and give the interviewee a visual aid. This also made it easier to stay within the subject as the respondent always had the questions accessible. Interviewer bias challenges the validity and reliability of research when the researchers do not start by building trust with their respondents (Mouselli & Massoud, 2018, p. 105). By introducing our thesis through a presentation, we intended to build their trust by introducing them to our scope and intentions.

Table 6 presents a complete list of the profile of the companies interviewed, the respondent's position, the theme of the interview and the duration. In qualitative research, data results from a multitude of diverse sources, including individuals, experts, or corporations (Azoury et al., 2018, p. 118). All of the respondents represent separate organisations and companies. They represent battery producers, recyclers, material producers, repurposers, universities, and other relevant organisations.

Table 6: The qualitative interviews performed digitally from January to March 2021.

Identification	Position	Company profile	Main theme	Duration
Battery Expert A	Project leader	Industrial Company	LIBs, second-life, recycling	75 minutes
Battery Expert B	Project engineer	Industrial company	LIBs, recycling, second-life	30 minutes
Battery Expert C	CEO	Industrial company	Recycling, LIBs	35 minutes
Battery Expert D	Vice President	Industrial company	LIBs, raw materials, second-life, recycling	45 minutes
Energy Analyst	Market analyst	Energy company	Energy storage technologies, power markets	35 minutes
Material Expert A	Researcher	Industrial company	Recycling, raw materials, market developments	40 minutes
Material Expert B	Researcher	Industrial company	LIBs, raw materials, recycling	40 minutes
Repurposer	CEO	Industrial Company	Second-life, LIBs	50 minutes 45 minutes
Researcher A	Researcher	University	Recycling, disassembly	35 minutes
Researcher B	Researcher	University	Raw materials, LIBs	35 minutes

An interview is, in essence, "a purposeful conversation between two or more people, requiring the interviewer to establish a report to ask concise and unambiguous questions to which the interviewee is willing to respond and to listen attentively” (Raudeliūnienė, 2018, p. 54). It brings with it the advantage of a collection of primary and sufficient information. Yet, it also provides challenges such as; record problems, lack of attention, time-consuming, and personal aspects (Raudeliūnienė, 2018, p. 54). An epistemological concern is the relation between the researcher and knowledge by questioning how knowledge is acquired. In this regard, the researcher must be aware of his/her own limitations as mistakes can be made or data can be misinterpreted. Luckily, we were both attending the interviews and taking notes. The fact that we were performing all interviews (bar one) sitting together mitigated some of the mentioned challenges, such as lack of attention. In addition, we did not feel that both being present confused the respondent as each interview was guided by only one of us.

An essential ethical concern in the data collection stage is the level of objectivity of the researcher, as maintaining objectivity is vital to avoid any personal selectivity occurring, whether intentionally or unintentionally (Azoury et al., 2018, p. 116). In spite of collaborating with a second-life EVB company, we have tried to avoid having a bias towards second-life when interviewing respondents on trade-offs between second-life and recycling directly. It was imperative for us to maintain a neutral standpoint as such an unethical attitude towards data collection may transfer negatively to the validity and reliability of the research (Azoury et al., 2018, p. 116).

3.3.1 Research ethics and anonymity

In regard to research ethics, respect for people and informed consent are fundamental principles (Azoury et al., 2018, p. 112). Informed consent means that the respondent understands what the researcher wants him or her to do and consents to the research study (Azoury et al., 2018, p. 112). Some general ethical issues entailed in research include: maintaining the participant’s privacy, attaining fully informed consent, guaranteeing the rights to confidentiality and anonymity, maintaining impartiality (Azoury et al., 2018, p. 115). These issues have been regarded during this research project as the thesis and its qualitative data collection has been performed in line with the governing guidelines of NSD, the Norwegian Centre for Research Data. However, as the number of Norwegian stakeholders in the LIB value chain is limited, people familiar with the sector could be able to identify some of the participants. To mitigate this risk, the details in Table 6 were generalised more than initially planned, e.g., “Industrial company” was used instead of describing the company’s sector such as “Metal producer” or “Battery producer”.

Hence, due to the relatively small size of the value chain and maintaining ethical integrity, it was chosen not to refer to interview objects by title or company. The interview objects will be referred to with their identification tag in terms of statements and direct quotes, as seen in Table 6. In the discussion, two of the interviewees will be described as representing battery producers. However, it will not be specified which respondent we are referring to. To further make sure that the participants cannot be identified, we have avoided including information from the interviews that might directly link to a specific company or person. Before each interview started, the interviewee was informed that the data would be anonymised. By informing about anonymity and the approval of NSD, the participants may be less reluctant about sharing information and thus speak more openly. We consider it unlikely that the anonymisation of the data gathered will affect the validity of the data collected or the conclusion for this thesis.

3.3.2 Analysis of data

Analysing the data was a central part of this thesis. In qualitative research, data should be analysed in-depth, and the significance of data should be truthfully interpreted (Azoury et al., 2018, p. 118). The data analysis was therefore performed with multiple steps, as seen in Table 7.

Table 7: Description of data collection, processing, and analysis steps.

Data analysis step	Description of the step
Data selection	- Initial meeting with the Repurposer presenting possible subjects and deciding on a relevant theme
Data collection from qualitative interviews	- Qualitative interviews of the informants - The interviews were performed online through Microsoft Teams or Zoom
Review of notes and individual analysis	- Review of the notes from each interview - Each interview is individually analysed while reviewing
Document with temporary findings	- During the latter step, created a document of temporary findings based on the review and individual analysis
Clarification and correction by the informants	- Interviewees were given the possibility to correct and clarify statements.
Joint content analysis	- Performed a joint analysis of all the interviews with the research questions kept in mind

Adding additional information	- If necessary, asked the informants for additional information to further clarify after the joint analysis
Analysis completion	- After adding the additional information, the analysis was completed
Analysis review	- Controlled notes from each interview again to ensure that all important information was gathered and that the analysis process was performed correctly

Before analysing the data, it was revised through data cleansing. We detected and removed erroneous, incomplete, or duplicated data. Doing this was critical to verify the validity and reliability of the data as analysing data that has not been carefully screened for problems can create highly misleading results (Aboujaoude et al., 2018, p. 42). After cleansing the data, it was transformed through a process of coding and classification so that they were ready for analysis.

The material from the interviews was analysed using theme content analysis. First, recurring categories were identified: Battery production, directives and regulations, costs and fee, recycling, repurposing, sustainability, market, materials, and future predictions. Then, these categories were explored with respect to the different points of view of the stakeholders. Thus, common perceptions of opportunities and challenges could be identified. This material was then analysed from a circular economy perspective, referring to the theory from the theoretical framework. The various stakeholders interviewed in the data collection has a wide variety of knowledge and experience with different industry backgrounds. A natural consequence of this is that while the respondents have high trustworthiness in certain areas, they might lack expertise in other areas. In the process of analysing the interviews and forming the discussion, these variances in knowledge have been considered. Moreover, statements of strong beliefs were given a higher consideration in the analysis of data. Hence, formulation of opinions such as: “I strongly believe (…)” or “I sincerely think (…)” were given more consideration than: “I am uncertain, but I believe (…)” or “it is hard to tell, but (…)”.

Once data have been analysed, they should be interpreted. Interpreting the analysed data implies that meanings are attached to the data. Data can be understood in different ways, therefore, interpretations coming from different people is valuable before the final evaluation of information (Aboujaoude et al., 2018). Discussing the data by ourselves and with our supervisor was thus a great asset in avoiding biased interpretations. This is also aligned with pragmatic epistemology through integrating different perspectives to help interpret the data (Davidavičienė, 2018, p. 19). Lastly, detailed results were compared to the results of past research and suggestions for future research were presented to further contribute to the literature on the topic.

3.4 Quality of research

As most of the empirical data gathered in this thesis came from interviews, the results are, to some degree, based on subjective judgement and biases. The interviewees' perspectives might be affected by their role, such as their position in a company or field of study. In fact, interviewee bias is a significant issue in semi-structured interviews as it likely affects the quality of data collected by the researchers. This type of bias occurs when the respondents misrepresent the truth, either consciously or unconsciously (Mouselli & Massoud, 2018, p. 106). This issue is taken into consideration when discussing the findings. Additionally, the number of interviews and the variation in their background partly mitigate this factor, as the various stakeholders will have different biases.

Based on the interviewees' experience and level of expertise, we are confident that the data gathered from the interviews held a high degree of validity. Also, as we feel that the respondents had good representativeness, which is a critical factor as it leads to more substantial external validity (Mouselli & Massoud, 2018, p. 103), however, it must be noted that some of the informants represent leading positions in their companies and specific parts of the value chain. Interviewing people in such position could perhaps lead to over-optimistic responses as they try to portray their company in the best possible way. If one is presented solely with good news, it is logical to wonder if the way the data was acquired results in it being valid. Still, from our perspective, each respondent gave seemingly authentic answers.

The trustworthiness or reliability of the study means that the results can be reproduced when performing the same investigation. Threats to reliability are theme or participant errors, theme or participant bias, observer error or observer bias (Saunders, Lewis, & Thornhill, 2009, pp. 156-157). Reliability concerns to which degree the data collection techniques or analysis procedures give constant findings (Saunders et al., 2009, p. 156). It follows that if others repeat the investigation with the same methods and a similar sample, they should arrive at the same results given that nothing has changed. Related to this, it is essential that the researcher avoids selective reporting in the form of desired data being reported while undesirable data gets neglected. In such a case, a repetition of the study would generate different results. In this regard, this thesis must be understood in relation to limited research experience and a limited research period of around four months.

We acknowledge that a mixture of academic peer-review, public policy, news, industry consultancy reports, and business research was reviewed, and there is a variety of quality in the evidence underpinning our analysis. Additionally, the interviews conducted with the stakeholders are subjective and does not necessarily represent the perspectives of their company or other companies in the same value chain. The interviewees were selected based on their position in the company, and they are believed to have sufficient competence to answer our questions precisely. Therefore, we consider the data gathered from the interviews to be valid.

Specific considerations fall outside of the scope of this paper. For instance, the Covid-19 pandemic might bring challenges, especially to the supply chain of materials. The Covid-19 pandemic has shed new light on the weak links in global supply chains (Althaf & Babbitt, 2020). In fact, the pandemic has hit both supply and demand for natural resources, and for many commodities, the impact on supply, caused by a squeeze on investment spending, will last longer than the impact on demand (Crooks, 2020). Yet, we feel like these considerations do not detract from the general validity of the presented results in terms of drivers for recycled material, recycling and second-life opportunities.

The results from the data collection are simultaneously presented and discussed in the discussion. The data from the interviews are combined with data from the literature review. Note that the discussion is based on the authors' subjective analysis, judgement, and interpretation of the data collection. For instance, what drives the demand for recycled battery materials in battery production is subjectively categorised. The categories are based on an interpretation of the interviewees' viewpoints. Others might analyse the data differently and thus, could achieve other results and conclude differently.

In terms of generalisation, there are several reasons to conduct research in the field of recycling and repurposing of batteries. One reason can be to develop new knowledge that might benefit the entire battery industry and take the field of study forward. Another reason for an individual company or for a country can be to develop its own ability to create efficient and profitable solutions and thus strengthen its own position in the value chain (Melin, 2019, p. 44). In regard to generalisation, it is crucial to recognise that different regions will have different incentives for repurposing and recycling. Moreover, we find it important that circular economy research is based on realistic assumptions and findings. Our pragmatic research philosophy is reflected in our belief in dealing with things sensibly and realistically in a way that is based on practical rather than theoretical considerations. For instance, the waste management hierarchy might be ideal in theory, but in practice, it does not necessarily provide the ideal guidelines for the pathway of each product and material.

3.4.1 Limitations

A holistic, systems-based approach to a circular economy and zero waste requires an assessment of all sectors and their interconnectivity (Mulvaney et al., 2021). In our thesis, we have not taken into consideration the interconnectivity of several of the sector's integral to EVBs. For instance, other electronic appliances consist of similar raw materials and could be used as secondary materials in sustainable battery production. Moreover, the growing market for renewable energy systems relies heavily on critical materials (Mulvaney et al., 2021). Yet, quantitative assessments of such impacts have not been performed. The development of demand for critical raw materials beyond EVBs has not been studied in this thesis.

Different research articles base their findings on different LIB technologies, recycling technologies, market shares, regions, et cetera. Studies rely on different expectations for the market share of cell chemistries in future EV sales. Consequently, they yield highly variable estimates for the recycling potential of the waste stream (Abdelbaky et al., 2021). For instance, the model in the research of L. Wang et al. (2020) was based on all LIBs being NMC, as well as other assumptions. In comparison, other studies might assume a different mix of battery technologies for similar studies.

Some studies are performed in China, where the energy mix and other criteria might lead to different results compared to similar studies elsewhere. In fact, Xiong et al. (2020) observe a significant deviation in environmental analysis and economic evaluation due to different recycling techniques, uncertain sources of data or poor data quality, and regional disparity (Xiong et al., 2020). Estimating recycling costs and greenhouse gas emissions is not straightforward and subject to uncertainty since recycling on a large scale is not taking place yet (Philippot et al., 2019). Notably, price and market size rely in part on data reported by industry consultants, whose data collection could involve a variety of methods or assumptions that are not always presented with the final data and whose intentions are not always declared. This is not a major limitation for this study, as most of the information gathered from literature has been used to describe general conditions and terms. Nevertheless, citing literature that base their findings on different presumptions could lead to some uncertainty and is therefore worth noting.

Regarding the data collection, we acknowledge that it was somewhat limited to stakeholders in the same network who could potentially represent similar views owing to the nascent industry they are a part of. In fact, non-probability sampling techniques, mainly work-based networks, have been dominantly used in our research. This is referred to as convenience sampling (Mouselli & Massoud, 2018, p. 104). This sampling process is highly likely to result in biased samples, which include specific types of respondents (respondents sharing similar characteristics) and exclude others (Mouselli & Massoud, 2018, p. 104). Due to the battery industry being in its infancy in Norway, the population is limited. This owes to the fact that the battery industry in Norway is limited to a low number of stakeholders, thus expert knowledge is restricted. Yet, we experienced different beliefs and ideas from the interviewees, which leads us to believe that despite some stakeholders being in the same network, it should not limit the findings of this study.

There is a lot of uncertainty associated with data and results, making it difficult to provide direction for the sustainable impacts of EOL options for EVBs. This is due to the lack of access to industry data, due to the nascent nature of the value chain, which leads to considerable uncertainty associated with the actual use of materials and authentic environmental, social and economic impacts of recycling and second life LIBs. Additionally, the domain of lithium-ion batteries is rapidly changing and vastly researched, which gives state-of-the-art research increased importance. Nonetheless, we believe that this being an abductive study allowed the study to adapt to recent industry trends. For instance, feedback on the proposed battery regulations from companies within the industry was not available for the first interviews in February as the feedback was not available until the end of February and the beginning of March. However, it gave inspiration for questions for the interviews in March. Similarly, knowledge of more widespread use of LFP batteries was not known prior to news releases and statements from VW and Tesla in February and March.

Despite the aforementioned remarks, we consider our results informative, valid and reliable. Our pragmatic epistemological standpoint and ontological concerns are aligned with how we have approached the methodological choices in this qualitative study. Furthermore, we believe our ethical choices as presented throughout the chapter, choice of the data samples, and the abductive nature of this study, further contribute to the validity and reliability of the data collection, processing, and analysis process.

4 Results and Discussion

Recycling spent EVBs presents an option for battery producers to acquire a sustainable supply of materials. Yet, EVBs can also be given a second life through repurposing as batteries often contain residual capacity that can be exploited in stationary electricity storage. Hence, there is a rationale for both recycling and repurposing as EOL strategies of spent EVBs. To better understand the potential for recycling and repurposing, the following section will investigate what drives the demand for recycled EVB materials. Based on these drivers, the potential for second-life will be discussed to see how repurposing could be influenced by the potentially increasing demand for recycled materials. Hence, market mechanisms that determine the rules of the game when it comes to the CE strategies repurposing and recycling are enlightened. Based on the data collection in combination with recent predictions from business and scientific research, a simplified prognosis of end-of-life LIB strategies in Norway will be presented. Finally, as concluding remarks, implications on the circular economy regarding the interplay between repurposing and recycling EVBs will be discussed.

4.1 Drivers of the demand for recycled materials

As stated above, this subchapter presents and discusses potential factors that could drive the demand for recycled battery materials. The drivers are categorically presented in subchapters, based on the most discussed subjects from the semi-structured interviews, before being summarised at the end.

4.1.1 Regulations

The revised rules proposed by the new Circular Economy Action Plan (2020c) on EOL vehicles are meant to promote more circular business models by linking design issues to EOL treatment, improving recycling efficiency, and considering rules on mandatory recycled content for certain materials. Especially the regulations requiring batteries to be placed on the EU market to contain recycled materials from 2030 (European Commission, 2020a) became a subject in many of the semi-structured interviews.

4.1.1.1 Mandatory requirements on recycled materials

From the data collection, there seems to be little doubt that a required share of recycled materials will have an influence on the market. Battery Expert A suggests that the EU's battery directive and regulations will significantly influence the demand for recycled materials. When asked which end-of-life strategy will be most widespread, second-life or recycling directly, the expert said it depends a lot on legislation: “If they ask for high recycling shares in new batteries, I think the automotive industry will buy as many batteries as possible to recycle this to use it in production". Battery Expert C states that "demands of a certain share of recycled materials will have a huge influence on battery production." Similarly, Calisto Friant et al. (2021) believe the EU's focus on closing resource cycles will without a doubt create an unprecedented boost for the recycling industry. As the required share of recycled materials will go from being a directive to regulations, it becomes an obligation for battery producers to comply. In that case, it could lead to "a competition amongst cell producers", says Battery Expert C. Battery Expert B agrees to this point, stating that there will probably be a battle for specific materials such as nickel and cobalt. However, that this also depends on whether regulations require recycled materials, specifically from batteries or recycled waste in general.

The targets of COM (2020) 798/3 might seem modest, but in reality, they will probably be difficult to achieve with EOL batteries available in Europe. However, the regulation does emphasise "waste" and not "waste batteries", which opens up for the use of production scrap. Therefore, Battery Expert D believes that acquiring recycled lithium could become a challenge since it is predominantly found in LIBs:

> *Lithium will likely be the biggest challenge, whereas nickel is found in other applications besides batteries and not as limited as lithium when it comes to recycling.*

Batteries containing expensive raw materials make them more profitable to recycle, states Material Expert B. The material expert adds that for cobalt and nickel-rich batteries, the use of recycled materials will be more easily facilitated and could even be profitable by itself without a push from regulations. Whereas for batteries containing cheaper materials, mandatory targets will be required to accelerate recycling.

Furthermore, there is nothing that says that recycled content must come from within Europe. Thus, Asian recyclers/material producers with a bigger scale and access to more recyclables might get an advantage, says Battery Expert D. The expert expresses concerns over the fact that consumer electronics often end up outside of Europe and that there is a much greater recycling scheme outside of Europe, such as in China. Hence, the regulations will not necessarily give Europe an advantage. Consequently, the regulation that is supposed to strengthen the European industry could end up being more advantageous for others. This challenge is also expressed by Material Expert B. The material expert is sceptical when it comes to percentual recycling requirements and believes that mandatory targets of recycled materials will not be that important. The expert thinks the actual use of recycled materials will be dependent on economic factors and raw material availability and that having specific targets of recirculated materials will complicate things for European industry.

The proposed EU regulations will have the ability to set high sustainability standards for batteries. However, it is done in an industry where other parts of the world control the value chain, which is an issue worth recognition. Hence, perhaps there is a tone of complacent optimism in Europe when it comes to recycling as incumbent players in Asia could be better positioned to meet the proposed regulations. Battery Expert D states that “Europe has looked at itself as technology experts, but we are lagging behind others. Therefore, we need to get going now”.

4.1.1.2 Industry viewpoints on proposed regulations

The self-descriptions on the websites of Nordic battery producers show a clear green common thread (Freyr Batteries, n.d.; Morrow Batteries, n.d.; Northvolt, n.d.-a). Sustainability, and its accompanying terms, is evidently valuable for these companies. Hence, recycling and recycled materials should perhaps be an interesting subject for battery producers. Still, except Northvolt, which according to their website, promises 50% recycled material by 2030 (Northvolt, n.d.-b), few battery producers seem to be proactively engaged in recycling and recycled materials. Battery Expert C states that it seems like battery producers are waiting for regulations before they follow mandatory targets for recycled materials. This could indicate that the demand for recycled content is not currently a pressing subject and will depend on regulations. A minor document analysis of feedbacks on the proposed battery regulations has been performed to get a better understanding of market viewpoints.

Referring to Table 3 in section 2.5.1.1, the feedback from companies in the European battery industry generally hints at an opposing stance toward the mandatory levels proposed by the European Commission. Battery producers Northvolt, Norsk Hydro and Equinor, Saft, and Freyr Batteries are all opposed to setting fixed targets. Nissan is also against these specific targets, and similarly, Eurometaux (representing the European metals industry) and EUROBAT (the association of European Automotive and Industrial Battery Manufacturers) are likewise against mandatory targets. Despite believing in producing battery cells with high levels of recycled raw materials, Northvolt opposes the introduction of mandatory levels of recycled content:

> *As the battery market is growing exponentially the production volumes are challenging to predict, hence the volumes of collected and recovered waste batteries are even harder to foresee. Setting mandatory levels of recycled content risks slowing market development if recovered volumes are insufficient to meet the demand in Europe. - Northvolt (2021)*

Alternatively, they propose that target levels can be easily updated and that the timeline for such thresholds are not introduced until the battery market reaches a steady state (Northvolt, 2021). Norsk Hydro shares similar beliefs:

> *Targets must be based on the certainty that enough secondary materials will be available in Europe to avoid market distortions and must include sufficient and credible verification of imported batteries. Recycled content is very sector-specific and it needs to be supported by a mature market. - Norsk Hydro (2021)*

Hence, both Norsk Hydro and Northvolt fear that market developments can be impeded by regulations. However, as commented by BMW Group, there is a revision clause in the proposed regulation so that targets potentially can be amended based on the market situation (BMW Group, 2021). Freyr believes that introducing mandatory levels of recycled materials in new batteries may result in an impediment to the producers' ability to meet market demand for batteries in terms of the input materials' quality (FREYR AS, 2021). The battery producer Saft prefers voluntary initiatives to increase the recycled content. The rationale for this is to avoid setting constraints with a 10 and 15-years horizon in an industry experiencing accelerated transformations (Saft, 2021).

> *Whilst the premises behind the setting of such an obligation are readily understandable, the benefit of requiring that recycled material which currently find their way into several industries should be purchased to feed the battery industry is highly questionable. Furthermore, the Commission is pursuing competing goals, an increase of recycled content in batteries on the one hand, and a longer battery first life, preferably followed by a second life on the other hand. These are structurally incompatible and should not be pursued concurrently for sound policy making. - Saft (2021)*

Despite strong opposition to mandatory targets of recycled content in battery production, there are also companies that welcome these regulations. Recyclers Fortum and Umicore and the BMW group are positive towards the mandatory targets in their feedbacks to the proposed battery regulations. BMW Group states that it is important that also imported batteries have to meet the requirements as set out in the new battery regulation to maintain fair competition and a common level playing field (BMW Group, 2021). Other than that, they welcome the targets.

> *The use of recycled materials in the production of new batteries will be an efficient and sustainable way to decrease the CO2-footprint in the life cycle of batteries significantly. Thus, we consider the recycled content requirements as set out in the new battery regulation as required and achievable. - BMW Group (2021)*

BMW Group also comments that for the end-of-life treatment, they aim to achieve high recyclability targets independent of the battery design. Additionally, they are exploring how cross-industry secondary material flows can support a circular economy even further with a special focus on consumer electronics (BMW Group, 2021). Similar to BMW, Fortum welcomes the targets:

> *This is a key measure to increase the demand for recycled raw materials and speed up investments in battery recycling. We urge the EU to also consider setting targets for the uptake of recycled raw materials in the manufacturing of portable Li-Ion batteries. - Fortum (2021a)*

However, like many of the other companies, they too emphasize the importance of ensuring that all batteries entering the EU meet the new, high sustainability standards set by the new regulation (Fortum, 2021a). One could argue that Fortum has a bias being a recycler, however, they are also one of Europe's largest energy producers and therefore could have interests in repurposing as well. Umicore, on the other hand, is a pure recycler. They express fears regarding the quality of recycling and downgrading of materials if mandatory targets are not enforced.

> *For metals that are mainly used in one or a few high-end applications, recycling "leakage" to lower-end applications is a real risk. For Co, Ni (with the right quality) and Li, batteries are the main application, and for these metals, quality recycling is not guaranteed. Consequently, it is recommended to create the right boundary conditions to avoid leakage of these critical materials towards other applications through "downcycling". Recycled content is a way to guarantee quality recycling. - Umicore (2021)*

Regulations of recycled content is a way to guarantee the quality of recycling as the recycled material will have to be battery grade for battery producers to comply with the legislative framework. Not setting regulatory targets for recycled content could lead to a lot of the recycled materials being downcycled (Umicore, 2021). This is a central argument for ensuring a circular economy where the quality of the material is maintained instead of being downgraded. If regulations are not in place, recyclers might end up using simpler processes to sell the recycled materials for a more significant profit to lower-end applications as the same material quality is not required (Umicore, 2021). To help with the regulations, Umicore state that it will be crucial that each battery producer contributes a fair share in the recycling costs to protect the competitive position of European battery manufacturers.

Regarding the proposed battery regulations, Researcher B questions: “How can one control that the producers use 20% recycled materials?”. Traceability is critical to ensure that the manufacturers comply with the given regulations. Battery producer Saft states in their response to the proposed battery regulations that “the impossibility to distinguish recycled material from virgin material renders the goal of accurately tracking the recycled content of finished products, especially those manufactured beyond the EU borders, an elusive proposition at best” (Saft, 2021). Nonetheless, in one of the interviews, Battery Expert C claims that a system of traceability is under development. Blockchain technologies can enable circular economic principles and be useful as digital ledgers to track EVBs provenance (Bonsu, 2020). Whether this or something similar will be the solution to problems regarding tracking recycled and virgin content in a battery remains to be seen.

In terms of the environmental aspects, one of the respondents explains that customers may have a somewhat higher willingness to pay for sustainable products that have a lower carbon footprint. Another respondent, one of the battery producers, was asked if they have (potential) customers or other stakeholders that specifically request or demand the use of recycled materials in their battery production. In response to this, the respondent said that:

> *Everyone knows that the regulations are coming. Those who make cathode materials will follow the regulations and figure out how to handle them. The battery producer will demand that the cathode material producer follows regulations, while the customers of the battery producers will demand the same from the battery producer.*

The respondent added that requirements include documentation, recycled content, CO2 emissions, and so on. Hence, based on the response, it seems like regulations will be the important element to ensure the environmental production of batteries. The same battery producer was asked what the most important factors regarding sustainability for their battery production are:

> *An important argument for us is hydro power, which is green energy. Even if electric vehicles are more environmentally friendly than traditional vehicles, the batteries should be produced renewably to reduce the CO2 footprint even further for the entire vehicle.*

This response could perhaps illustrate that the demand for recycled content is less pressing than the need to produce lithium-ion batteries with renewable electricity. This is in line with Costa et al. (2021), stating that the electricity mix that is used to power the battery factory is a central parameter for the impact of battery manufacturing on climate change, whereas the effect of mining and refining of materials on the carbon footprint is relatively small. This insinuates that battery production with renewable energy is environmentally preferable compared to using recycled materials. Yet, the study of Tran et al. (2018) shows considerable net benefit in terms of metal and mineral savings. Therefore, Tran et al. (2018) concluded that the implementation of resource management practices based on the circular economy is environmentally beneficial from a resource perspective.

Based on the feedback from battery stakeholders on the proposed regulations, battery producers seem to be most opposed to the mandatory requirements of recycled cobalt, nickel and lithium. Conversely, the most supportive of the regulations are the recyclers who naturally see the proposed targets as an assurance of future business. Despite some opposition to mandatory targets from these various industry stakeholders, the mandatory targets will indeed have a significant effect on the end-of-life market if we are to believe the respondents of this study. Battery Expert A claims that regulations are necessary since “with regulations people start to care”, meaning it could spike the necessary push towards a circular economy. It is therefore believed that the introduction of mandatory targets will have a serious effect on the market, and it is considered an essential driver of the demand for recycled materials in battery production. Table 8 showcases the main findings from the interviews related to regulations on recycled content and corresponding literature findings.

Table 8: Summary of the findings regarding the proposed battery regulations. Own elaboration with categorisation based on the most central findings from the interviews and associated literature findings.

Theme	Qualitative findings	Literature findings
Recycling	- Batteries with more expensive raw materials are more profitable for recycling and could perhaps be viable without a push from regulations.	- High cobalt content leads to high profitability (Mossali et al., 2020). The electrode materials with high-value materials is vital for the profitability of recycling (Thies et al., 2018).
Recycled content	- Demanding a share of recycled content will have a significant influence on battery production. - For batteries with cheap materials, mandatory targets from regulations are necessary to enable viability. - EU regulations could have an unfortunate effect where Asian companies gain an advantage.	- The EU's focus on closing resource cycles will create a boost for the recycling industry (Calisto Friant et al., 2021). Using recycled materials in new batteries will efficiently decrease the CO2 footprint of batteries (BMW Group, 2021). - For low-cost batteries, recycling is economically unattractive, so legal requirements are important (Doose et al., 2021).
Traceability	- Traceability is vital to ensure the origin of materials, and a system is needed to ensure that a battery producer actually utilises recycled content, thus that regulations are followed.	- It is impossible to distinguish recycled material from virgin material (Saft, 2021). Blockchain technologies can enable circular economic principles and be useful as digital ledgers to track EVBs provenance (Bonsu, 2020).

The presence of mandatory levels of recycled content in battery production is likely to significantly affect the market. Introducing the targets will drive the recycled material demand as electric vehicle OEMs will be obligated to procure batteries produced with a certain amount of recycled materials. The respondents agree that the effect such mandatory targets will have is significant. Yet, there is some fundamental opposition to introducing mandatory levels as communicated by Material Expert B and Battery Expert D, especially related to concerns over Chinese dominance. Similarly, many of the European stakeholders have communicated opposition to the mandatory levels in their feedback to the proposed battery regulations. However, the transition to a closed-loop value chain seems to be generally appreciated by both the industry and the respondents. Since the majority of the respondents believe mandatory levels of recycled material will greatly affect the market, it is identified as an essential driver for the demand for recycled battery materials.

4.1.2 Raw material supply

Global supply chain disruptions are anticipated to become increasingly frequent and severe in the future, particularly given the looming threat of climate change (Althaf & Babbitt, 2020). An extensive rationale for recycling is, therefore, that it creates a resilient supply of raw materials. The demand for raw materials for battery production is believed to increase rapidly as a result of the electrification of the automotive industry and other industries. This might lead to a market shortage for materials, as demand outgrows supply. However, the opinions on his topic are divided. Researcher B fears that the EU’s aggressive electrification and lack of battery material production will lead to a shortage, especially for lithium and cobalt. Material Expert A, on the other hand, is confident that the increased demand for materials will be met by new investments in mining and material production as the price rises. Hence, the expert does not believe that the delivery of cobalt and nickel will become a problem.

Evidently, there are opposing beliefs amongst the respondents regarding whether there will be supply challenges. The same uncertainty can be seen in the literature. Some scholars see a potential supply risk for lithium and cobalt (Olivetti et al., 2017; Yan et al., 2020). There are also supply concerns regarding nickel and cobalt (Crooks, 2020; Pelegov & Pontes, 2018; Turcheniuk et al., 2018), especially cobalt (Baars et al., 2021; Gourley et al., 2020; van den Brink et al., 2020). However, there are different views as Olivetti et al. (2017) see no detectable supply concerns of nickel and manganese, and Y. Ding et al. (2019) see no demand and supply risks of lithium and cobalt in the short term. Battery Expert A states that “some say that there will be a shortage and some say that there will not be a shortage.” The expert goes on to say that it will depend on the battery directive. Such a statement demonstrates the significance regulations will have on the market.

According to Researcher B, there is an issue regarding the rapid expansion of cobalt production. Due to the complexity of the mining process, it might take over a decade to establish a mine and efficiently produce cobalt. As a consequence, the cobalt industry might not be able to expand quickly enough to meet the growing demand for battery materials. Opening new mines could be a smart move to meet future demand, yet companies must be careful since they run the risk of introducing mining initiatives for metals that will no longer be in demand. Following this line of logic, cobalt is a risky metal to invest in with respect to mining expansion since the material is dominated by LIB applications, and the trend is to use less cobalt in LIBs. Hence, the risk associated with investing in cobalt mining and extraction activities could increase the demand for recycled materials.

Researcher B explains that when cobalt is produced, it is a by-product of copper and nickel refining. Therefore, the process is not optimised for cobalt, and approximately 50% of the material is lost during the refining process. On the other hand, when LIBs are recycled, roughly 90% of the cobalt is retrieved, which means it can be recycled several times with minimal material loss. If battery-grade quality is achieved, it can be used for multiple life cycles in LIBs. Because of the inefficient production method and potential shortage in the future, cobalt has the highest need and potential for recycling. Yet, according to Abdelbaky et al. (2020), the market is shifting toward higher energy density technologies, with the new EVB generations trending toward minimal cobalt content. This could result in an increase in nickel demand which shifts the burden onto nickel (Baars et al., 2021). In order to avoid the latter, technological developments should be combined with an efficient recycling system, according to Baars et al. (2021).

As both seen in the literature review and the data collection, recycling is feasible if the battery electrodes contain highly valued metals such as cobalt and nickel. This is because there could be a sufficient gap between the procurement and recycling cost, especially if there will be a tight supply of nickel and cobalt in the 2020s or early 2030s, which some scholars and business researchers predict (Crooks, 2020; Mayyas et al., 2019). A higher price of raw materials driven by growing consumption and tighter virgin supply means that recycling will be more profitable, but it also means that other cheaper materials will get more attention. Using more abundant and cheaper materials in battery production subsequently leads to recycling becoming less profitable, creating a dilemma between the forward and reverse supply chain.

4.1.2.1 Securing supply

As the demand for battery materials increases, the availability might decrease. This is true if the supplier market is unable to keep up with the demand. Battery Expert D believes we will see increased competition among suppliers. This incentivises manufacturing companies to secure their supply, either by long-term contracts, a diverse selection of suppliers or by controlling a more significant portion of the value chain. Material Expert B stated that in order to protect own interest, a common strategy for companies is to have multiple suppliers and for the suppliers to have multiple customers. This reduces the upstream risk of depending on few suppliers. Material Expert B also states that it is vital to establish an industry ecosystem that can support a battery cell factory. “You have to establish an industry around the battery cell factory,” says the expert while referring to anode and cathode material production. Recycling of spent batteries could become a part of such an ecosystem securing the supply of secondary materials. The expert concludes that “it is reasonable to recycle. It enables having a bigger share of the value chain in geographical proximity”. In light of the large quantities needed in the future, recycling materials will increasingly become essential to reduce the EU’s dependency on third-country markets.

A benefit of local recycling is that it is less affected by the market as it could provide an in-house source or at least a domestic source of critical materials. Therefore, it mitigates the risk of a price increase or market shortage of battery materials. In the case of raw material price fluctuations, many firms end up with reactive strategies to material price shocks, which are less optimal than proactive strategies such as the circularity strategies recycling, remanufacturing and reuse, and may also exacerbate the situation, driving prices higher and for a more extended period of time (Gaustad et al., 2018). Additionally, recovering the materials in LIBs decreases the need for new raw materials and improves energy security by reducing imports. Reducing imports of virgin raw material is a compelling argument, mainly since many of these materials are transported around the world, with extraction and refining often being located in different geographical locations. For instance, over half of the cobalt in use is from Congo, whereas Australia and Chile control around 80% of lithium production (Chen et al., 2019). However, for the argument of reduced imports to be valid, the recycling process must occur at a local level. As mentioned by Researcher B, one European recycler sends their slag to Australia for lithium refining. If parts of the battery must be transported across the globe for further recovery of materials, some of the environmental rationales for recycling is lost. Such export should be avoided to secure an independent local secondary supply chain without the reliance of external participants.

Material Expert B talks about anode production in regard to securing supply. Anode production is first and foremost happening in China, with them controlling around 70% of graphite production (Chen et al., 2019). “It is important to commence production outside of China, to avoid being dependant on it.” The expert adds that there is nothing wrong with the production in China but that it is a matter of reducing supply risks. Europe and its industry want to be able to control the supply to a greater extent to achieve a complete value chain, claims the expert. Issues related to the geographically concentrated supply and the dominance of Chinese participants were also expressed by Researcher B. The respondent said that one of the problems with the cobalt mines in Congo is that a significant share is owned by Chinese companies, which gives them control over the supply. If China experience cobalt supply deficits, their cobalt production and refining will likely be prioritised for domestic battery manufacturers (Gourley et al., 2020). In such a scenario, European battery producers would have to obtain cobalt from elsewhere, with recycling possibly combating supply concerns. In relation to this, Malinauskaite et al. (2021) state that recovering materials through recycling can alleviate societal concerns as it can help reduce dependency on foreign primary resources.

One respondent states that there will be battery production in the EU because "customers want it, and the European Commission wants more production within Europe". But with large-scale battery production in Europe, raw materials will have to be supplied from other parts of the world as there is little domestic supply in Europe, and recycling will not provide a sufficient supply of materials until a steady-state market is reached. Based on long battery lifetimes and multiple end uses, recycling is unlikely to provide significant short-term supply (Olivetti et al., 2017). As per Gourley et al. (2020), a more effective and lasting solution than recycling for the sustainable future of LIBs is the development of cobalt-free cathode materials. This argument seems to be reflected in recent business trends as more companies are pushing towards more widespread deployment of LFP batteries, e.g., recent plans of utilising LFP batteries by Volkswagen and Tesla (Ribeiro, 2021; C. Xu et al., 2020) and the influx of Chinese vehicles (Valle, 2021). In fact, the use of less valuable metals was mentioned by one of the battery producers as they aim to achieve material cost reductions. Moreover, BMW Group comments in their feedback to the proposed battery regulations that they see "great opportunity in accelerating circular economy if the quota of critical raw materials sinks while the market of recycled materials takes up" (BMW Group, 2021). Hence, a combination of more diverse battery chemistries and LIB recycling is likely to be two critical factors securing a steady supply of raw materials.

Table 9: Summary of the findings regarding raw material supply.

Theme	Qualitative findings	Literature findings
Supply of battery materials	- Aggressive electrification and lack of battery material production can lead to a shortage, especially for lithium and cobalt. Still, new	- Some scholars see a potential supply risk for lithium and cobalt (Olivetti et al., 2017; Yan et al., 2020). There are

	investments in mining and material production as price rises can ensure the safe delivery of cobalt and nickel. - It takes many years to establish a new cobalt mine. Therefore, the supply might lag behind a rapidly growing demand.	also supply concerns regarding nickel and cobalt (Crooks, 2020; Pelegov & Pontes, 2018; Turcheniuk et al., 2018)
Other materials	- Cheaper materials are attractive alternatives for battery manufacturers to achieve cost reductions and to avoid dependence on high-value materials.	- There are prospects of broader use of LFPs in EVs, e.g., Tesla and Volkswagen will equip more vehicles with LFP (Ribeiro, 2021; C. Xu et al., 2020).
Decrease import	- Local supply of materials offers an environmental rationale for recycling. However, exporting the slag from the recycling process across the globe would limit this rationale. - The supply of materials from within Europe to increase resilience might create a demand for recycled materials.	- Recycling eases the pressure on resources and the environmental burden caused by LIBs (Liu et al., 2021). - Recycling materials can reduce dependency on foreign primary resources, with additional social impacts, such as reducing child labour and conflicts (Malinauskaite et al., 2021).

The trends observed in this section could significantly affect the demand for recycled battery materials. The potential of a material shortage will increase the rationale for recycling to fill the gaps in the market. Whether supply gaps and shortages occur is hard to estimate and depends on market and chemistry developments. A cramped supply of critical materials is likely to drive the demand for recycled material significantly. Locally sourced materials through recycling provide both an environmental rationale and improved supply resilience. As a consequence of the increased demand for materials and a slow response time in raw material production, the pressure on recycling of spent EVBs could be considerable in the near future.

4.1.3 Lithium-ion battery value

Economic factors have significant importance as companies are always seeking to achieve profits. This is illustrated by what Battery Expert A expresses when talking about lithium. “Lithium is currently too cheap to mine new compared to recycling.” The expert continues to say that “if it is cheaper to mine new, people will decide to mine new.” This statement demonstrates that economics could show the pathway for the demand for recycled battery materials. Material Expert B states that the way batteries are built today, recycling of the materials is viable due to the economic significance of the materials. This is similar to what Steward et al. (2019) found with all recycling methods being economical with current raw material prices and battery composition, granted a high volume.

Today you have to pay a gate fee to recycle, as mentioned by Battery Expert B and C. Battery Expert B thinks that gate fees will disappear, which will make recycling more viable. Similarly, the Repurposer believes that the cost and gate fee of recycling will gradually go from being a liability to becoming an asset. Battery Expert C think that batteries will have diversified gate fees. Some batteries have less value in recycling, such as LFP batteries. NMC, on the other hand, has a higher value due to its cell chemistry. Batteries with a high content of cobalt and nickel have an advantage, adds the expert. When asked about the potential impact of negative gate fees, Battery Expert C says that it will have an impact without a doubt. The expert adds that the gate fee is not the only value to consider. The total value includes carbon footprint, raw material use, and the advantages of repurposing/reuse/recycling, which will all need to be holistically assessed. Battery Expert C adds that not all gate fees will necessarily become negative as the content defines the value of each distinct battery. The respondent goes on to say that the gate fee for LFP is 3-4-5 times higher than for NMC.

> *Chinese car producers often use LFP, which are amazing batteries that are good to repurpose but awful when it comes to recycling. - Battery Expert C*

Battery Expert C therefore strongly believes in the repurposing of LFP batteries to cover the cost for car producers. “LFP will continue to have a high gate fee and therefore repurposing will have to be the value-adding factor after first life”, according to the expert. Battery Expert D has a similar line of thought, saying that LFP will be cheaper to produce but contain a lower residual value which will imply a lower value of recycling.

> *One can make batteries with a high share of nickel. These will have a lot of value in end-of-life. These batteries cost more to produce with virgin materials but will have a higher residual value. LFP will be cheaper to produce but will have a lower residual value and thus a lower recycling value. - Battery Expert D*

Therefore, it makes sense to delay the recycling of LFP batteries and higher gate fee batteries to prolong the economic value of these batteries. The data collection and literature (Mossali et al., 2020; Thies et al., 2018) clearly concur that recycling of NMC batteries is more viable compared to recycling of LFP batteries. Moreover, the recycling of NMC batteries with high cobalt and nickel content is more profitable compared to recycling NMC batteries with low cobalt and nickel content. In the end, the question of recycling lithium-ion batteries is an economic one, concludes Battery Expert B. Economic rationality and competitiveness needs to be sufficiently secured from the viewpoint of consumers, to whom the price will be downstreamed.

However, there are challenges that can complicate the economic potential of recycling. Battery Expert A thinks the most prominent issue regarding recycling is the lack of labelling of cells. “The recycler has no clue what chemistry is inside”. The expert adds that NMC, which is the most common chemistry, has a diverse share of materials used in the electrodes. Depending on what the battery consists of, one can create an optimal recycling process. But when you do not know the battery chemistry, you recycle different batteries together in a non-optimised process. This could affect the viability of recycling and, therefore, ultimately hinder the demand for recycled materials. Nonetheless, labelling is proposed in the new EU regulations and will be introduced as already mentioned in section 2.5.1.1. This could take care of the problem, but if regulations are introduced in 2027, labelled batteries will not return on a large scale from their first life until around 2040.

Table 10: Summary of the findings regarding the EVB value.

Theme	Qualitative findings	Literature findings
Virgin versus recycled material	- If mining is cheaper, mining will prevail over recycling. This is particularly relevant for lithium, which is hard to recover.	- Recycling lithium is currently not viable as it is hard to recover and costly (Bonsu, 2020). Recycled lithium is much more costly than extracted lithium (Reid & Julve, 2016, p. 26).

Gate fee development	- Cell chemistry is an important driver of the viability of recycling since it dictates the recycling fee. - Batteries with a high nickel and cobalt content are expected to have a decreasing gate fee, which could even become negative. The gate fee for low-value batteries such as LFP is much higher than NMC, and the gate fee of LFP is not expected to decrease.	- Some cell chemistries like NMC contain a higher share of valuable metals compared to other cell chemistries like LFP (Thies et al., 2018), making recycling of NMC more profitable compared to LFP (Mossali et al., 2020). - Cobalt-rich batteries mandate a lower gate fee, whereas LFP mandates a higher recycling fee (Baltac & Slater, 2019, p. 46).

From an economist's perspective, the demand for recycled materials will only be present if it is able to compete with virgin materials in terms of cost. As Battery Expert A said: "We live in a capitalist's world, so if mining is cheaper, we will buy the cheapest." An important conclusion from this section is to address various battery technologies individually regarding their end-of-life viability in recycling and second-life. For lithium-ion batteries containing a high amount of valuable material, particularly cobalt, the economic driver will put greater weight on recycling, increasing the demand as it could offer a cheaper supply of raw materials than extracting virgin materials. On the other hand, technologies consisting of less expensive materials will have a lower value at the end of their life, rendering them less attractive for recycling. Nonetheless, it can be concluded from this section that the economic factor will have a significant influence on the demand for recycled battery materials.

4.1.4 Market and technological development

The factor of time, encompassing market and technological developments, has become a subject in almost every interview. The exact future market of recycling is heavily dependent on the scale of the electric vehicle expansion, raw material market, future technologies of LIBs, and policies. One of the respondents representing a battery producer stated that they are going to begin big scale battery production in a few years, which implies that the market for end-of-life must be considered in the late 2030s. This presents a challenge for them as the market could be very different in the future. For instance, alternative battery technologies that are not lithium-ions have been identified in the literature review and some of the interviews, such as lithium-sulphur. These could become dominant in the 2030s, which means that some of the materials from existing batteries could become irrelevant for new batteries. Worst case, some materials recovered in recycling facilities could end up being in surplus if the transitions to new technologies happen abruptly.

One of the respondents points out that a challenge with end-of-life LIBs is time. “From a battery is produced to its repurposing/recycling, it takes a lot of time which can influence the will to invest.” The same respondent later adds that battery producers will have to decide if they want to outsource recycling or do it themselves but that it is too early to make precise plans for recycling for many battery producers. This was supported when interviewing a battery producer as their focus was on more urgent matters, such as initiating production. When asked about plans for repurposing and recycling, the response from the battery producer was that this is far into the future and that one will have to look into the market 15 years on from now. Therefore, as of today, their focus in regard to recycling is on internal waste in the production facility.

In addition to the development of battery technology and manufacturing processes regarding the LIB value chain, the EV market and social behaviours are transforming. Fewer people see a necessity in owning a car due to sharing platforms and other transportation systems (Pedersen, 2020). Correspondingly, Material Expert A strongly believes in a shift towards shared mobility and different consumer behaviour where fewer people own vehicles or even get their driver’s license. This was also used as an argument as to why the material expert did not believe in supply gaps or shortages of materials for EVB production. Shared mobility and fewer car owners will contribute to fewer vehicles on the market, and thus lower demand for battery materials, stated Material Expert A. At the same time, cars would likely be utilised more efficiently if used in car-sharing platforms, which could lead to a shorter lifespan of the vehicles.

Kamran et al. (2021) find that a widespread behavioural shift from conventional vehicle ownership to shared mobility could drive the demand for virgin battery metals into negative territory earlier than what would otherwise be the case. Material Expert A also argues that the Covid-19 pandemic has facilitated the transition towards digitalisation, hence there will be a less significant need for physical transport, e.g., digital consultation with doctors and working digitally from home. Consequently, the European car fleet could be somewhat lower in the future, thus lower demand for EVBs and battery materials if the beliefs of Material Expert A and Kamran et al. (2021) hold true.

One of the technological challenges regarding both repurposing and recycling is to establish an efficient, automated disassembly system, according to Researcher A. There are currently concerns related to safety when disassembling batteries, concurs Researcher A and Sommerville et al. (2021). Researcher A comments that they use little machinery in China as a result of manual labour being cheap. In Europe, where manual labour is expensive, automation will be necessary to make disassembly safe and cost-effective, adds the respondent. Automation could prove instrumental in achieving a viable large scale recycling industry as it could allow higher recycling productivity and lower recycling fees (Baltac & Slater, 2019, p. 39). Researcher B believes that recycling is dependent on economies of scale to accelerate. Hence when there is a higher volume of returning batteries, the viability of recycling will further improve as it will enable economies of scale for recyclers.

Demand for recycled materials from EV manufacturers is essential. The respondent representing a battery recycler claimed to have had multiple meetings with car manufacturers showing a big interest in recycling. One of the things the car manufacturers were interested in knowing was calculations on the benefit of recycling. “These car manufacturers see recycled materials as a competitive edge,” says the respondent. Perhaps the interest from EV manufacturers could imply that they are eager to increase the focus on recycling and usage of recycled materials. If that is the case, it could send an important signal in the market and subsequently increase the demand for recycled materials.

Table 11: Summary of the findings regarding the market and technological development of EVBs.

Theme	Qualitative findings	Literature findings
Future EVB market	- Hard to precisely predict how the market develops. This can affect stakeholders’ will to invest. - New battery technologies can lead to the recycling of certain materials losing significance.	- As the EU want to be more self-sufficient with EVBs, the value of the European battery market might reach 250 billion euros (Krukowska et al., 2021).
Car-sharing and digitalisation	- Car-sharing services could contribute to a lower than expected vehicle fleet in the future. A behavioural shift with home offices and more digital interactions could reinforce this.	- Transportation services have the potential to make much more efficient use of individual vehicles (Kamran et al., 2021), hence less material throughput (Bocken et al., 2014, p. 50).

Economies of scale	- Recycling could be dependent on economies of scale to accelerate. Hence when there is a higher volume of returning batteries, the viability of recycling will further improve.	- The total amount of returned batteries is an essential factor (Li et al., 2018). Recycling is economical with current raw material prices and battery composition if the volume is high (Steward et al., 2019).
Automation	- Automation might be a vital step in achieving economies of scale to make recycling more viable.	- Automation could allow higher recycling productivity and lower recycling fees (Baltac & Slater, 2019, p. 39). It reduces processing costs and safety concerns (Or et al., 2020).

There is a fair amount of uncertainty regarding the future of lithium-ion batteries. Market trends such as car-sharing and increased digitalisation curtailing the need for transportation could reduce the pressure on resources and production. Moreover, the rapid advancement of technology, potential diversification of chemistries, and the uncertain lifespan of EVBs are among many uncertainties that can affect future end-of-life strategies. Automation and economies of scale are important elements for recycling to prosper. Because of these considerations, the development of market and technology has been identified as an important factor driving the demand for recycled battery materials.

4.1.5 Summary of drivers

Considering the three pillars of sustainability, economic drivers seem to be the most prevalent. Social and environmental factors, such as concerns regarding ethical sourcing of raw materials and reducing imports and virgin material extraction, are also mentioned in some of the interviews. Similar to these findings, Steward et al. (2019) believe environmental and social aspects could contribute to the need for more recycling of EOL batteries, but state that lower cost of recycled materials is expected to be the main driver for recycling. Hence, it seems like the EOL destination of spent EVBs is determined by economic rather than environmental or social criteria. As demonstrated in the literature, recovered battery materials could save the total cost of LIB production (Mayyas et al., 2019; L. Wang et al., 2020; Xiong et al., 2020). Yet, favourable economics may not be sufficient alone, and a regulatory driver may be necessary to develop and maintain a viable LIB recycling industry (Mayyas et al., 2019). This is similar to the above findings, where regulations have been identified as essential to provide an extra push for recycling EVBs directly after first life. The shift to specifying relevant metals for recycling will help recyclers operate their process in an economically feasible manner, with maximum recovery for these metals (Abdelbaky et al., 2020).

To summarise the main drivers behind the demand for recycled battery materials, an unordered list is presented in Figure 10. The list is mainly based on the information collected during the interviews in combination with literature findings. Note that the elements of the list are based on the authors' subjective interpretation of the data and literature collection. The drivers can be summarised as follows: Regulations of recycled content will significantly influence the end-of-life of LIBs; raw material supply gaps and supply shortages could further push towards recycling but also pushes towards the use of different materials; the value of the spent LIB dictates if it will be recycled directly; car-sharing and a decrease in vehicle fleet could lead to lower pressure on the supply of materials. The most important factors will be further broken down in the following subchapter to demonstrate how different variations of these and other drivers will push the agenda towards recycling directly and others towards repurposing.

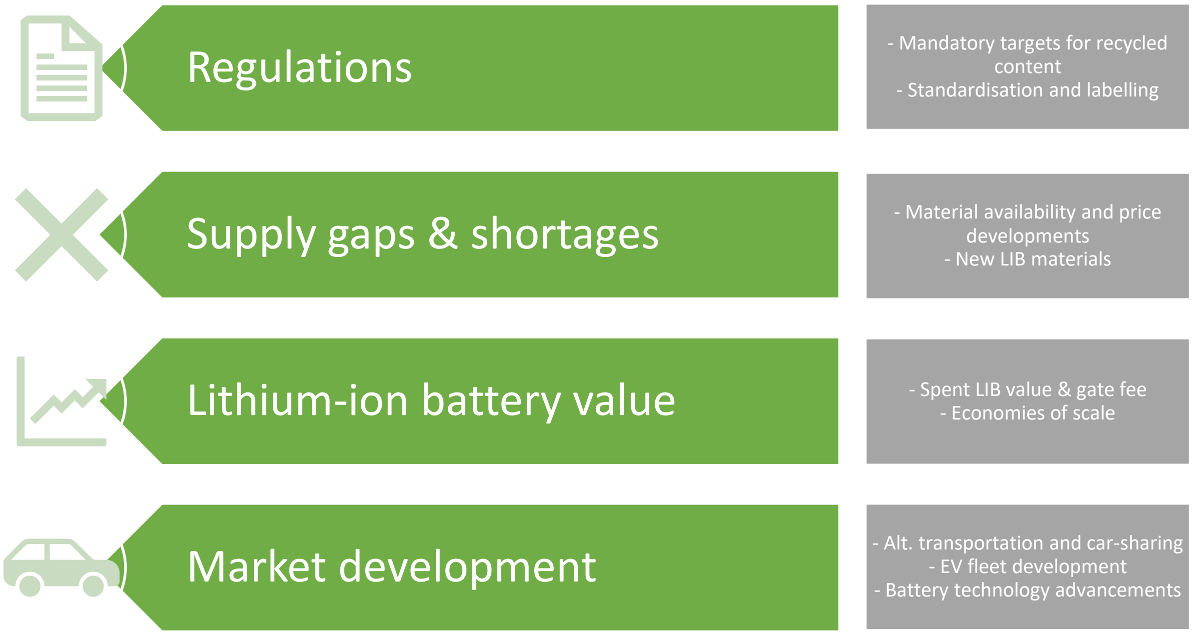

Figure 10: A list of the main drivers for the demand for recycling and recycled battery materials.

These drivers will most likely levitate the agenda towards recycling as they contribute to increasing the rationale for recovering battery materials through recycling. Mainly the implementation of regulations on recycled content and supply fears, including shortage of supply and price upsurges, are direct drivers for the demand for recycled battery materials. The economic viability of recycling, such as reduced or even negative gate fees, could soar the share of recycling relative to repurposing. More profitable recycling could subsequently lead to a higher demand for recycled materials. All in all, there seems to be a transition to large scale recycling which the aforementioned drivers support.

4.2 Market opportunities for second-life

The majority of the respondents believe in recycling as the dominant end-of-life strategy. This is in line with what Niese et al. (2020) expect, as they predict that only 20% of end-of-life LIBs will be repurposed. As demonstrated in the last subchapter and summarised in Figure 10, there are multiple drivers for recycled material in battery production. Equally, there are factors that will influence the viability of repurposing as well. Figure 11 illustrates how some of the identified drivers of demand for recycled materials in battery production could affect the end-of-life market.

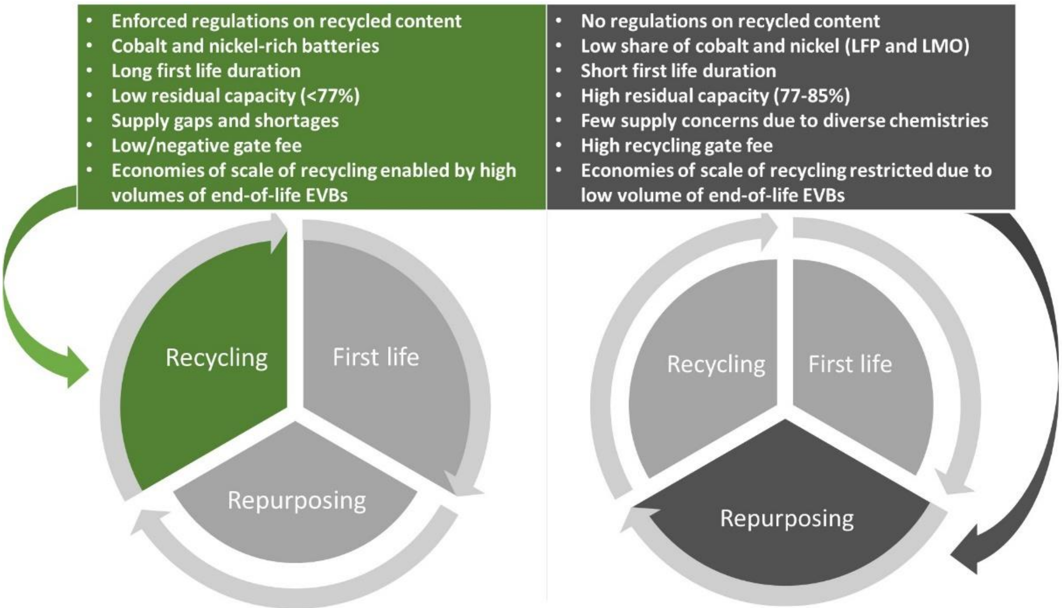

Figure 11: The left box in green shows the drivers for the demand for recycled materials. These drivers will push the agenda towards recycling, as seen in the simplified circular value chain to the left. The grey box to the right shows factors that would impede recycling, i.e., where repurposing is the more attractive EOL strategy.

The simplified circular value chain to the left shows how a long first life, in combination with various factors such as enforced regulations on recycled content, cobalt and nickel-rich cathodes, low residual capacity, raw material supply fears and challenges, decreased gate fees, and economies of scale, contribute to recycling being prioritised. Conversely, the simplified circular value chain to the right has a short first life duration. A shorter first life duration implies that the battery will not be as technologically inferior compared to a newly produced battery. Additionally, a postponement or even termination of regulations on recycled content, a higher share of battery types with low-value materials, high residual capacity, few supply concerns, higher gate fee, and limited economies of scale could impede recycling. In such a case, repurposing could become a dominant end-of-life strategy. Hence, there is a combination of regulatory, technological, environmental, economic, and societal factors that influences the potentials of repurposing and recycling.

The figure above illustrates opposing drivers affecting whether the batteries will go towards recycling or repurposing. These factors are based on the findings in the data collection as presented in the previous subchapter and are supported by the literature. For instance, the residual capacity deciding the ideal end-of-life strategy is based on findings from Wu et al. (2020), where spent batteries with less than 77% capacity will be recycled. Long first life duration is a factor pushing the agenda towards recycling due to technological advancements leading to spent batteries being outdated compared to purposed batteries, as commented by Researcher B. Battery Expert B thinks that as the gate fee decreases, second-life subsequently becomes more expensive due to competition from increased profitability of recycling. Hence, as illustrated in the figure, a low gate fee mandates recycling while a high gate fee mandates second-life.

Based on the findings, it seems evident that some factors will enable a market where the materials of EVBs are quickly recovered through recycling. A market where EVBs are recycled would be further supported by standardisation of battery components, modules and cells, and battery designs that render disassembly easy. As denoted by Researcher A, this would simultaneously render repurposing more viable since both repurposing and recycling shares this stage. Moreover, literature, e.g. Alamerew and Brissaud (2020), and respondents Researcher A and Battery Expert A concur that access to the usage history of the battery would further enable repurposing. Cooperation with vehicle OEMs can give repurposers a competitive advantage as they have access to the BMS of spent batteries, says Battery Expert A. Additionally, the feasibility of second-life will depend on numerous factors. According to the literature, the value of second-life batteries is determined by battery design, their condition after their first life, the intended second-life use for the battery and the cost/value of recycling (Costa et al., 2021).

Xu et al. (2021) state that going directly to recycling is a wasteful way as the remaining capacity (between 80-60%) is not exploited. Most of the respondents of this study share a similar belief. Still, there is a disagreement on whether second-life is fully viable in practice, especially considering the economic potential of repurposing. According to Material Expert B, the price difference throughout the day (and night) drives the demand for batteries to store electricity. This price difference will only grow, claims the expert, and this will be the most crucial driver for batteries. An important note regarding this is that the power price is different in different regions. As mentioned by Energy Analyst and Battery Expert A, the power price in Norway is relatively low compared to some other European markets, and this is a challenge for the profitability of storage, especially if the price remains at a stable low level. Another issue expressed by Battery Expert A is that a second-life battery is more unreliable than a new one, and if the battery does not work, you have to pay a lot of fees. “I am pretty sure that power companies wouldn’t like the idea of used batteries,” says the expert, primarily referring to critical applications.

In general, the economic prospects of storage are not very bright (Hiesl et al., 2020). Most studies calling for additional storage capacities put the focus on the technical point of view, neglecting the economic performance (Hiesl et al., 2020). Similar concerns have been noted by Zink and Geyer (2017), claiming that proponents of the circular economy have tended to look at the world purely as an engineering system and have overlooked the economic part of the circular economy. Battery Expert A, which has done a substantial amount of research on battery electricity storage, supported this by saying that the research was focused on the technical side. The expert believes the economic prosperity of battery storage is rather slim and acknowledges that there are few proofs of economic viability.

Nevertheless, Battery Expert A sees potential for second-life to support the grid locally because batteries have a very short response time and are therefore suited for grid balancing and peak-shaving. Other feasible applications mentioned by respondents include using battery packs for fast EV charging or energy storage in cabins. Battery Expert A says that “if you have a rural EV charging station, then you can use cells in parallel. If one of them stops working, then it is not a big drama”. These are non-critical areas where the lower price of a repurposed battery might give second-life a competitive advantage over new batteries, says Battery Expert A. This demonstrates that the quality of a battery is not vital in every second-life application. Hence, Researcher B’s argument of outdated batteries will not always lead to it going directly to recycling as some might accept lower quality for their electricity storage needs, such as in cabins or rural EV charging infrastructure. Material Expert B also believes in the potential for second-life, claiming that China has already done it and “it has become mega-business" there. The respondent adds that it can be used for radio towers and other applications where you need a steady power connection. Additionally, Battery Expert A mentions economic cases if batteries can be added to maintain peak times instead of grid operators having to increase the grid capacity, which would be more extensive. This is in line with Harper et al. (2019), stating that energy storage is sought-after in areas where weak grids require reinforcement and Wu et al. (2020) asserting that energy storage could reduce grid infrastructure costs.

Figure 11 only presents outer points, with all factors stimulating either side. This is, however, rarely the case in real life, as these factors might behave either independently or in correlation, and they depend on a variety of aspects. The difficulty in dealing with the influencing factors is that they are dynamic (e.g., changing mix of battery types over time) and that they are interrelated (Thies et al., 2018). For instance, few supply concerns due to diverse EVB chemistries and a raw material market without shortages or price gaps could decrease the demand for recycled materials. At the same time, such a scenario would also mean that the gate fee does not decrease owing to a higher share of LFP batteries. This would reinforce the potential for repurposing as a way of getting value out of the battery before material recovery. On the other hand, the mandatory targets of recycled materials can lead to side effects. Battery Expert A argues that manufacturers might buy up more spent batteries to meet the demand for recycled materials, and the price will consequently increase. The unnatural rise in demand, and therefore the price for spent batteries, has a negative effect on the market for second-life. If the goal is to reduce the release of climate gases and utilise the resources efficiently, these regulations might miss the target completely by driving the materials out of use sooner than necessary. To quote Battery Expert A: "This does not make sense, as most of the batteries still are in good shape and usable in second-life applications."

In terms of market developments, one must acknowledge that the technological advancement of battery types could lead to recycling becoming less of a significant supply for these new types. If in 10-15 years, batteries no longer contain nickel and cobalt, recycling could lose its appeal, and this might pave the way for repurposing. Intentions of this were communicated in one of the interviews by one of the battery producers explaining that using cheaper materials is "good business" and would increase the appeal of repurposing. Adding to this, the profitability of batteries can increase as energy prices will rise. One of the respondents states that we are in a changing scenario. "When incentives disappear, and we move to renewables, which are more expensive than coal, then the energy prices will rise, and then batteries might be feasible economically.” For instance, if gas plants eventually are closed, the market becomes increasingly attractive for batteries as more capacity that can handle rapid demand changes will be needed.

There are market opportunities for second-life due to energy storage increasing in importance, and some spent EVBs being more appropriate for repurposing than recycling. In terms of market potential for second-life, some of the respondents in this study are optimistic. Material Expert B believes in second-life and says that it has considerable potential. Material Expert A, on the other hand, believes that most EVBs will be exploited in their first use, leaving few spent batteries with enough capacity for second-life. Battery Expert A is pretty sure that second-life will be an essential part of the future but is cautious when asserting just how important it will become. Despite some optimism regarding second-life, there are current challenges that can affect the potential of repurposing.

4.2.1 Regulations & Directives

As stated by Battery Expert B and C, as of today, the manufacturer of the battery is responsible for the EOL treatment, including the gate fee, even after second-life. This makes it difficult to repurpose batteries, as it requires tight cooperation between two parties. We have to see a change where those who repurpose batteries takes over the responsibility and have to pay the gate fee, comments Battery Expert C. Battery Expert B further explains that processes are underway to change the regulations so that the company responsible for repurposing is responsible for the disposal at EOL too. The BMW Group also addresses this topic as a response to the proposed regulation of EVBs: “The producer or importer of electric vehicle batteries cannot be held responsible for reuse of battery in a vehicle application by another economic operator and second-use products put on the market by independent operators.” If the requested adjustment of the regulations is implemented, it might catalyse the second-life market. It simplifies the procurement of spent EVBs as the manufacturer no longer remains responsible for the EOL disposal and will therefore be more willing to sell to a third-party battery repurposer.

According to Researcher A, second-life has potential for large-scale only if the disassembly and reassembly of the packs can be done efficiently. One of the main constraints of automation is the lack of information available about the spent batteries, the researcher says. Better labelling and standardisation are important steps to simplify the repurposing process. From a manufacturer’s perspective, however, there is little motivation to label the batteries, as they already know the details and composition of each model. Furthermore, standardisation is not desired because the uniqueness of batteries is often associated with the company’s competitiveness. Therefore, political incentives are crucial to make the battery market more transparent. In the interview with Battery Expert A, this argument is underlined as one of the main constraints regarding an effective, large-scale battery repurposing industry. In addition to the content and configuration of the batteries, the secrecy of BMS is also a challenge, as it contains information about the history and usage of LIBs. Access to the battery’s history enables repurposers to better calculate the remaining capacity and optimise the second-life battery pack. Both Researcher B and Battery Expert A say in two separate interviews that not having the proper insight or access to the BMS is a major issue regarding the potential for second-life. Without it, safety margins must be included to prevent the battery from over- or undercharging, resulting in less capacity available for use.

4.2.2 Storage market considerations

Another critical barrier for repurposing has been the continually improving economics and performance of new batteries. The price of new batteries falling while performance improves could effectively price out used batteries for some applications. Battery Expert A states that “new batteries get cheaper and cheaper. A new battery you buy today is cheaper than a five year old similar battery.” It is also suggested in the literature that costs decline more rapidly for LIBs produced for stationary applications (Ziegler & Trancik, 2021). This would strengthen the argument that new LIBs purposedly produced for stationary applications could approach the price of spent EVBs. Moreover, technological improvements mean that, in essence, a spent EVB of 70-80% capacity is equal to 50-60% capacity if compared to a new battery as capacity “increases” about 3% per year (Zhao et al., 2021). Hence, price developments and technological improvements present a challenge for second-life viability. At some point, however, the price and improvements will most likely stagnate. At this point, spent batteries might not be as outdated technologically and can therefore compete against first-use batteries. Battery Expert A believes that second-life will be far more feasible as the battery price stagnates.

The market for second-life will depend on the demand for energy storage. Hence, besides factors that drive the demand for recycled materials in battery production, the demand for electricity storage will dictate if and to what degree repurposing precedes recycling. Yet, one of the current problems is that almost all newly produced batteries are instantly procured by vehicle manufacturers, “leaving nothing for the electricity storage market”, states the Repurposer. In essence, this means that grid operators and those looking for a battery for stationary storage could be forced to acquire spent batteries to get a reliable supply. If the market for LIBs is absorbed by vehicle OEMs, some of the demand for battery storage would have to be supplied from elsewhere. If the energy storage market in the future is significant and the supply of storage technologies is restricted, spent EVBs would become very attractive.

The Energy Analyst believes that Europe will focus more and more on hydrogen. However, hydrogen is a long-term storage option and thus not in direct competition with batteries. Still, the argument of the analyst is that the European market above all needs long-term flexibility over days and weeks, and in such cases, batteries have limited value. Zerrahn et al. (2018) state that broadening the electricity sector to include flexible additional demand, for instance, related to heating, mobility or hydrogen production, could decrease the need for electrical storage such as batteries. Essentially, cost-efficient solutions optimally combine renewable capacity expansion, renewable curtailment, and electrical storage (Zerrahn et al., 2018). But in terms of environmental criteria, curtailing renewable energy is logically not preferred if we are to rapidly shift from fossil energy solutions. Hence, the grid becoming more and more renewable paves the way for a multitude of electricity storage solutions, and considering that LIBs are expected to become the most cost-competitive of these solutions (Schmidt et al., 2019), both purposed and repurposed batteries will likely prosper in the future.

A potential challenge regarding the potential for repurposing is the fear of cannibalisation. Niese et al. (2020) claim that fear of cannibalisation could mean that battery producers would want to avoid a market for repurposed batteries. The argument is that battery producers would want to avoid cannibalising sales of purposed batteries through repurposing. However, this was denied by one of the respondents representing a battery producer. The respondent commented that it is important to repurpose the batteries before they are recycled. When confronted with the possibility of cannibalisation, where battery repurposing could hinder sales of purposed batteries, the battery producer confidently stated that the fears of this are low. The respondent argued that the market for batteries is so significant and that new applications and markets will enable both purposed and repurposed batteries in the market and that these would not limit each other.

To summarise, the market opportunities for second-life will likely depend on the drivers of demand for recycled battery materials. With enforced regulations from 2030, battery producers will have to acquire recycled battery materials which means that many spent batteries will be prioritised for recycling. Still, there are opportunities for repurposing EVBs, especially if the battery is of type LFP or LMO (or LMO/NMC), for healthy batteries with decent residual capacity (above 77%), if technological advancements of new batteries do not render spent battery useless, and if the market for raw materials is not restricted. Moreover, the electrical storage market requirements will determine the demand for second-life. If battery production continues to be absorbed by EV OEMs, repurposed batteries will have to provide the necessary supply of LIBs in stationary energy applications.

4.3 End-of-life market

Based on the identified drivers of demand for recycled materials, as well as the observed challenges and benefits of second-life, the potential for repurposing and recycling will be discussed.

4.3.1 Market share

Many different opinions and predictions were revealed in the interviews regarding the share of recycling and repurposing of end-of-life EVBs. Researcher A thinks there is room for both. While Battery Expert B thinks that “a lot will go to recycling, but a lot could go to second-life as well”. Battery Expert C says that the demand for recycled battery materials will be significant in the future as more and more people demand recycled materials in their batteries. Battery Expert C believes that recycling will dominate in Europe for a while as a noticeable share of batteries will not come from end-of-life in the nearest future, instead, they will come from accidents, faults, repairs, and so on, making them unobtainable for repurposing. In Norway, where a decent share of end-of-life is appearing, it might be different and perhaps a greater potential for repurposing in the coming years, adds Battery Expert C.

Norway already has a considerable volume of batteries owing to an early expansion of electric vehicles, which creates an opportunity to establish large-scale recycling to take an early market position. In combination with the processing of materials and cell production, this could create a strengthened competitive position (Valstad et al., 2020). Thus, there might be pressure on recycling in Norway to create a grand recycling scheme. This is argued for in a 2020 report from the Confederation of Norwegian Enterprise regarding green electrical value chains (Valstad et al., 2020).

The rationale is that the significant volume of batteries in use in Norway can help create a large-scale recycling scheme and take early positions in the recycling business. Researcher B supports this rationale stating that second-life will have to be dropped to be able to get started with recycling as it will be dependent on economies of scale to accelerate. In fact, an obvious consequence of second-life is that recycling is delayed. Depending on the application, the battery, and its usage, the delay might range from a couple of years to 30 years (Casals et al., 2019), but typically 10 years (Akram & Abdul-Kader, 2021; Reid & Julve, 2016, p. 26). The dilemma of delaying recycling was pointed out by Researcher B:

> *A consequence of second-life is that the spent batteries are not available for recycling for another 10 years. To properly get started with recycling, second-life cannot dominate too much of the market. – Researcher B*

Ultimately, it is probably an economic issue whether a spent LIB is recycled directly or repurposed. An example of this is comparing LFP and NMC batteries. In about 10 years, we will start to see end-of-life LFP batteries owing to the current intake of Chinese cars in the Norwegian EV fleet. As LFP batteries are not considered profitable for recycling due to their cell chemistry consisting of less valuable materials, repurposing can play an essential role for these batteries, according to Battery Expert C. In contrast, NMC batteries will be more profitable to recycle directly after first-life, especially if they have high cobalt content. Regarding recycling of LFP, it could become more viable as researchers are looking for effective ways of retaining the cathode and anode in their original form to use as new batteries after thermal treatment (Forte et al., 2020). As pointed out by Melin (2019), this would require technological developments and effective value chains designed explicitly for LFPs. Such tailored value chains would conflict with what researchers are requesting in terms of flexible recycling facilities that can handle various LIB technologies (Mayyas et al., 2019).

While having an additional source of battery metals through recycling can be compelling for battery producers looking to secure supply sustainably, it will be critical that recycled materials are sufficiently cost-competitive with virgin materials for this path to gain scale. Raw materials account for 60-70% of LIB cells business, thus the cost impact from raw materials is drastic on the battery makers profit (Pillot, 2019). Using recycled content would therefore be more profitable for a battery producer if the value does not reach parity to the virgin material value. But the price for recycled content could increase as the competition of recycled materials among battery producer intensifies, claims Battery Expert D. Furthermore, the battery cost and commodity price correlation is much lower than the correlation between the battery cost and the production volume (Philippot et al., 2019). Also, the electricity mix that is used to power the battery factory is a key parameter for the impact of battery manufacturing on climate change, while the effect of mining and refining materials is comparatively small (Costa et al., 2021). These economic and environmental considerations could demonstrate that recycling is less of a pressing matter for battery producers in achieving green and profitable production.

4.3.2 Lifetime & end-of-life treatment

Formulating a universal battery lifetime model representing all commercial EVBs is infeasible since the market is shared among various OEMs employing different cell chemistries, cooling systems, and management systems (Abdelbaky et al., 2021). Material Expert B says, “there is a lot of uncertainty regarding how long a battery lasts”. Looking at previous research, the estimated expected lifespan of batteries seems to increase with time, from 5-7 years (Reid & Julve, 2016) and 9 years (Richa, Babbitt, & Gaustad, 2017), up to around 12-15 years (Akram & Abdul-Kader, 2021; Tadaros et al., 2020). One of the respondents representing a battery producer referred to a lifetime of 12 years in their first life. Based on the most recent research trends found in the literature and beliefs from the interviewees, an estimate of 12-15 years for the majority of presently produced EVBs seems probable.

10% of batteries do not come to recycling facilities due to reasons such as batteries being damaged, landfilled, or improperly collected and transported (Akram & Abdul-Kader, 2021). According to some of the respondents, one could expect that some EVs will be sold to Eastern Europe and other parts of the world, which could lead to more EVBs being lost. Additionally, some consumers might hold on to their vehicles for a long time as they accept lower capacity due to urban short distance needs as EVs with 60-80% residual battery capacity could still meet daily travel requirements in most cases (Hossain et al., 2019; C. Xu et al., 2020). Some EV owners might be reluctant to give away their batteries unless they are appropriately compensated for it. Consumers might think that if someone is making money off their products, they would need a monetary incentive to give it away. Batteries with positive value are often a part of a vehicle with high value. Hence the EV and EVB could be sold instead of recycled. The same goes for car dismantlers who would logically perform salvation based on economic incentives. Based on all of these considerations, it is assumed that 10-15% of batteries will not reach recycling facilities after 15 years.

Throughout this thesis, residual capacity and inherent raw material value have been identified as important factors when determining if a battery should be repurposed or not. Battery cells with a capacity higher than 80% could be reused or repurposed, in line with what L. Wang et al. (2020) believe in their model. Similarly, Baars et al. (2021) assume that batteries with a capacity below 80% are directly recycled, whereas batteries with a capacity between 85% and 80% are repurposed. The battery type will also dictate if the battery is repurposed or recycled.

Based on the findings from the data collection regarding battery types and the aforementioned literature findings regarding residual capacity, batteries that have below 80% residual capacity and a high content of nickel and cobalt will most likely be sent directly to recycling. Conversely, end-of-life batteries with low-value materials such as LFP and LMO could still be repurposed even with below 80% residual capacity due to their low recycling value. In practice, EVBs will likely reach EOL together with the car, hence not when it reaches 80% of original capacity, but when the owner chooses to wreck their vehicle (Martinez-Laserna et al., 2018). If this is the case, it could present a rationale for recycling directly as most batteries could have a residual capacity well below 80%.

In addition to residual capacity and the battery type, the lifetime will be an attributing factor. As stated by Material Expert A, EVs with batteries that are more than 14 years old are unlikely to be repurposed. This is because of technological development, rendering purpose-built batteries superior. The benefit of a long first life in vehicle applications is supported by the fact that it is the preferred way to maximise the cost-efficiency of the batteries (Martinez-Laserna et al., 2018).

4.3.3 Norwegian EOL battery market

Based on numbers from a report by the Norwegian Institute of Transport Economics, combined with previously discussed predictions, this section will present prognoses of how the composition of spent LIBs returning from first use in Norway will develop in the coming years. In order to estimate the distribution of the returning EVBs, several simplifications have been made. From the literature review, a trend where the lifetime of EVBs is increasing over time was identified, rendering it difficult to estimate the time of return precisely. For the sake of this prognosis, the expected lifetime of the batteries is set to a fixed 12-year time frame, and it is predicted that 85% will return at this point. These numbers are based on the arguments mentioned above from subchapter 4.3.2. By applying these estimates in combination with the estimated amount of introduced battery capacity, presented in Figure 3, the following diagram presents battery technologies returning from first use in Norway:

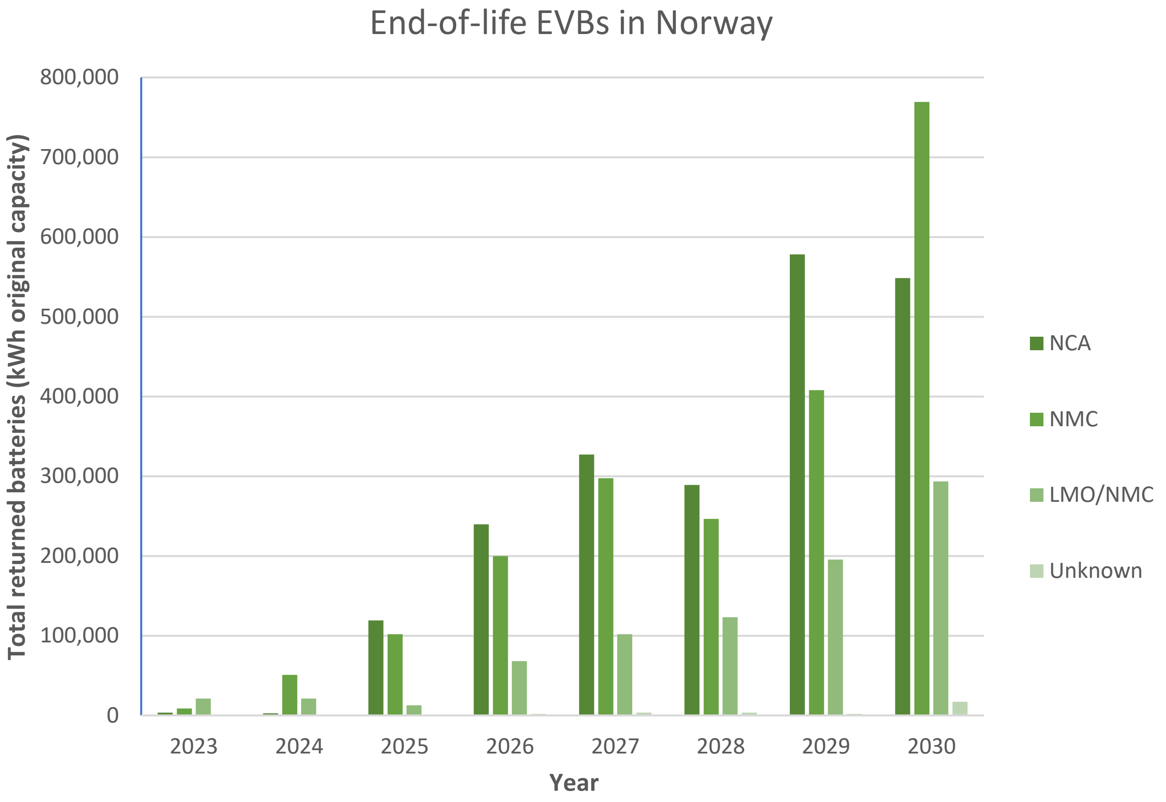

Figure 12: The estimated total amount of returned batteries from the Norwegian market (kWh original capacity). Based on data from Figenbaum et al. (2020).

The total kWh in this figure represents the specified capacity when the battery was new, not the end-of-life capacity. The number of cars the data represents varies widely in terms of brand and model. A typical battery pack of a passenger car ranges from 18.7 kWh in the original VW E-up to 100 kWh for the Tesla Model S and X Long Range editions (Figenbaum et al., 2020, pp. 28-29). Consequently, each segment of 100,000 kWh might translate to anywhere between 1,000 to 5,350 EVs. Assuming the average battery size is 45 kWh, the number of EVs per 100,000 kWh is 2,222. As the LIB technology develops, the capacity of a car’s battery pack is increasing, making the average EV from 2021 having a larger capacity than its predecessors from 2016. Hence, the increase of battery capacity is not necessarily linear with the number of EVs returning from the market.

In this figure, LFP is not included, as this technology had not noticeably entered the Norwegian market by 2018. Additionally, this figure represents a simplified case where the batteries introduced each subsequent year will be used in EVs for precisely 12 years. In practice, however, the lifetime of the batteries is believed to follow a probability distribution, in addition to a random failure factor, representing car crashes or other damages, making the battery inadequate for EV use. The implementation of these factors will likely even out the spikes in the diagram (e.g., the return of NMC in 2030) by distributing the time for the returning batteries over several years in either direction. However, despite the simplifications, the data presented is believed to give a reasonable prognosis of returned EVBs in the next decade.

The introduction of Chinese car brands in the Norwegian market increases the diversity in the EVB park, as they more commonly use the LFP technology. Plus, with the recent announcements from Volkswagen and Tesla to start the employment of LFP in entry-level cars (Ribeiro, 2021), it becomes clear that there will be an increase in LFP batteries in the market. Consequently, there will be an escalating number of LFP batteries returning from first use as the technology takes a portion of the market. However, the majority of these are not believed to return until after 2030, given that their expected lifetime is 12-15 years. Hence most of the batteries reaching end-of-life will be NMC, NCA and LMO/NMC. These will contain various amounts of valuable nickel and cobalt, rendering recycling more viable because of a lower gate fee. Combined with the fact that Norwegian companies could seek to establish large-scale recycling, it is likely that many of these batteries will be recycled directly after reaching EOL.

As previously mentioned, Battery Expert C claims LFP batteries will have a good potential for repurposing, considering the lower profitability of recycling them. However, as per the Repurposer, the recycling value of a battery type is not that decisive for the viability of second-life. The Repurposer claims that there are disadvantages with LFP as it is less viable for more complex energy systems. NMC and LMO/NMC have more stable electrical impedance compared to LFP. Constructing energy systems with LFP is expensive, and LFP is more viable in simpler systems, adds the Repurposer. Hence, there could be potential for repurposing in the coming years, despite the fact that most end-of-life batteries will contain high-value materials.

To summarise, one of the things Figure 12 shows is that the volume of spent batteries becomes more and more significant towards 2030. At that point in time, the argument of postponing recycling to get higher volumes becomes less valid as technological advancements of recycling and economies of scale will render recycling ventures more viable. As the LIB recycling sector is starting to expand and the demand for recycled materials in European LIB production increases, it is uncertain whether the additional time second-life brings creates circular benefits or is a hinder to sustainable LIB production. The graph also tells us that most end-of-life batteries will be NMC or NCA, and some LMO/NMC. These batteries contain various levels of valuable cobalt and nickel, thus, as per Battery Expert C and Baltac and Slater (2019), mandating recycling because of expected lower gate fees. Still, as per the Repurposer, these batteries can provide solid energy storage systems. Some of them, especially those with a higher residual capacity, could be repurposed, adds the Repurposer. Yet, if the proposed regulations with mandatory levels of recycled materials are enforced in 2030, this will further contribute to a strong rationale for directly recycling batteries to meet the expected material demand in EVB production in the 2030s. Based on these considerations, it is expected that recycling directly will prevail over repurposing in the upcoming years in Norway. This is further supported by the fact that the Norwegian electricity grid has low power prices and a high share of hydropower, curbing the local need for second-life electricity storage.

4.4 Implications on circular economy

Evaluating what would be an ideal pathway for products and materials in a circular economy is not an easy task as rebound effects can be hard to foresee, markets and technologies evolve, and various regions have different ground rules. Current research proposes that repurposing, being higher in the waste management hierarchy and extending the battery's life cycle, is the preferred option. The literature often concur that going directly to recycling is wasteful, that cascaded use through a second life should be prioritised over lower levels of the waste hierarchy, that recycling should be used as a final option, et cetera (Basia et al., 2021; Mossali et al., 2020; Richa, Babbitt, & Gaustad, 2017; White et al., 2020; Xu et al., 2021). Olsson et al. (2018, p. 2) claim that "the processes of reuse/repurpose and recycling are complementary to each other, and the largest sustainability benefit can be reached if EV batteries are first reused and then recycled." There is little negating amongst the interviewees that this is an optimal path for circularity, but the practical implementation of this route could be more thoroughly explored. The belief that repurposing brings the most sustainability value to the circular value chain could lead to poor decision-making in end-of-life processes as stakeholders could be misled to believe that repurposing is always the best option.

Ahuja et al. (2020) have a neutral line of thought, stating that it is essential to remember that despite the benefits, repurposing of EVBs would interrupt the type of supply loop envisioned by the circular economy objectives and will delay recycling. Recycling directly, instead of repurposing, would bring some of these high-demand critical materials back into the value chain faster. Therefore, the benefits derived from repurposing must be balanced against the impact of the delay in the availability of the materials contained for recycling (Ahuja et al., 2020). To visualise the delay introduced by repurposing, an altered version of the circular value chain for EVBs, from Figure 9, is proposed in Figure 13. The figure illustrates how repurposing affects the lifecycle of the batteries, adding an additional loop to the circular value chain.

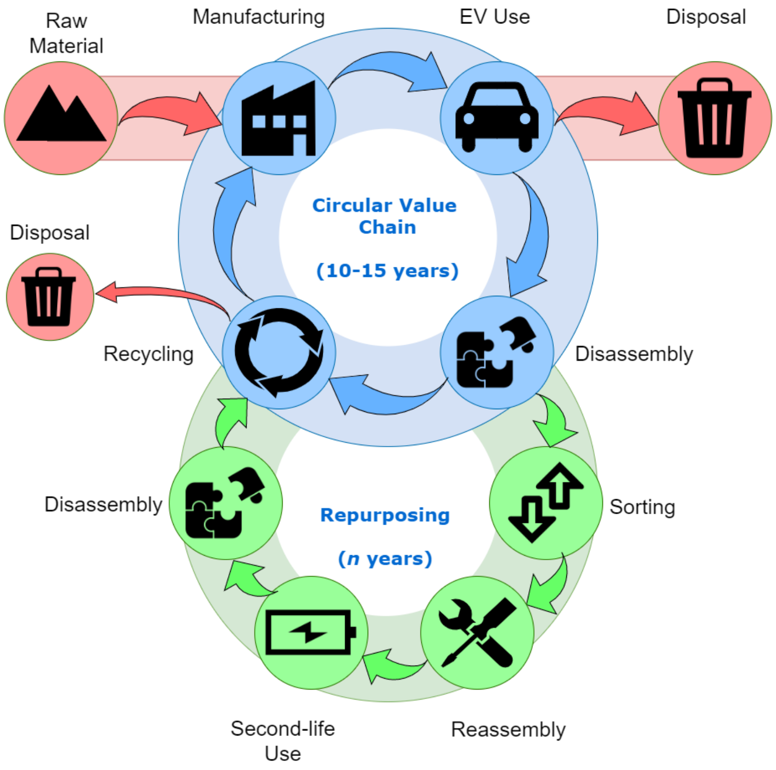

Figure 13: Own elaboration of how repurposing adds an extra loop in the circular value chain of LIBs, delaying the recycling by "n" years. Additionally, it shows that recycling does not recover 100% of the materials. A part of it will still end up as disposal or recovered as energy.

Based on findings from the literature and interviewees, the average duration for the LIBs first lifetime is set to 10-15 years. The estimated duration of second-life applications differs based on charge cycle requirements, as mentioned by the Repurposer. Therefore, the lifetime is set as an unknown value *n*, but based on literature, it will often be around 10 years (Ahmadi et al., 2014; Akram & Abdul-Kader, 2021; Reid & Julve, 2016, p. 26). The figure underlines that the two paths are not exclusive as the stream of EOL batteries could be divided where some batteries are recycled directly, while others are first repurposed. For instance, referring to previous discussions and Figure 11 from section 4.2, battery types with high-value materials and low residual capacity could follow a path of directly being recycled, whereas battery types with low-value materials and high residual capacity could take part in an extended loop. A circular value chain in which LIBs are recycled directly might seem non-intuitive to a circular mindset. However, it is essential to weigh all relevant factors and base the decision thereafter, as what initially seems like the better option might have unforeseen consequences. Assessing different CE strategies for the circular value chain of LIBs with a holistic approach could potentially lead to a different perspective on the waste management hierarchy.

4.4.1 A holistic approach

Considering that the EV and LIB industry is rapidly growing and demand for new materials and more batteries is ever-increasing, it is essential to acknowledge that the value of a battery should not be deemed by one product or one life cycle; it should be valued by its continuous circularity which includes multiple life cycles and the market as a whole. The circularity of a product should not be treated in isolation following the closed-loop principle but instead address circularity issues as interrelated activities, as they could positively or negatively impact each other (Bonsu, 2020). As stated by Calisto Friant et al. (2021), to manage complex trade-offs and synergies, it is vital to integrate the climate, ecological and circularity transitions from a holistic perspective. Correspondingly, Battery Expert C states that “it will be decisive that stakeholders consider the total value, covering carbon footprint, raw material use, how to define that repurposing is better than recycling and vice versa.”

Concerns related to ethically sourced materials was mentioned by several respondents. The interviews with the battery producers demonstrated that they have intentions to use ethically sourced materials as it is an integral part of their sustainability strategy. In relation to this, material procurers must be aware of trade-offs as acquiring ethically sourced materials could put pressure on other miners who might source materials unethically for other clients who do not have the same ethical procurement standards. Instead, demand for recycled materials could potentially relieve some of the overall pressure on mining.

While the market is growing, recycling can provide a vital secondary supply until the market reaches a steadier state. Repurposing an EVB would delay the recycling of the materials, which is unfortunate in a market where the demand for specific materials is increasing. With that said, repurposing could also delay the production of purpose-built batteries for electricity storage applications. Richa, Babbitt, Nenadic, et al. (2017) finds that EVB repurposing in a stationary application has the potential for dual benefit, both from the perspective of offsetting initial manufacturing impacts by extending battery life span as well as avoiding production and use of a less-efficient lead-acid battery system. The efficiency of EVBs is confirmed by the Repurposer, “The benefit of EVBs is that they are high-quality because of the strict regulations regarding vibrations, changing temperatures, dust-resistance and the need to sustain many charging cycles."

For each specific context, the waste hierarchy and the frameworks which are inspired by it, such as Potting et al. (2017) and Blomsma et al. (2019), could be adjusted. These frameworks are based on macrosystems and therefore function as general guidelines. However, they are not designed for a particular context. For instance, Richa, Babbitt, and Gaustad (2017) found that a closed circularity in which LIBs are reused in EVs was less desirable than a more open-loop option of repurposing into energy storage despite this going against the idea of traditional circular economy philosophy that product reuse is superior to repurposing in the waste management hierarchy. This illustrates how the order of circular strategies is not always accurate. Results from the same analysis of a LIB waste hierarchy performed by Richa, Babbitt, and Gaustad (2017), suggest that recycling should be considered after cascaded use options for EVBs. The authors claim that metal recovery would require policy and technology development to create collection programs, improve recovery efficiencies, and add economic incentives. Considering the rapid development of collection and recycling programs, for instance, Hydrovolt in Norway, and increasing recovery efficiencies, some of these developments are already confronted. Thus, their conclusion on prioritising cascaded use over recycling would perhaps be changed in the present or future market. Still, Battery Expert A acknowledges that "it is great to have second-life as you delay the recycling process because there is no recycling process now that is optimal." Hence, the argument of delaying recycling through repurposing is seemingly still valid.

In a complex market with supply challenges, spikes in material prices and increasing demand, directly recovering materials through recycling could prove essential for European battery producers to meet the growing demand without the need to expand the virgin material production significantly. Therefore, one could argue that recycling and prevention are interconnected. Following the same logic, one could say that prevention and repurposing are also intertwined as repurposing can prevent the need to produce purpose-built LIBs for electricity storage applications and thereby also reduces the demand for virgin materials. In order to illustrate these interconnections, an altered version of the waste management hierarchy is proposed, shown in Figure 14.

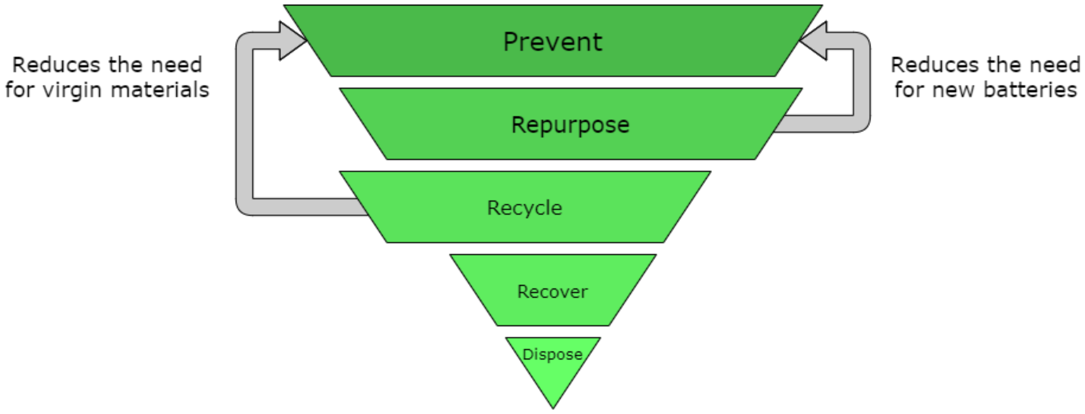

Figure 14: Own elaboration on the waste management hierarchy, based on Harper et al. (2019), in the context of spent EVBs. Illustrates how recycling and repurposing are affected by their abilities to prevent the making of new batteries and reducing the need for virgin battery materials.

The figure depicts how the important CE principle of prevention has the potential of "pulling" on both recycling and repurposing, increasing their significance in the waste management hierarchy. As per Morseletto (2020), the hierarchy is not rigid. The product and conditions need to be adapted based on the context. Hence, in some scenarios, repurposing will be the preferred option, while in others, recycling might result in a better outcome. The existence of exceptions and rebound effects underlines the hierarchy's need for situational adaption (Morseletto, 2020).

An essential link between repurposing and a circular economy is the time lag introduced by second-life applications. The time lag added could be pretty significant, depending on the application. This is a critical factor in a period of time where production is exponentially increasing, and technology is continually developing. While added lifetime is beneficial from the environmental perspective, it might be harmful from a circular value chain perspective, as it delays the return of materials. Europe, being a region with little to no virgin raw materials, has a strong rationale for acquiring materials through recycling. The eventual massive returns of spent batteries could become the urban mining of Europe, preventing further resource extraction and creating supply security and resilience.

In a circular economy, production is replaced by sufficiency (Stahel, 2016), hence it is preferable to keep what is produced for as long as possible. Employing such a theoretical implementation of circular economy is, in practice, complex since a significant share of materials is still used to build up new products, markets and infrastructure and is thus accumulated in the material stock of society. Hence, the potential for reducing primary raw material consumption is limited, even for a highly developed economy like the EU, as pointed out by Fellner et al. (2017). It is only when consumption and production are balanced, and material stock is rather constant that the circular economy can evolve to its full potential (Fellner et al., 2017). According to Material Expert B, the division of the EOL treatment might be approximately 50-50 between repurposing and direct recycling if the demand and supply for battery materials stabilize. This implies that both recycling directly and repurposing preceding recycling can become attractive options in the future.

4.4.2 The aspect of time

A key consideration regarding the end-of-life treatment of EVBs is that new batteries will outclass spent batteries in terms of technological advancements. Hence, repurposing might lose a lot of value in markets where technology rapidly evolves. Researcher B confirms this by stating that “10-year-old batteries will be outdated quickly. So, when today’s batteries have finished their first life, the technology is likely outdated.” With an increase in the expected lifetime of EVBs seen in recent research, reaching up to 15 years, the retired batteries would be even further outdated. Additionally, technological development contributes to more efficient batteries and better battery management systems, which are considered to prolong the life span of EVBs in the future (Tadaros et al., 2020). Moreover, as new technologies evolve, they might require different materials. This could imply that the materials in spent batteries no longer can be utilised in the production of fresh batteries made up of other materials, rendering some of the recycled materials redundant in this case. However, as both Researcher B and Umicore (2021) states, recyclers might end up using simpler processes to treat certain materials that do not need to be battery-grade quality. By doing so, they can sell the materials to lower-end applications where the required material purity is not as high. For cobalt, however, batteries are the main application, and as a result, there might be a surplus of cobalt if future lithium battery technologies no longer use it.

Kamran et al. (2021) claim that the time lag imposed by second-life on the eventual recovery of battery metals is relatively short, which in some cases can be true. But certain second-life applications can have a significant lifetime of over 10 years (Casals et al., 2019). Additionally, one can question the economic viability of second-life if the life span is “relatively short” as the net present value could be negative if the application has a payback time that exceeds the life span. For instance, even if the cost-effectiveness proved higher for second-life batteries than new batteries for fast EV fast-charging storage systems in the study of Kamath et al. (2020), the economic payback time was too high to justify the investment. Moreover, the environmental rationale weakens as a shorter second life may threaten the prominent environmental impact mitigation achieved when integrating repurposed batteries (Martinez-Laserna et al., 2018).

4.4.3 Rebound effects

As introduced in the paper of Zink and Geyer (2017), rebound effects remind us that circular is not necessarily sustainable and better for society. Companies can make recyclable products with very little chance of those products ever being recycled. An example of a rebound effect in the context of EVs is that car-sharing in cities could replace walking and commuting. Hence, despite car-sharing being a circular service, it can contribute to an overall increase in production as urban residents who would otherwise commute or walk choose to drive. With that said, it could lead to fewer people owning cars as people choose car-sharing over car-owning, thus freeing up resources. With a similar line of thought, a repurposed EVB can contribute to unnecessary consumption if it is used as energy storage instead of practising flexible consumption facilitated by smart applications.

Lowering the price of battery production by using cheaper, more abundant materials could at first seem like a circular strategy aligned with the pillars of sustainability and responsible resource consumption. For instance, increasing the content of manganese while lowering the cobalt content could create an immediate positive impact for the economy (manganese is cheaper) and society (cobalt mining brings concerns regarding mining conditions). Yet, such a decision could have several negative impacts on the reverse supply chain. It lowers the potential for recycling, thus short-term profits are prioritised over long-term circular viability. S. Wang and Yu (2020) found that along with the evolution of LIBs, such as lower cobalt content, the environmental impact and profitability of recycling decreases. Hence, what sometimes seems intuitive, could do more environmental harm than good, illustrating the need to evaluate material impacts or by contextualizing critical aspects such as environmental justice (Mulvaney et al., 2021).

An example of a positive rebound effect from using high-quality batteries is the increase in range for EVs. Using cobalt and nickel is often negatively perceived due to high price and some concerns of supply. However, using cobalt and nickel increases the battery’s energy density, enabling EVs with a higher range (Mayyas et al., 2019; Olivetti et al., 2017). This is likely why Volkswagen plans to employ nickel-rich NMC in high-end models (Ribeiro, 2021). If the overall EV fleet increases its range, the need for charging stations will decrease compared to an EV fleet with a lower range. Hence, the pre-emptive measure of lowering the price of batteries through lower quality EVBs could lead to negative rebounds where more infrastructure is needed. Paradoxically, repurposed EVBs has been suggested to provide storage for EV fast-charging infrastructure, especially in rural areas. Hence, second-life batteries with low-value materials can end up being used to support infrastructure that is needed to support the same low-value batteries owing to an EV fleet with a lower range. With that said, the use of second-life EVBs supporting fast EV charging stations could last for over 30 years, according to Casals et al. (2019). Hence, they would contribute to a durable infrastructure, which is in line with the circular economy.

4.4.4 The sustainability of battery production

Ideally, stakeholders in the end-of-life circular value chain could seek opportunities that have the most preventive impact. There are some actions that can support both sustainable battery production and second-life batteries simultaneously. Resource-rich countries could integrate renewable energy content into mining operations (Bonsu, 2020). By repurposing LIBs, minerals-rich developing countries (with abundant solar energy) could benefit from battery pack technology for cleaner technology and energy storage systems. A repurposed energy storage system can enable optimal use of both solar photovoltaics and grid electricity retrieved at low cost from the grid. This will help address societal challenges such as irregular and random electric power outage usually experienced within some of these countries (Bonsu, 2020). Consequently, the repurposing of LIBs would contribute to more sustainably sourced virgin materials rendering the procurement of these materials more attractive for European battery producers.

Without a timely, reliable and sustainable material supply, the pace of the energy transition will be inhibited as it would hinder the expansion of LIB production and the green benefits it brings. If repurposing is implemented on a large scale, additional lithium and other metals would need to be mined to satisfy demand resulting from a delay in material recycling (Ahmadi et al., 2014). The benefits derived from repurposing an entire battery must therefore be carefully assessed and balanced against the impact of the delay in the availability of the materials contained in the battery (Ahuja et al., 2020). This is especially important for Europe since the desire to create a competitive and sustainable battery manufacturing industry is immense.

There is consensus in Europe that there is a great need for sustainable battery production, making Europe less dependent on external supply. To catch up with the fierce competition from mainly Asian countries, Europe has to strengthen all steps of the battery value chain, starting from ensuring a secure and sustainable supply of battery raw materials to the battery manufacturing industry (European Commission, 2018). Governments have long been reluctant to prioritise environmental before economic growth, but, increasingly, the two will likely become interlinked. In this study, regulations have been identified as one of the most critical drivers for the demand for recycled content in LIB production. Such legislation could be an indication that the EU prioritises the environment and values sustainable battery production.

A combination of various circular economy strategies is vital for an efficient implementation of circular economy in the context of EVBs. Even if recycling is likely to dominate in a scenario where regulations and economic development of recycling take place, repurposing will still be an attractive option, as asserted by several of the battery experts and the Repurposer. Moreover, as pointed out by Bonsu (2020), policies transitioning from linear to a circular economy should not only be about recycling raw minerals, addressing waste or repurposing battery for energy storage applications but must focus on closing the loop in an integrated manner. An integrated manner considers taking account for equitable jobs and greenhouse-gas emissions within the value chain, protecting the natural environment, and ensuring responsible natural resource consumption and production patterns.

5 Conclusion

Transitioning to a circular economy with recycling and repurposing could displace our need for freshly mined metal and help save the planet for future generations as materials and products are preserved. Europe has ambitious plans for battery production and a circular economy, and recycled materials could become essential in realising these plans. In this regard, it is important to understand what drives the demand for recycled materials. Findings based on the interviews with battery producers, metal producers, researchers, and other stakeholders in the battery value chain, demonstrated that implementing mandatory targets on recycled content is the most central factor driving the demand for recycled content in battery production. Supply gaps and shortages have also been identified as important drivers as the fear of global supply disruptions and ambitions of supply resilience can be met by locally recycled critical materials. Environmental and societal drivers were identified but considered less important in comparison with economic drivers as increased viability of recycling through economies of scale and lower gate fees for certain battery technologies will likely push the end-of-life agenda towards recycling. Furthermore, market developments, such as rapid advancement of technology and potential diversification of chemistries, can affect future end-of-life strategies. Our findings underscore the importance of analysis to understand at what point in the waste management hierarchy the most significant environmental, societal, and economic benefits are accrued.

An essential argument regarding the handling of LIBs is that different technologies and first life histories will provide different end-of-life possibilities. In general, cobalt and nickel-rich cathode chemistries, such as NMC, will likely be preferred for recycling. In comparison, LFP and LMO technologies will be preferred for a preceding second-life because of their lower material value. Since most spent batteries returning in Norway are NMC and NCA, there is, therefore, a rationale for recycling these directly if the demand from battery producers is high. Instead, LFP and LMO would be given an extended life through repurposing to prolong its value before being recycled. Still, there is a potential for NMC in second-life since they could construct more complex storage systems compared to LFP. Additionally, the general idea that batteries will return at 80% capacity is not a guarantee. Customer behaviour will likely vary greatly, and some vehicle owners might use their EV until the battery pack is rendered worthless. This illustrates the difficulties of predicting the time of return on spent EVBs as well as their condition.

As the market for LIBs is rapidly growing, the increased demand for battery materials will likely cause recycling to be the favoured EOL strategy short-term, bearing an additional benefit of potentially reducing the need for virgin raw materials. Even if recycling directly is believed to be dominant, the market for repurposed EVBs will exist and could considerably contribute to a sustainable transition to a power system driven by renewable electricity by providing affordable and accessible energy storage options. Enlarged mandatory levels of recycled content and abrupt supply issues could impede the second-life market as the demand for recycled materials increases. Likewise, no, or lower than expected, mandatory targets of recycled materials in battery production, steady material supply through economic, political and geographical stability, and diversified battery chemistries among battery producers can drive the agenda towards repurposing as the demand for recovered metals will decrease. The viability of second-life batteries will be further based on the residual capacity and the price and technological difference between spent and new batteries. Moreover, high and volatile power prices command the profitability of batteries, which means that, above all, regions with a high share of variable renewable energy having to replace fossil energy will be more profitable for second-life.

5.1 Future research

There are still many undiscovered areas for further research to investigate, including trade-offs between recycling and repurposing. How difficult is it for firms to adopt circular economy strategies and apply them to critical material issues? Are some circular economy strategies better for some situations or products? If more firms and regions adopt the same strategies, what are the impacts at the global level? While regulations and supply chain challenges offer a compelling argument for recycling, further analysis of the economics of recycling are needed to fully understand to what degree LIBs will be recycled in the following years and the correlation with future lithium-ion battery production.

An ideal scenario for a research methodology would possibly be to combine both aspects of quantitative and qualitative research to enrich the quality and reliability of the research. A research project could start with a qualitative research method that leads to a more in-depth understanding of a specific phenomenon or reveals variables connected with a particular theoretical model. Once this is done, then the use of quantitative research methods would trail to test the established relationships among the model's variables in an attempt to generalize findings (Azoury et al., 2018, p. 119). Building on a greater understanding of the demand for recycling of LIBs, as presented in this study, future research could simulate probable scenarios based on sensitivity analysis, Monte Carlo simulation, and similar quantitative statistical methods.

It is crucial to quantify the metals in retired lithium-ion batteries and how recycling and repurposing can relieve stress on metal resources and mining activities. Various degrees of uncertainty are tied to future regulations and unknown market conditions, such as the possible mass penetration of LIBs into other markets within the transport sector and beyond. Hence, research on this subject should persistently be performed to gain up-to-date insights and contribute to the continuous advancement of the field.

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7 Appendix

7.1 A - Interview Guide

The interview guide was used as a general template. For each individual interview, a PowerPoint was made containing an introduction to our thesis, the scope of the interview and our questions for the respondent.

Fase 1: Rammesetting

1. Løs prat (1-2 min)
    - Introduksjon av deltagere
    - Uformell prat
2. Informasjon (2-3 min)
    - Studentene forteller om bakgrunnen og formålet for intervjuet. Forklarer at det er i forbindelse med masteroppgave i industriell økonomi og teknologiledelse i samarbeid med bedrift *****. Forklarer videre at oppgavens tema er elbilbatterier og deres fremtid i lys av sirkulær økonomi.
    - Studentene opplyser om at alle deltagere vil bli holdt anonyme, og at eneste mulighet for gjenkjennelse er hvis respondentene selv leser oppgaven og husker hva de selv uttalte.
    - Til slutt spørres det om noe er uklart og om respondenten eventuelt har noen spørsmål før intervjuet starter.
    - Dersom relevant, spør man intervjuobjektet om tillatelse til å gjøre opptak slik at intervjuet kan gjennomgås i etterkant.

Fase 2: Erfaringer

3. Overgangsspørsmål: (5 min)
    - Hva slags erfaring har respondenten?
    - Har respondenten noe relevant erfaring med elbilbatterier, råmaterialer, sirkulær økonomi eller andre relevante temaer? Inviterer respondenten til å fortelle om egen jobb og erfaring.

Fase 3: Fokusering

4. Nøkkelspørsmål: (10-15 min)
    - Her stilles det direkte spørsmål knyttet til det aktuelle temaet for intervjuet, for eksempel:

i. Spørsmål om utviklingen av elbilmarkedet i Norge, og hvordan denne påvirker din bedrift.
ii. Utviklingen av elbilbatterier i Norge og internasjonalt framover. Trender, prognoser, vesentlige endringer.
iii. Markedsmulighetene for gjenbrukte batteriløsninger for privatpersoner og/eller profesjonelle aktører.
iv. Muligheter for resirkulering av elbilbatterier.
v. Etterspørsel etter resirkulerte materialer.
vi. Underliggende drivere for batteriutvikling.

Fase 4: Tilbakeblikk

5. Oppsummering (ca. 5 min)
    - Oppsummering av intervjuet og eventuelle funn. Har studentene forstått respondenten riktig?
    - Få klarhet i eventuelle gjenstående spørsmål.
    - Er det noe respondenten vil legge til avslutningsvis? Noe som er viktig å få med?
    - Har respondenten spørsmål til studentene?

7.2 B – NSD

To comply with National law for data privacy we sent our project proposal to NSD for approval of data collection.

Vil du delta i forskningsprosjektet

”Gjenbruk kontra resirkulering av elbilbatterier”?

Dette er et spørsmål til deg om å delta i et forskningsprosjekt hvor formålet er å studere hvorvidt etterspørselen av brukte elbilbatterier til resirkulering vil dominere potensialet for gjenbruk av det. I dette skrivet gir vi deg informasjon om målene for prosjektet og hva deltakelse vil innebære for deg.

Formål

Temaet vi har valgt for oppgaven omhandler kort fortalt gjenbruk/resirkulering av elbilbatterier, og hvilke faktorer som vil påvirke disse batterienes fremtid. Da er verdien av batteri-råvarer fremover og etterspørsel etter resirkulert materiale til bærekraftig batteriproduksjon i Europa spesielt relevant.

Oppgaven er avsluttende masteroppgave i studiet Industriell Økonomi og Teknologiledelse.

Hvem er ansvarlig for forskningsprosjektet?

Universitetet i Agder er ansvarlig for prosjektet.

Videre skrives oppgaven i samarbeid med *****.

Hvorfor får du spørsmål om å delta?

I forbindelse med oppgavens tema er vi interesserte å undersøke hva bransjeaktører tenker om fremtiden for elbilbatterier i Norge. I den anledning ønsker vi å foreta 6-7 intervju og henvender oss derfor til ulike bransjeaktører.

Hva innebærer det for deg å delta?

I dette prosjektet utføres en kvalitativ metode med semi-strukturerte intervju. Opplysningene samles inn gjennom notater fra intervjuene.:

- Hvis du velger å delta i prosjektet, innebærer det et intervju på ca. 30 minutter. Intervjuet inneholder spørsmål om markedsutsikter knyttet til elbilbatterier.

Det er frivillig å delta

Det er frivillig å delta i prosjektet. Hvis du velger å delta, kan du når som helst trekke samtykket tilbake uten å oppgi noen grunn. Alle dine personopplysninger vil da bli slettet. Det vil ikke ha noen negative konsekvenser for deg hvis du ikke vil delta eller senere velger å trekke deg.

Ditt personvern – hvordan vi oppbevarer og bruker dine opplysninger

Vi vil bare bruke opplysningene om deg til formålene vi har fortalt om i dette skrivet. Vi behandler opplysningene konfidensielt og i samsvar med personvernregelverket.

- Ved Universitetet i Agder er det bare forfatterne av masteroppgaven og veileder som har tilgang til opplysningene.

Deltakerne vil ikke kunne gjenkjennes i masteroppgaven, annet enn at deltakerne selv kjenner igjen det de selv har sagt. Ingen opplysninger, annet enn svar fra intervjuene og en anonymisert kode (eks.: Respondent 1), vil inkluderes i oppgaven.

Hva skjer med opplysningene dine når vi avslutter forskningsprosjektet?

Opplysningene anonymiseres når prosjektet avsluttes/oppgaven er godkjent, noe som etter planen er 14. mai 2021. Personopplysninger vil da elimineres.

Dine rettigheter

Så lenge du kan identifiseres i datamaterialet, har du rett til:

- innsyn i hvilke personopplysninger som er registrert om deg, og å få utlevert en kopi av opplysningene,
- å få rettet personopplysninger om deg,
- å få slettet personopplysninger om deg, og
- å sende klage til Datatilsynet om behandlingen av dine personopplysninger.

Hva gir oss rett til å behandle personopplysninger om deg?

Vi behandler opplysninger om deg basert på ditt samtykke.

På oppdrag fra Universitetet i Agder har NSD – Norsk senter for forskningsdata AS vurdert at behandlingen av personopplysninger i dette prosjektet er i samsvar med personvernregelverket.

Hvor kan jeg finne ut mer?

Hvis du har spørsmål til studien, eller ønsker å benytte deg av dine rettigheter, ta kontakt med:

- Universitetet i Agder ved veileder: Benedikte Wrålsen, +47 993 79 716, benedikte.wralsen@uia.no.
- Vårt personvernombud: Ina Danielsen, +47 452 54 401, ina.danielsen@uia.no.

Hvis du har spørsmål knyttet til NSD sin vurdering av prosjektet, kan du ta kontakt med:

- NSD – Norsk senter for forskningsdata AS på epost (personverntjenester@nsd.no) eller på telefon: 55 58 21 17.

Med vennlig hilsen

Andreas Olav Hallingstad og
Torleiv Wegner Grønningen Aa

Benedikte Wrålsen
(Forsker/veileder)
