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The operational environment for repurposing electric vehicle lithium-ion batteries for energy storage applications in the EU

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Abstract

In response to climate change, the transport sector is transitioning to electric vehicles powered by lithium-ion batteries. The sustainable management of end-of-life electric vehicle batteries is an important task typically achieved by recycling. However, there are higher-level circular strategies that result in greater environmental benefits. One of these strategies is repurposing, in which a product is adapted for a different purpose. Repurposed batteries have a lower carbon footprint and can help supply the growing demand for energy storage systems. These aspects make repurposing an interesting research topic.

This thesis aims to define the operational environment for repurposing electric vehicle lithium-ion batteries for energy storage systems in the EU. The main objective is to discover challenges and barriers for repurposing operations. In addition, possible solutions to the identified challenges are explored. To achieve these objectives, semi-structured key stakeholder interviews were conducted with 22 participants from the EU.

Eight challenges affecting repurposing were discovered from the interviews. These include the uncertain economic viability of second-life batteries, low availability of electric vehicle batteries, lack of battery information, safety concerns, regulatory shortcomings, and consumer preferences. The interview findings were supported by an extensive literature review. These challenges were further explored, and five common drivers were found pointing to the essential factors for repurposing. These include the financial aspects, actions of car manufacturers, various factors steering electric vehicle batteries towards recycling, reputational harm to second-life batteries, and role of consumers.

The research findings suggest that there is a diverse variety of complex challenges affecting repurposing. In addition, the low availability of electric vehicle batteries and new electric vehicle battery designs are potential barriers for repurposing operations. It can also be concluded that the actions of car manufacturers strongly influence repurposing operations, and economic aspects have a pivotal role in the feasibility of the second-life business.

Keywords electric vehicles, lithium-ion batteries, second-life batteries, repurposed batteries, circular strategies, circular economy

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Tiivistelmä

Vastauksena ilmastonmuutokseen liikenneala on siirtymässä litiumioniakuilla toimiviin sähköajoneuvoihin. Sähköajoneuvojen käytettyjen akkujen kestävä käsittely on tärkeä tehtävä, joka tyypillisesti saavutetaan kierrätyksellä. On kuitenkin olemassa korkeamman tason kiertotalousstrategioita, jotka johtavat suurempiin ympäristöhyötyihin. Yksi näistä strategioista on uudelleenkäyttö, jossa tuote mukautetaan eri tarkoitukseen. Uudelleenkäytettyjen akkujen hiilijalanjälki on pienempi, ja ne voivat auttaa vastaamaan energian varastointijärjestelmien kasvavaan kysyntään. Nämä näkökulmat tekevät uudelleenkäytöstä mielenkiintoisen tutkimusaiheen.

Tämän diplomityön tavoitteena on määritellä toimintaympäristö sähköajoneuvojen litiumioniakkujen uudelleenkäyttöön energian varastointijärjestelmiin EU:ssa. Päätavoitteena on löytää haasteita ja esteitä uudelleenkäytölle. Lisäksi kartoitetaan mahdollisia ratkaisuja tunnistettuihin haasteisiin. Näiden tavoitteiden saavuttamiseksi suoritettiin puolistrukturoidut keskeisten sidosryhmien haastattelut 22 osallistujan kanssa EU:sta.

Haastatteluista löytyi kahdeksan haastetta uudelleenkäytölle. Näitä ovat toisen käyttöiän akkujen epävarma taloudellinen kannattavuus, sähköajoneuvojen akkujen alhainen saatavuus, akkutietojen puute, turvallisuushuolet, sääntelyn puutteet ja kuluttajien mieltymykset. Haastattelutuloksia tuki laaja kirjallisuuskatsaus. Haasteista tunnistettiin viisi yhteistä ominaisuutta, jotka viittaavat olennaisiin tekijöihin uudelleenkäytölle. Näitä ovat taloudelliset tekijät, autonvalmistajien toimet, erilaiset sähköajoneuvojen akkuja kierrätykseen ohjaavat tekijät, toisen käyttöiän akkujen mainehaitat, sekä kuluttajien rooli.

Tutkimustulokset viittaavat siihen, että uudelleenkäyttöön vaikuttaa monenlaisia monimutkaisia haasteita. Lisäksi sähköajoneuvojen akkujen alhainen saatavuus ja uudet sähköajoneuvojen akkumallit ovat mahdollisia esteitä uudelleenkäytölle. Voidaan myös todeta, että autonvalmistajien toimet vaikuttavat merkittävästi uudelleenkäyttöön ja taloudellisilla tekijöillä on keskeinen rooli toisen käyttöiän akkujen kannattavuuteen.

Avainsanat sähköajoneuvot, litiumioniakut, toisen käyttöiän akut, uudelleenkäytetyt akut, kiertostrategiat, kiertotalous

Preface

For the last six months, I have been working hard on my thesis. Working with such an interesting and fascinating research topic has been a real honor. However, I am also feeling excited about the future after graduation.

I want to thank my advisor Anna Tenhunen-Lunkka for her support, encouragement, and feedback throughout the thesis. Also, to Fride Vullum-Bruer, your valuable feedback was much appreciated. I want to thank my supervisor Annukka Santasalo-Aarnio for her guidance and feedback.

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I want to thank my family and friends for their support. Especially, I want to thank my mom for always believing in me and for her encouraging words in times of doubt. Finally, I want to thank my fiancé Mikko for all the love and support during this thesis process, you are my rock.

Otaniemi, 26 February 2023
Nina McDougall

TREASoURcE

This thesis is conducted for TREASoURcE, a four-year project (2022-2026) receiving funding from the European Union under No. 101059491, the Horizon Europe research and innovation program. TREASoURcE aims to initiate systemic change by developing systemic circular economy solutions in cities and regions for currently underutilized or unused plastic waste, end-of-life electric vehicle batteries, and bio-based waste and side streams. Implementing these solutions together with companies, societies (including citizens, consumers, communities, and regional actors), and experts in the field is expected to significantly increase product and material circulation in the Nordic and Baltic Sea Regions.

Regarding the battery value chain, TREASoURcE has two objectives. The first is to evaluate the possibilities and potential of using end-of-life electric vehicle batteries as energy storage systems. The second is to demonstrate the functionality and sustainability of second-life energy storage systems connected to photovoltaics in three demo cases. This thesis supports the TREASoURcE project by assessing the operational environment for repurposing operations, focusing on identifying the challenges and barriers as well as possible solutions for the issues found. Thus, this thesis contributes to achieving the objectives of work packages one and four of the project.

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Abbreviations

BEV	battery electric vehicle
BMS	battery management system
BVC	battery value chain
CE	circular economy
CRM	critical raw material
DIY	do-it-yourself
DOD	depth of discharge
DV-IC	differential voltage and incremental capacity
EC	European Commission
ECM	equivalent circuit model
EEA	European Economic Area
EFTA	European Free Trade Association
EIS	electrochemical impedance spectroscopy
EMF	Ellen MacArthur Foundation
EOL	end-of-life
EP	European Parliament
EPR	extended producer responsibility
ESS	energy storage system
EU	European Union
EUCO	European Council
EV	electric vehicle
EVB	electric vehicle battery
IEA	International Energy Agency
LFP	lithium iron phosphate
LIB	lithium-ion battery
LNMO	lithium nickel manganese oxide
LMO	lithium manganese oxide
NCA	nickel cobalt aluminum oxide
NMC	nickel manganese cobalt oxide
NMCA	nickel manganese cobalt aluminum oxide
OEM	original equipment manufacturer
REACH	Registration, Evaluation, Authorization, and Restriction of Chemicals
RES	renewable energy sources
RUL	remaining useful life
SEI	solid electrolyte interphase
SESS	stationary energy storage system
SLB	second-life battery
SOC	state of charge
SOH	state of health
XCT	X-ray computed tomography

1 Introduction

In response to climate change, many sectors are undergoing prodigious transformations to reduce anthropogenic emissions. While the energy sector is phasing out fossil fuel-based production with renewable energy, the transport sector is replacing internal combustion engine vehicles with electric vehicles (EVs). In 2021, around 16.5 million electric passenger light-duty vehicles were in use worldwide, three times more than in 2018. In Q1 2022, two million EVs were sold globally, 75% more than the previous year. The International Energy Agency (IEA) has estimated the global EV stock in 2030 for three different scenarios ranging from 200 to 350 million. Compared to the current global EV stock of 16.5 million, it is evident that there will be considerable growth ahead, albeit the degree of growth remains uncertain. [1]

As a result of an extensive set of policy incentives, Norway has become the global leader in EV adoption [2]. In 2021, the share of EVs in Norway was 22.2%, of which battery electric vehicles (BEVs) contributed 16% [3], while in Finland, the share of BEVs had yet to reach the first percentage [4]. At the end of Q3 2022, almost 80% of newly sold passenger cars in Norway were BEVs [5], while the corresponding share in Finland was only about 16% [6]. Despite the different growth rates, the transport sector is becoming electrified worldwide. Although this transition contributes to the decarbonization of the transport sector, with it comes environmental responsibilities. For instance, EVs are powered by lithium-ion batteries (LIBs), which must be managed sustainably once reaching their end-of-life (EOL). Large volumes of EOL EV LIBs are already expected to enter the market by 2025. [7]

LIBs consist of many metals, such as cobalt, copper, lithium, and nickel, of which cobalt and lithium are considered critical raw materials (CRMs) [8]. Recovering these valuable metals is crucial for conserving natural resources and securing future material needs. Recycling is currently regarded as the main strategy for managing EOL electric vehicle batteries (EVBs). However, there are still significant materials losses in the recycling processes, which is not sustainable [7]. For instance, despite being considered a CRM, lithium is hardly recycled in the European Union (EU) due to its high cost compared to primary supplies [9]. Repurposing, which means adapting a product for a different purpose, is a higher-level circular strategy than recycling. Generally, a higher-level circular strategy results in greater environmental benefits [10]. Thus, repurposing EOL EVBs before recycling would reduce the carbon footprint [11] and eliminate the need to manufacture new batteries [12].

EVBs have strict performance criteria as consumers require safe and reliable EVs. Due to battery degradation, an inevitable phenomenon in electrochemical batteries, an EVB is typically replaced once it has 70-80% of its original energy storage capacity left [12]. Despite reaching its EOL for demanding EV applications, the battery's remaining capacity is sufficient for applications with less strict performance criteria, such as stationary energy storage systems (SESS) [7]. From this arises an opportunity to enhance circularity in the EV battery value chain (BVC) and help supply the growing demand for energy storage systems while creating new sustainable business models. These aspects make repurposing an interesting and important topic for research.

This thesis aims to define the operational environment for repurposing EV LIBs for energy storage applications in the EU. More specifically, the objective is to identify challenges and barriers affecting repurposing operations and discover possible solutions to overcome the identified issues. Based on these objectives, three research questions are formed:

- What kind of regulatory environment do EU legislation and standards create for repurposing operations?
- What are the key challenges and barriers for repurposing operations?
- What actions and measures could support repurposing operations?

The thesis consists of a literature part, including a regulatory and state-of-the-art review and an experimental part of key stakeholder interviews. The regulatory review assesses the EU regulatory environment affecting repurposing operations. The national battery strategies and legislation are also reviewed for Finland and Norway. The regulatory review aims to discover possible regulatory obstacles and enablers for repurposing operations. The state-of-the-art review assesses the current state and challenges of the repurposing process. Also, the various energy storage applications and examples of second-life energy storage projects are presented. Other challenges affecting repurposing operations are also introduced. The key stakeholder interviews aim to discover challenges and barriers affecting repurposing operations and find possible solutions to overcome them. Various stakeholders, such as researchers, repurpose operators, and end-users, participated in the research.

The geographical scope of this thesis is the EU. However, the national regulatory framework of Finland and Norway is also reviewed because the second-life battery demos in the TREASoURcE-project will be conducted in these countries. Furthermore, as Norway is the global forerunner in EV adoption, it is a reference point for investigating possible advances in the regulatory framework. Other battery technologies, such as nickel-metal hybrid and lead-acid batteries, are excluded from the scope of this thesis, as LIBs have gained a dominant position in automotive applications due to their higher specific energy (Wh/kg and Wh/L), cycle life, and efficiency compared to the other technologies [13].

2 Circular economy

According to a report by Michaux (2021) [14], there are not enough metals, including lithium, cobalt, and nickel, for LIBs to replace the entire internal combustion engine vehicle fleet with EVs and to supply the global demand for power storage, see Figure 1. These numbers include the metals for only one generation of EVBs. The same number of metals is needed to produce new EVBs every ten years. Additionally, by 2050, the global vehicle fleet considered in Michaux's scenario will have increased by 60% [15]. Beyond EVs and battery power storage, these same metals are also used for consumer electronics and other applications like metal alloy and ammunition production [14]. These aspects further increase the demand for finite battery metals.

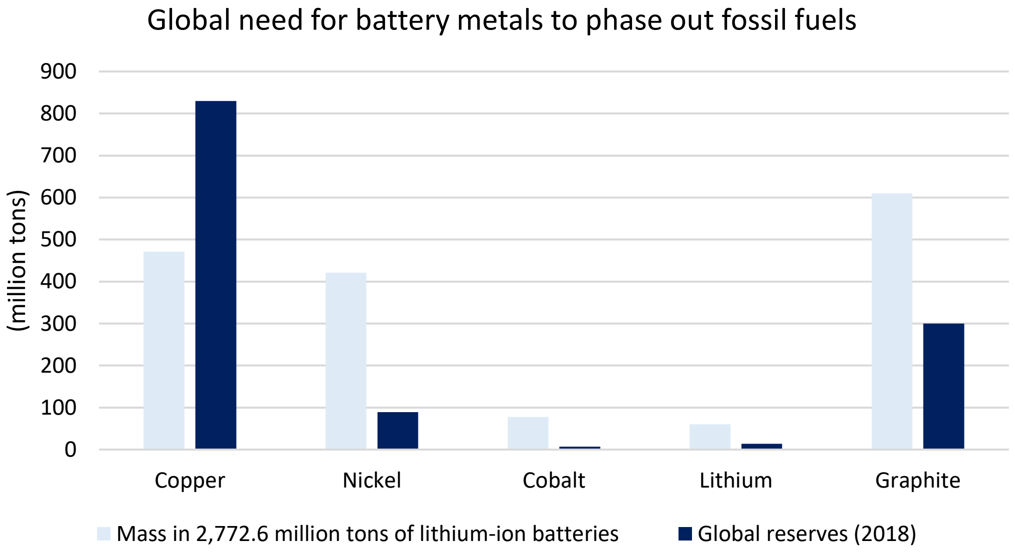

Figure 1. Metals needed for EVs and power storage. Redrawn from [14].

The global demand for batteries is estimated to increase 14 times by 2030, and the EU alone could account for 17% of this demand [16]. By 2035, renewables are projected to make up 50% of electricity production, and due to their intermittent production, the balancing needs of power systems are increasing accordingly [17]. However, the power production technologies are not the only thing changing, but also the amount of energy needed. By 2050, the world population is estimated to be 9.7 billion [18], and global energy use has increased by 50% [15]. As a result of this growth, by 2050, three planets' worth of resources could be needed to maintain the current lifestyle [19]. This seems like an impossible equation, and it is if humanity continues its current way of living.

Ever since the industrial revolution, economic growth has been closely linked to increasing production, consumption, and resource use [20]. Today we live in a linear economy in which finite resources are extracted to make products that are used and then thrown away – “take-make-waste” [21]. According to the Ellen MacArthur Foundation (EMF), a foundation aiming to accelerate the transition to circular economy (CE) and a global thought leader on the topic, waste is a concept that humans have introduced. There is no waste in nature, instead, it is a result of design choices. [22] This unsustainable way of living comes with a high cost, it is detrimental to the environment, cannot supply the growing population with essential services, and leads to strained profitability [23]. Therefore, economic growth must be decoupled from the consumption of finite resources, which is aimed to be achieved with CE.

According to the EMF, CE is a systems solution framework, driven by design based on three principles: 1. eliminate waste and production, 2. circulate products and materials, and 3. regenerate nature [21]. The first principle is about designing products so that no waste is generated: materials must reenter the economy after the end of their use [22]. The second principle aims to circulate products and materials at their highest value, to prioritize prolonging, reusing, and refurbishing, and considering recycling only as the last option [24]. The third principle focuses on regenerating nature by employing farming practices and returning biological matter to the earth [25].

There are several circular strategies to reduce the consumption of natural resources and minimize waste generation. These strategies can be ordered by priority based on their level of circularity. In general, the higher level of circularity results in greater environmental benefits. Potting et al. (2017) [10] have introduced a 9R framework in which ten circular strategies are placed in a hierarchy where they are arranged from high circularity (low R-number) to low circularity (high R-number), see Figure 2. Regarding circularity, strategies for smarter manufacture and product use (R0-R2) are ranked highest. Next, come various strategies (R3-R7) to extend product lifetime. Lastly, with the lowest level of circularity, there are two strategies, recycling (R8) and recovery (R9), to manage EOL products. Despite ranking the lowest, most circular policies and targets currently focus on R8-R9 strategies [26].

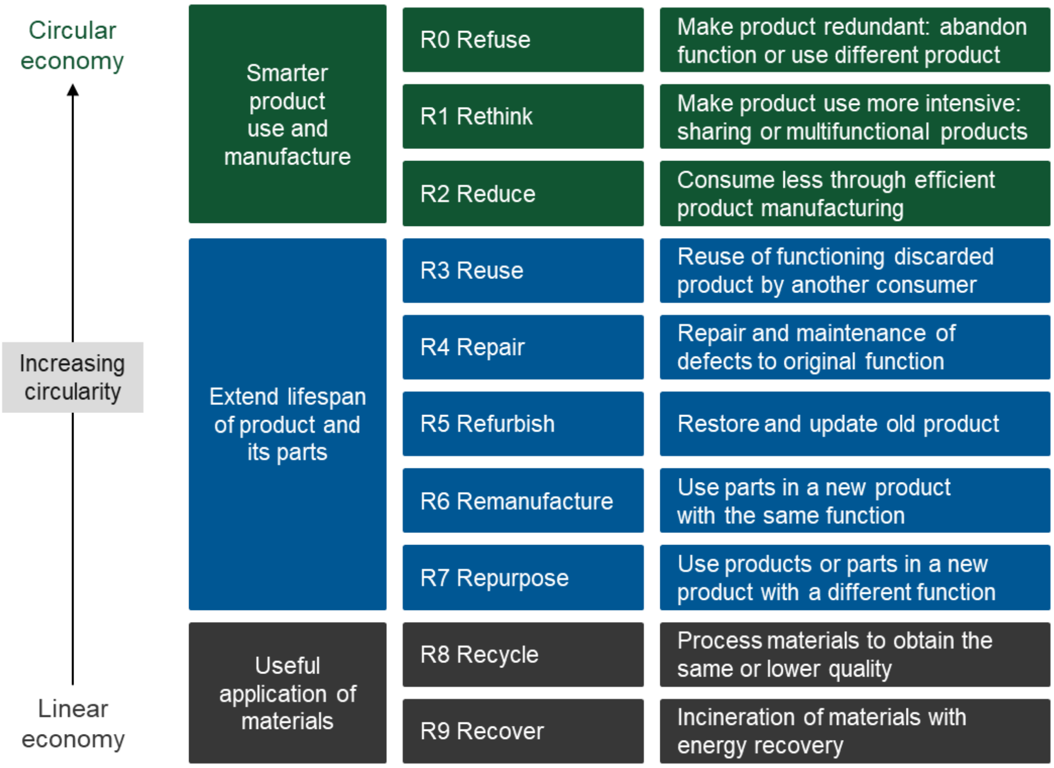

Figure 2. 9R strategies prioritized by level of circularity. Adapted from [10].

The current EU regulatory framework requires only 50% of the average weight of an EVB to be recycled, after which the remains can be disposed of in landfills or by incineration [27]. For example, in Finland, at least 50% of an EVB is recycled, after which the remains, such as plastics, are incinerated to recover energy. The ashes and other unburnable residues are disposed of in landfills. [28] In addition, lithium, which is a CRM, is hardly recovered in the EU as it is not cost-efficient [9]. Based on this, the current EV BVC is still very linear and has untapped circular potential, see Figure 3.

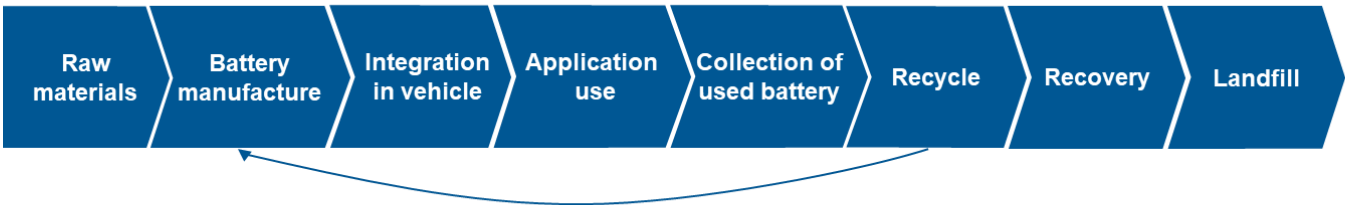

Figure 3. The current linear EV BVC. Adapted from [29].

As stated by Hua et al. (2020), to capture the maximum value of an EOL EVB, it should first be remanufactured for automotive applications, then repurposed for less demanding applications such as SESS, and only finally recycled [30]. However, it should be noted that remanufacturing is not within the scope of this thesis and the focus is only on the repurposing strategy. According to a study by Tao et al. (2021), if an EVB is first repurposed and then recycled instead of directly recycled, its carbon footprint and energy use can be reduced by 8-17% and 2-6%, respectively [11]. Another study by Richa et al. (2017) states that repurposing EVB for SESS could reduce energy demand and global warming potential by 15% to as much as 70% under ideal conditions [31]. However, the most significant environmental benefit of repurposing is eliminating the need to manufacture new batteries. The battery manufacturing process is energy-intensive and requires the extraction of virgin and CRMs. Especially lithium extraction consumes large amounts of water. [12] In conclusion, repurposing extends the battery lifespan, which leads to environmental benefits and increases the circularity in the EV BVC. These circularity-enhancing steps are highlighted in light blue, see Figure 4.

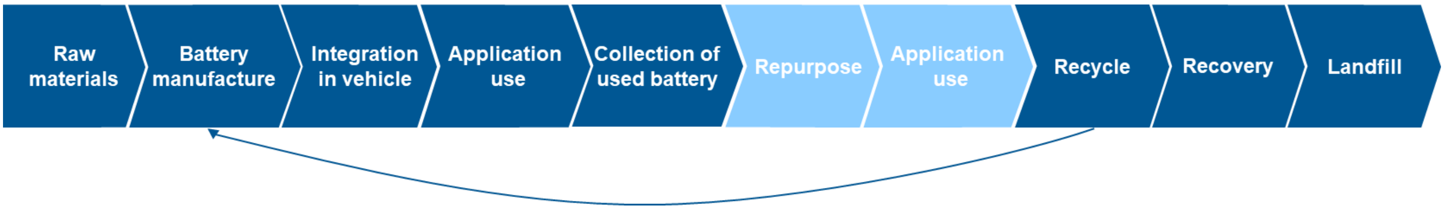

Figure 4. A more circular EV BVC. Adapted from [29].

The IEA has stated that global battery and mineral supply chains must expand tenfold to meet projected demand. The additional number of mines needed by 2030 is estimated to be up to 50 lithium, 60 nickel, and 17 cobalt mines. [32] This exemplifies the vast demand pressure faced by the mining industry. Building new mines can take up to ten years [31], so a sufficient supply of battery metals might be a future challenge. For instance, in May 2022, lithium prices were seven times more than in 2021 due to unprecedented demand for batteries and a lack of sufficient investment in new supply capacity [32]. BloombergNEF (2020) has estimated that the global battery storage capacity will be more than 500 GWh in 2030, and by 2050 it will have increased ninefold to 4,500 GWh [33]. While IDTechEx has assessed that by 2030 the second-life battery capacity will hit over 275 GWh per year [34]. Thus, repurposing EVBs could help supply the demand for battery storage.

In conclusion, the prioritization of higher-level circular strategies has many advantages. Repurposing EVBs before recycling results in reduced carbon footprint and energy use. In addition, repurposed EVBs can help supply the growing demand for battery storage while alleviating the demand pressure for new metals, giving the mining industry more time to set up new mines. Repurposing also provides additional time to develop more cost-efficient recycling processes, e.g., to recover lithium from EVBs. All these aspects highlight the benefits of enhanced circularity in the EV BVC and transition to CE.

3 Lithium-ion batteries

A lithium-ion cell consists of a cathode, an anode, a separator, an electrolyte, and two current collectors, see Figure 5. During discharging, the stored chemical energy is converted to electrical energy: lithium ions (Li^+) move from the anode to the cathode through the electrolyte, resulting in a flow of electrons from the anode to the cathode in an external circuit. Since this process is reversible, the opposite occurs during charging. [35] The depth of discharge (DOD) measures how much of a battery's capacity will be used for the application, and the state of charge (SOC) measures how much effective energy is left in the battery at a given moment. The C-rate is the rate at which a battery is charged or discharged. [36] When charging a battery at 1 C, the current rate is such that it takes one hour to charge it from zero to 100%.

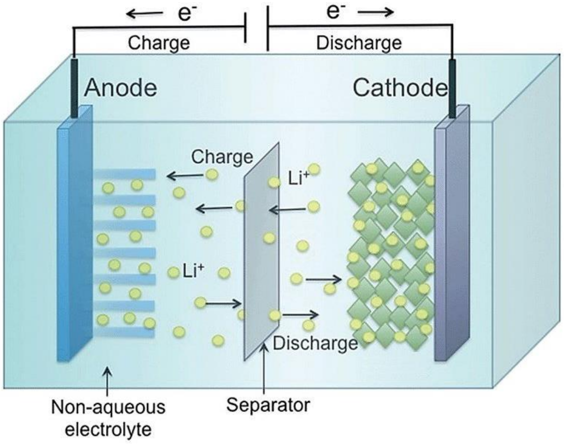

Figure 5. A lithium-ion battery cell, used with the permission of [37].

The three main cell configurations for LIBs are cylindrical, prismatic, and pouch, see Figure 6. These configurations differ in size, geometry, and individual cell parameters such as capacity and supplied power. The dimensions of these cell types vary between manufacturers, especially for the prismatic and pouch configurations. However, there are standards that define the dimensions of cell designs. [38] All three cell types are used in EVs [39].

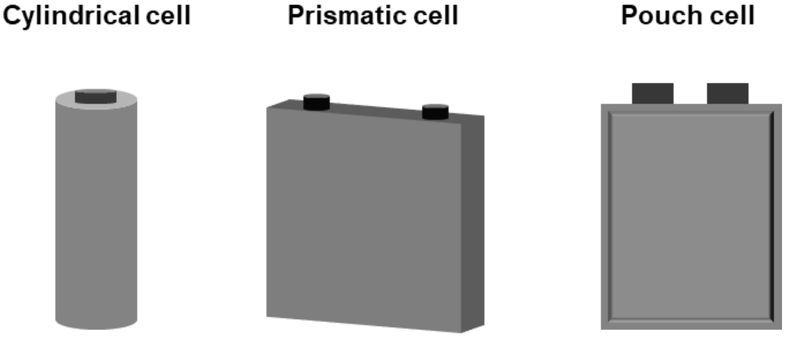

Figure 6. The three cell types for LIBs. Redrawn from [38].

A single lithium-ion cell is not enough to power an EV. Therefore, several cells are combined in series and/or in parallel to form modules, which are assembled into a battery pack, as illustrated in Figure 7 [40]. A battery management system (BMS) is also incorporated into the battery pack. The primary function of the BMS is to ensure safe and reliable operation, but it also enables more efficient performance and a longer battery lifetime. The BMS also provides essential information on different parameters, such as the state of health (SOH), which determines the remaining capacity of the battery compared to its initial value. [41]

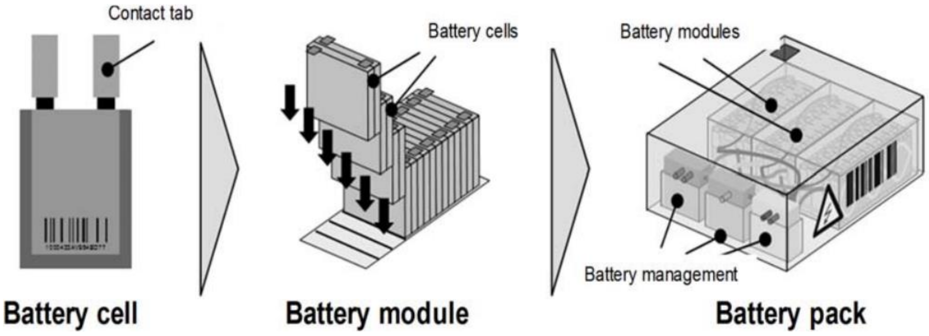

Figure 7. The assembly from battery cells to a battery pack [40].

A key defining feature of LIBs is their cathode chemistry, determining battery performance and material requirements. The three most essential cathode chemistries for automotive applications are lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA), and lithium iron phosphate (LFP), see Figure 8. Both NMC and NCA are nickel-based chemistries that offer high specific energy density, resulting in longer driving ranges. Hence, nickel-based chemistries have become increasingly dominant, for instance, in 2021, they accounted for 85% of EVB demand. The remaining 15% of the demand was covered by LFP chemistries that have resurged during the last years. Compared to nickel-based chemistries, LFP has a lower cost, longer cycle life, and is more stable, reducing the risk of catching fire. However, its specific energy density is typically only 65-75% compared to an NMC811 battery (nickel: 80%, manganese: 10%, and cobalt: 10%). [1]

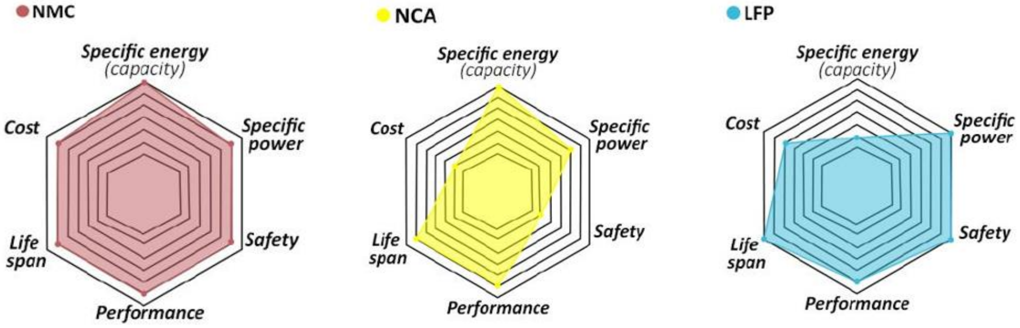

Figure 8. Features of NMC, NCA, and LFP cathodes. Adapted from [42].

There are a few reasons for the resurgence of LFP batteries. First, they contain no cobalt or nickel, leading to cost advantages in a high commodity price market. Second, a recent innovation in cell-to-pack technology results in lower dead weight and higher energy density on a pack level, which is about 85% of an NMC811 battery. Third, LFP production has traditionally occurred in China due to patents that charge license fees if LFPs are used outside China. These patents expired in 2022, making manufacturing and sales abroad more appealing. For these reasons, LFP batteries are expected to grow globally. For example, in Q1 2022, half of the EVs produced by Tesla used LFP. [1] Also, LFP chemistries are expected to account for 42% of EVB demand by 2023, including variants such as lithium manganese iron phosphate, with added manganese further improving specific energy density [43].

Cathode chemistries constantly evolve to reduce material dependency and achieve longer driving ranges and lighter batteries. For instance, many cathode chemistries, such as NMC and NCA, contain cobalt. This is problematic because two-thirds of the global cobalt production is mined in the Democratic Republic of Congo under dire working conditions, including child labor [9]. In recent years, automakers have substituted cobalt with nickel, as seen in the change from NMC622 to NMC811, while others have started using LFP batteries. Likewise, it is predicted that by the end of the decade, new chemistries like lithium nickel manganese cobalt aluminum oxide (NMCA), using more manganese, will become common to reduce the pressure on nickel. [43] Also, lithium manganese oxide (LMO) and lithium nickel manganese oxide (LNMO) are being developed, which have higher voltages and eliminate the need for cobalt.

Automotive original equipment manufacturers (OEMs) design various EVB packs, typically specific to each EV model, with different physical configurations, module structures, battery shapes, and internal chemistries [30]. Figure 9 shows three EVB packs of car manufacturers Tesla, BWM, and Nissan from 2014. As can be seen, there are significant differences between the EVB packs, such as cathode chemistry, cell configuration, number of cells per module, module size, number of modules per pack, pack size and weight, voltage, and capacity. In addition to the evolving cathode chemistries, the EVB capacity has grown significantly in recent years. According to the IEA, between 2015 and 2021, the average battery capacity increased by 60%, and if the trend continues, battery capacities are expected to increase further by up to 30% in 2030. [1] Therefore, EVBs possibly facing repurposing will consist of many different variations as the different properties of LIBs are constantly developing, and the EVB designs vary between OEMs.

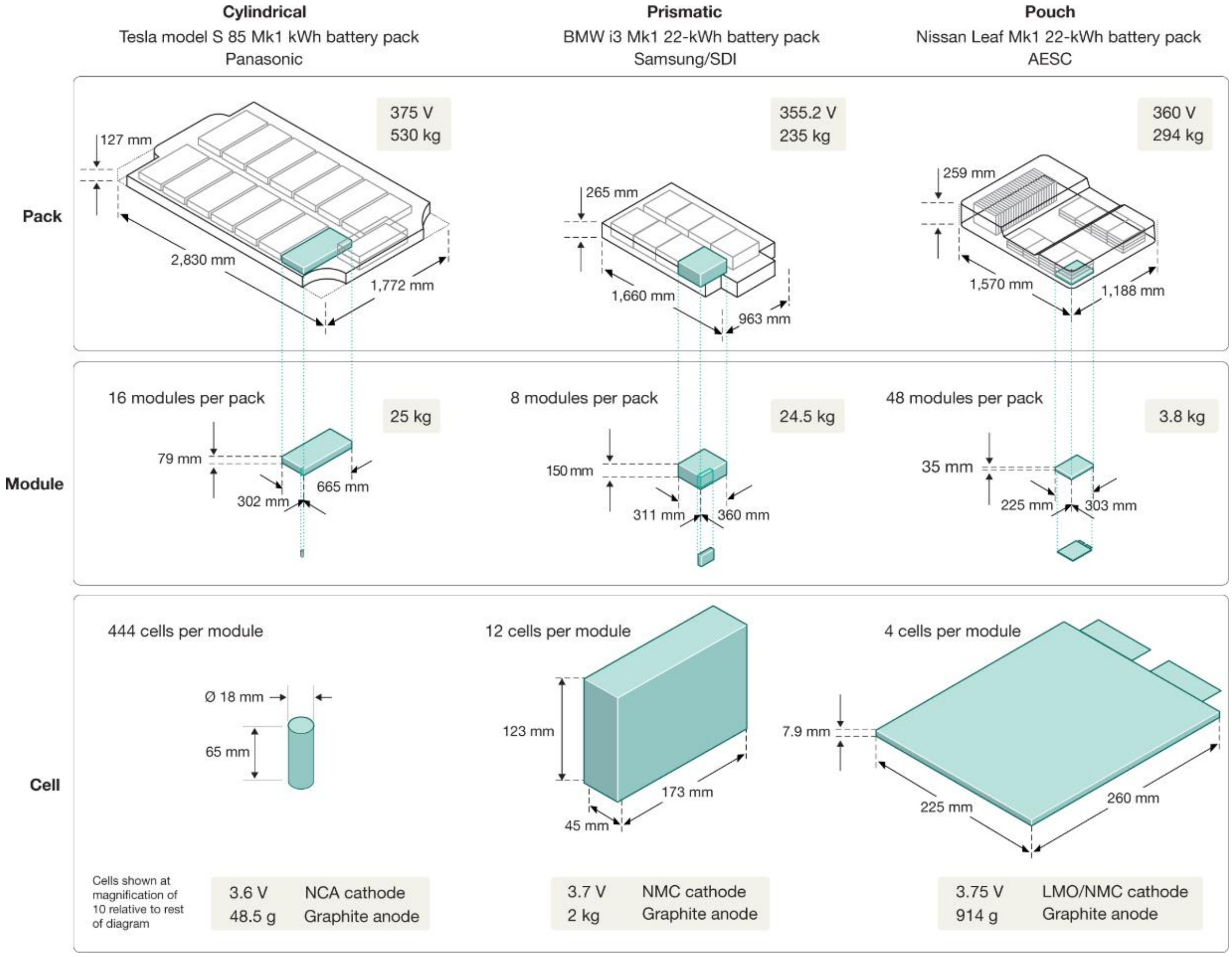

Figure 9. Various battery packs for EVs. Reprinted by permission from [44].

As the EVB undergoes discharge and charging cycles, it slowly degrades and loses its capacity, i.e., the ability to store energy [7]. The complex battery degradation mechanisms include both chemical side reactions (solid electrolyte interphase (SEI) formation, lithium plating, dendrite formation, etc.) and physical structural changes (particle cracking, fragmentation, delamination, etc.). These mechanisms result in three degradation modes: 1. the loss of lithium inventory, 2. the loss of active material, and 3. the increase of impedance, all of which ultimately lead to capacity and power loss of the EVB [45]. For instance, the loss of lithium inventory can occur due to lithium being trapped in the SEI layer, in the anode or cathode structure, or lithium plating, etc. Whereas the increase of impedance can occur due to growing SEI or cracking of particles causing detachment from the current collector, etc. The battery degradation mechanism and modes are presented in Figure 10.

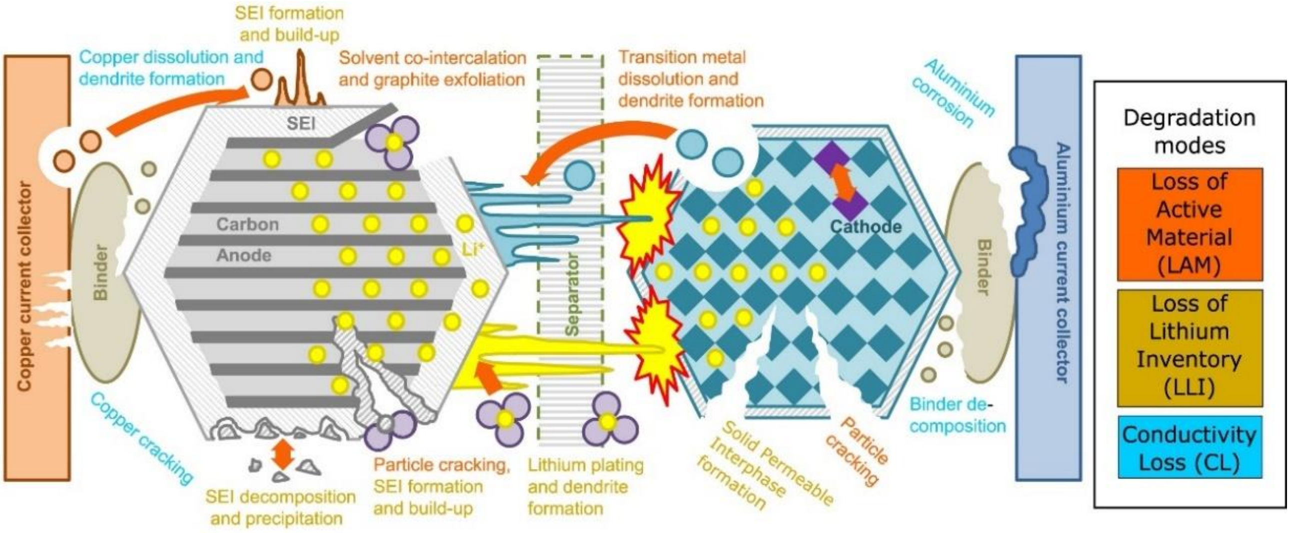

Figure 10. Degradation mechanisms and modes in LIBs [46].

The EVB should be replaced once its SOH reaches 70-80%, which is insufficient to ensure proper performance [47]. Also, when the EVB degrades beyond 70-80%, its behavior becomes more unpredictable and unsafe to be used in EVs. For these reasons, the EVB has reached its EOL. EVBs are expected to last 8-10 years [30]. However, EVBs can also reach their EOL due to traffic or other accidents [7].

LIBs are generally considered safe due to their low failure rate of one in ten million. However, fire or even explosion situations can follow during a LIB failure. This is caused by thermal runaway, which can occur due to an internal or external short circuit of the battery or an external heat source like fire. In addition, battery degradation, physical damages, high currents and voltages, recharging in freezing temperatures, inadequate storage temperatures, and complete discharging of the EVB increase the risk of thermal runaway. [7] Therefore, safety is increasingly important for EVBs that will be repurposed as they have experienced harsh conditions during their first life.

4 Regulatory review

This chapter examines the current and upcoming regulatory environment affecting repurposing operations in the EU, Norway, and Finland. The focus is on identifying potential obstacles and enablers affecting repurposing operations. First, relevant EU legislation is introduced, after which national legislation and strategies are reviewed for Norway and Finland.

4.1 European Union

Before diving into the EU regulatory framework in more detail, it is essential to distinguish the differences between the various types of legislation. First, a regulation is a binding legislative act that must be applied throughout the EU. Second, a directive is a legislative act that sets out goals that all EU countries must achieve. However, it is still up to the individual countries to draft legislation to achieve these goals. [48] In addition, standards are technical documents designed to be used as a rule, guideline, or definition to increase product safety and quality [49].

4.1.1 Current regulatory environment

The Waste Framework Directive 2008/98/EC is relevant because it defines the general definition of waste, introduces the waste hierarchy, and establishes a common framework for the extended producer responsibility (EPR). Article 3 defines waste as “any substance or object which the holder discards or intends or is required to discard” [27]. Article 4 sets the foundation for waste management with a five-step waste hierarchy of prevention, preparing for reuse, recycling, other recovery, and disposal. However, reuse is defined as “any operation by which products or components that are not waste are used again for the same purpose for which they were conceived” [27]. This would imply that EOL EVBs should be reused for the same purpose, i.e., as the power source for EVs. Although the waste hierarchy does not explicitly mention repurposing, it strives for the best environmental outcome, so repurposing should take place before recycling. This reasoning is supported by an example of the waste hierarchy concept for EOL EVBs, where the reuse segment also includes repurpose applications, see Figure 11 [45]. However, the waste hierarchy could be complemented with other circular strategies, which are currently not mentioned. Moreover, EVBs are under EPR, which means that the producer of the EVB (manufacturer or importer of the car) must take care of waste management of EOL EVBs at their own expense; the common practice is to pay for EVB recycling. [7]

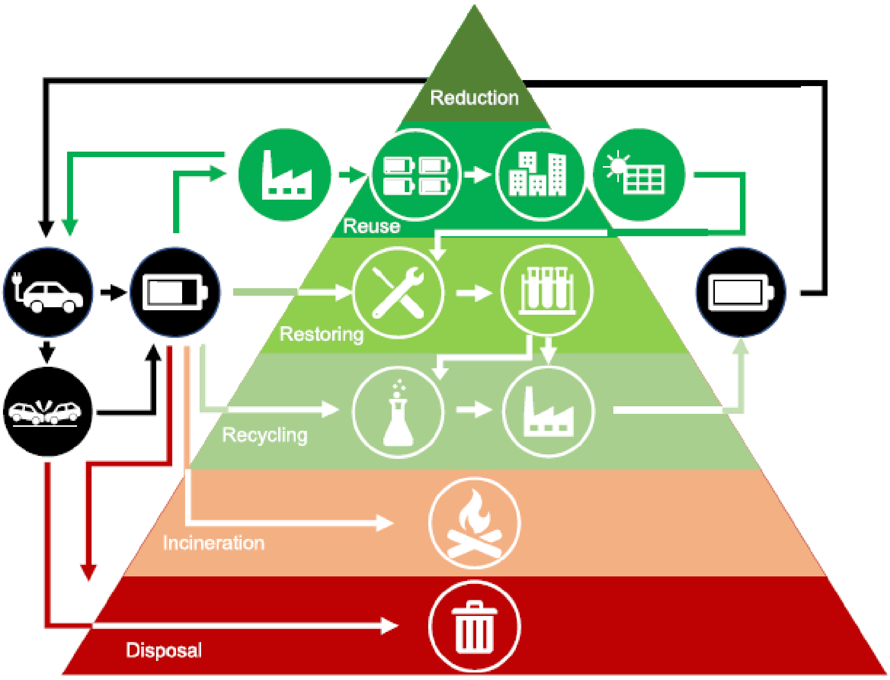

Figure 11. Waste hierarchy and retirement options for EVBs [45].

The Batteries Directive 2006/66/EC is the primary EU legislation concerning batteries. It aims to protect and preserve the environment by minimizing the adverse effects of batteries and waste batteries. Thus, it prohibits certain hazardous substances in batteries and sets requirements for waste management and recycling targets for EOL batteries. It also classifies batteries into three categories: portable (electronic devices), automotive (starting, lighting, and ignition power), and industrial (EVs and other industrial applications). It enforces the EPR, which aims to steer EOL batteries to appropriate waste management. It also includes requirements for labeling batteries and their removability from equipment. To achieve a high level of material recovery, it includes recycling efficiency targets of 65% for lead-acid batteries, 75% for nickel-cadmium batteries, and 50% for other waste batteries, including EVBs. However, the collection rates for EOL batteries only apply to portable batteries, excluding EVBs. The Batteries Directive has no requirements or targets regarding repurposing EVBs for other applications. Instead, the focus is on recycling. [7] [50, 51]

The following safety legislations are also relevant for repurposing EVBs. The General Product Safety Directive 2001/95/EC aims to ensure that only safe products are sold on the market. The Low Voltage Directive 2014/35/EU sets safety requirements for electrical equipment. Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) Regulation (EC) No 1907/2006 is relevant due to the chemical substances present in batteries. There are also many standards related to battery safety, which can be found on the EU's batterystandards.info website. [7]

There are also various legislations related to the transportation of EOL EV LIBs. Directive on the inland transport of dangerous goods 2008/68/EC and the European Agreement concerning the International Carriage of Dangerous Goods by Road have packing and storage requirements related to logistics. The requirements vary depending on whether the battery is transported inside a product or is it an EOL battery. In addition, before LIBs can be transported, they must pass the UN 38.3 test, in which they are tested against, among others, shock, external short circuit, impact, crush, and forced discharge. An important thing to note is that if the BMS of the EVB is replaced during the repurposing process, the UN 38.3 test must be redone, which is expensive and results in additional costs. The safety standard IEC EN 62281: Safety of Primary and Secondary Lithium Cells and Batteries During Transport is also relevant for repurposing operations. [7]

There are currently no standards in the EU that cover repurposed battery systems. However, in the US and Canadian markets, there is the UL 1974: Standard for Evaluation for Repurposing Batteries, which deals with aspects such as safety, disassembly, examination, analysis of BMS data, and testing related to the repurposing of EVBs for energy storage systems (ESS). However, the development of similar standards for the EU is underway. Legislation about ESS is also relevant, as EVBs are repurposed for different energy storage applications. However, there are no existing legislations focusing on the safety of ESS. Thus, other existing safety standards related to, e.g., the fire safety of buildings, are applied for ESS. Furthermore, there is currently no legislation concerning the long-term storage of EOL EVBs. [7]

In conclusion, the current regulatory environment for repurposing is poorly regulated. There are no standards stipulating which measures and procedures must be done for EVBs to be repurposed. Similarly, there are no testing or safety standards for ensuring the safety of repurposed EVBs, which have a greater risk of thermal runaway. Thus, repurposing operators are currently operating under a free market.

4.1.2 Upcoming regulatory environment

In 2019, the European Commission (EC) completed an evaluation of the Batteries Directive. Overall, it was found to be out of date due to new socioeconomic conditions, technological developments, markets, and uses of batteries. For instance, the Directive does not address the second life of advanced batteries, making the development of repurposing approaches more difficult. In addition, the recycling targets only apply to certain battery metals such as lead and cadmium, with the exception of lithium and cobalt, both of which are CRMs and present in LIBs. [52] As a result of the evaluation and the establishment of the Strategic Action Plan for Batteries, it was deemed necessary to modernize the legislative framework.

In December 2020, the EC proposed a comprehensive new Battery Regulation to repeal Directive 2006/66/EC and amend Regulation (EU) 2019/1020. The proposal is part of the European Green Deal and other related initiatives, including the Circular Economy Action Plan and the Industrial Strategy. The legislation process has been progressing well. In March 2022, the European Parliament (EP) adopted the amendments, and the European Council (EUCO) agreed on a general approach to the new Regulation. In December 2022, the EUCO and EP reached a provisional political agreement on the content of the Battery Regulation. In January 2023, the official draft negotiation text was published [53]. Next, the EUCO and EP must formally approve the agreement so it can enter into force, which is expected to take effect by Q2 2023 [54]. [9, 55-57] Below, the contents of the Battery Regulation proposal have been reviewed. The official draft negotiation text was not reviewed due to the limited time frame of the thesis.

The Battery Regulation has three main objectives: 1. strengthen battery sustainability, 2. increase resilience and close material loops, and 3. reduce environmental and social impacts. To achieve these objectives, the proposal introduces new innovations: another battery classification category for only EVBs, a requirement for recycled content in new batteries with mandatory minimum levels, safety requirements for stationary battery energy storage systems, increased recycling efficiencies, and specific material recovery targets for cobalt, copper, lead, nickel and lithium, requirements for repurposing industrial and EVBs for a second life, requirements for labeling and information, a BMS and a battery passport. [9] The overall goal is that all batteries on the EU market are sustainable, circular, high-performing, and safe throughout their entire life cycle and that they are collected, repurposed, and recycled, thus becoming a real source of valuable raw material [16].

Article 12 considers the safety aspects of stationary battery energy storage systems, typical applications for repurposed EVBs. Stationary battery energy storage systems shall be accompanied by technical documentation demonstrating that they are safe during their normal operation and use, including evidence that they have been successfully tested for the safety parameters laid down in Annex V, for which state-of-the-art testing methodologies should be used. The safety parameters include thermal shock and cycling, external short circuit protection, overcharge protection, over-discharge protection, over-temperature protection, thermal propagation, mechanical damage by external forces, internal short circuits, and thermal abuse. [58]

Article 13 requires that as of 1 January 2027, batteries should be labeled with a QR code to provide information such as battery type, model, chemistry, and contained CRMs. Article 14 requires that EVBs shall include a BMS storing parameters relevant for assessing the SOH and remaining useful life (RUL) of EVBs and that repurposing operators can also access the BMS. The parameters for determining SOH include remaining capacity, overall capacity fade, remaining power capability, and power fade, remaining round trip efficiency, actual cooling demand, the evolution of self-discharging rates, and ohmic resistance and/or electrochemical impedance. Similarly, for determining the RUL, the parameters include the dates of manufacturing of the EVB and putting it into service, energy throughput, and capacity throughput. [58]

Article 59 has requirements for repurposing EVBs. First, repurposing operators shall be given access to the BMS to assess the SOH and RUL of the EVB. Second, information relevant to the handling and testing of EVBs, including safety aspects, shall be provided to the repurposing operators. Third, repurposing operators shall ensure that the examination, performance testing, packing, and shipment of EVBs and their components are performed with adequate quality control and safety instructions. Fourth, the repurposing operators shall ensure that the repurposed EVBs comply with the Battery Regulation and other relevant legislation and technical requirements for their specific purpose of use when placed on the market. However, if demonstrated that an EVB subject to repurposing was placed on the market before specific requirements about carbon footprint, recycled content, performance, durability, and supply chain due diligence, the obligations under those provisions shall not apply to that EVB when repurposed. Fifth, to document that a waste EVB, subject to repurposing, is no longer waste, the EVB holder shall demonstrate the following upon a request: 1. evidence of SOH evaluation or testing, 2. certainty of further use with an invoice or sale contract, and 3. appropriate protection against damage during transport, loading, and unloading. [58]

Article 64 concerns the electronic exchange system that contains information about the battery manufacturer, type, model, composition, technical performance, and carbon footprint of EVBs. The information and data shall be sortable and searchable for third-party use. Article 65 discusses the battery passport, an electronic record for EVBs that provides information about the SOH and RUL. The battery passport should enable second-life operators to make business decisions based on data. By 1 January 2026, the electronic exchange system and battery passport should be used for EVBs. [58]

No quantitative requirements are set for repurposing, e.g., X% of EVBs deemed suitable for repurposing should be repurposed before recycling. Instead, the Battery Regulation has introduced several targets for recycling. For instance, Article 8 requires that as of 2030, industrial batteries, EVBs, and automotive batteries that contain cobalt, lead, lithium, or nickel in active materials shall be accompanied by technical documentation demonstrating that those batteries contain the mandatory minimum shares of recovered content, as shown in Table 1. Article 57 sets minimum recycling efficiency targets, for LIBs, the target is 65% by 2025, and it will be further increased to 70% by 2030. Article 57 also sets material recovery targets for waste batteries, as presented in Table 1. [58] Some of the proposal's recycling targets were updated in the official draft negotiation text, shown by red numbers in Table 1 [53].

Table 1. Recycling targets of the proposal and official draft (in red) [53, 58].

	Year	Cobalt	Copper	Lead	Lithium	Nickel
Minimum recovered content in new batteries	2030	12% → 16%	-	85%	4% → 6%	4% → 6%
	2035	20% → 26%	-	85%	10% → 12%	12% → 15%
Material recovery targets for waste batteries	2027	90%	90%	90%	35% → 50%	90%
	2031	95%	95%	95%	70% → 80%	95%

The proposal for a Regulation on Ecodesign for Sustainable products sets new requirements to make products more durable, reliable, reusable, upgradable, reparable, easier to maintain, refurbish and recycle, and energy and resource efficient [59]. Thus, introducing several circular strategies for improving the circularity, energy performance, and other environmental sustainability aspects of products. Based on the objectives of the new proposal, repurposing EVBs is desirable as the battery extends its life cycle.

There are also new standards under development. For instance, CLC/TC 21X is involved in the standardization of second-life LIBs. This includes prEN IEC 63330:2022 related to the requirements for the reuse of secondary batteries, which is under approval, and its forecasted voting day is in September 2023. In addition, prEN IEC 63338 concerns the general guidelines on the reuse and repurposing of secondary cells and batteries, which is under drafting, and its forecasted voting day is in February 2024. [60]

In conclusion, the new Battery Regulation aims to support the practical application of the waste hierarchy, where repurposing takes place before recycling. For instance, the requirements to provide relevant information can facilitate repurposing operations. In addition, according to the Ecodesign Regulation, sustainable products with minimal environmental impact should be the norm in the EU. Therefore, both Regulations encourage repurposing operations. However, the demanding recycling targets could be a threat because EOL EVBs might be steered directly toward recycling instead of repurposing. Thus, the new Battery Regulation will create a regulatory environment that supports recycling EOL EVBs more than repurposing them. Nevertheless, the new requirements will create a small legal framework for repurposing operations compared to the current regulatory environment. Finally, the content of the Battery Regulation proposal should be treated with caution, as changes have already been made to it, which can be seen in the official draft negotiation text. Thus, once the Battery Regulation enters into force, it is advised to review the contents of the final official text.

4.2 Norway

The new Battery Regulation will be enforced in all 27 EU Member States. However, countries such as Norway, Iceland, Liechtenstein, and Switzerland are not members of the EU. Instead, they are the four members of the European Free Trade Association (EFTA), an intergovernmental organization established to promote free trade and economic integration between its Member States within Europe and globally. Furthermore, the European Economic Area (EEA) Agreement unites the EU Member States and three EFTA countries – Norway, Iceland, and Liechtenstein – in the Internal Market. The EEA Agreement requires incorporating EU legislation regarding the four freedoms, state aid, competitions, and horizontal policies. [61] Thus, Norway must implement EU laws concerning competition, investments, labor, procurement and sale of services, banking and insurance, and trade in goods [62]. The proposal of the Battery Regulation is marked with "Text with EEA relevance," which implies that the new Regulation will be incorporated into the EEA Agreement [63]. Therefore, once the Battery Regulation enters into force, its contents will be updated in the legislation of Norway. For instance, currently, Norway's waste recycling and treatment regulation, *Forskrift om gjenvinning og behandling av avfall (avfallsforskriften)*, follows the requirements of the EU Batteries Directive [64].

An unregulated market for EOL EVBs is growing in Norway due to the absence of a regulatory framework. Car wreck companies and private people sell EOL EVBs online, and the highest bidder gets the battery. As a result, many do-it-yourself (DIY) projects are taking place, such as reusing EVBs for EVs or repurposing them for residential energy storage applications [65]. This is problematic because EVBs unsuitable for reuse or repurpose applications may be used due to the absence of safety protocols and standardized procedures. Thus, the safety aspects of both reuse and repurpose are crucial to be included in the legislative framework to avoid accidents when working with EVBs and to ensure adequate safety of second-life applications. [7]

In June 2022, Norway launched its first national battery strategy, part of Norway's green industrial initiative [66], to develop a complete, profitable, and sustainable BVC, from mineral extraction to recycling. The contents of the battery strategy include the Norwegian Government's vision for a sustainable BVC, a description of the BVC and Norwegian actors, technology development, market conditions, trends, European mobilization, and Nordic cooperation, and ten actions for sustainable industrialization. However, the main goal of the strategy is to make Norway an attractive host country for private capital and significant investments throughout the entire BVC, which would create thousands of new jobs and lead to an estimated turnover of 90 billion NOK in 2030. [67]

The strategy highlights the strengths of Norway in becoming a leading host country within the BVC. These include renewable electricity at competitive prices, expertise in the relevant industry, the world leader in the transport sector's electrification, a skilled workforce, and stable political governance. Furthermore, the ten actions to attract investments to the battery industry include 1. leadership in sustainability, 2. attractive hosting, 3. industrial partnership with other countries, 4. capital, loans, and guarantees, 5. competencies, 6. abundant renewable power supply, 7. industrial sites and infrastructure, 8. coordinated public processes, 9. pilot municipalities in growth, and 10. tomorrow's battery solutions in a strengthened ecosystem. [67]

The strategy also presents the entire BVC, as shown in Figure 12. Once the EOL battery is collected, there are two alternative options. The battery can either be repurposed for a second-life battery system or recycled into materials that can be reused for battery manufacturing or used for other purposes. However, the second-life battery systems will eventually face recycling. The strategy also discusses the different Norwegian repurposing actors. For second-life battery systems, it mentions ECO STOR, Evyon, Alternative Energi, and Marna Energi, which provide battery energy storage systems for households, often in combination with solar and wind power production, and Hagal, which offers single-cell monitoring to maximize the utilization of used and new batteries. It also identifies that the repurposing of batteries could be an attractive opportunity for value creation in Norway, as they are at the forefront of EV adoption. [67]

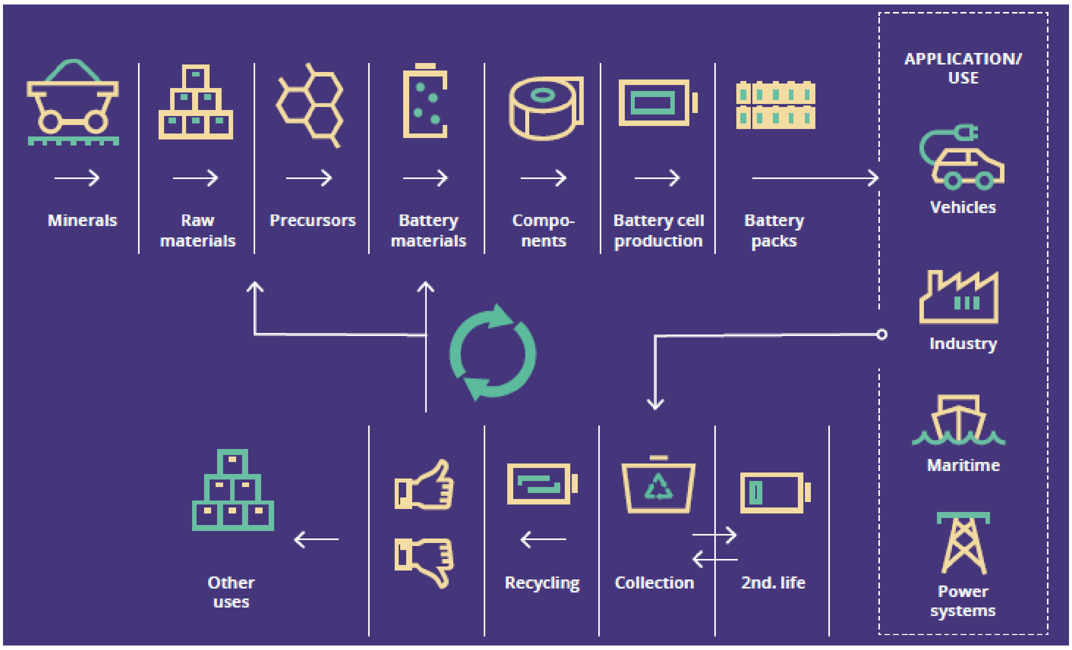

Figure 12. BVC in Norway's battery strategy. Reprinted by permission of [67].

The main recycling actors Hydrovolt, Nikkelverk, and Resitec are also introduced. The strategy emphasizes that Norway has an excellent starting point for recycling due to its specialized competence and industrial facilities already in operation. The new recycling requirements of the Battery Regulation are also acknowledged. Many of the ten actions introduce supporting measures for large-scale establishments such as recycling facilities. For instance, action four discusses the financial challenges of establishing large facilities, which is why the Government is considering granting guarantees, loans, and equity to support major investment projects. In addition, action seven aims to provide access to industrial areas with adapted infrastructure, especially for new large-scale establishments. Also, action nine emphasizes supporting pilot municipalities hosting major industrial establishments. [67]

In conclusion, the battery strategy recognizes that repurposing is an opportunity to manage EOL batteries. It also acknowledges that various actors are already in the field and that repurposing is a potential new area in which Norway could thrive. However, the ten actions do not introduce support intended explicitly for repurposing. Instead, the support is aimed at large establishments like recycling. Still, it is essential to note that even though the ten actions do not specifically focus on repurposing, this does not mean that the supportive measures cannot be applied to repurposing operations. The Norwegian battery strategy does not introduce targets or requirements for repurposing EVBs. Therefore, the current and upcoming regulatory environment created by EU legislation also applies in Norway.

4.3 Finland

As Finland is part of the EU, it currently follows the Batteries Directive. The Finnish Government Act on batteries*, Valtioneuvoston asetus paristoista ja akuista (2014/520)*, has incorporated requirements of the Batteries Directive [68]. The Finnish Waste Act, *Jätelaki (646/2011)*, states that operators other than the producer may offer services related to the reuse of products or their preparation, so it is not limited to the manufacturer's right. [69] Therefore, operators other than battery manufacturers should have the opportunity to establish reuse or repurpose services for EOL batteries.

In January 2021, the Ministry of Economic Affairs and Employment published Finland's national battery strategy, which aims to strengthen the competitiveness and sustainability of Finland's battery sector. The vision is that, by 2025, the Finnish battery cluster will be a forerunner that provides skills, innovation, sustainable economic growth, well-being, and jobs in Finland. To achieve this, the strategy has identified seven objectives, 1. growth and renewal of the battery and electrification sector, 2. increase investments in the battery and electrification sector, 3. actors of the battery and electrification sector cooperate to promote competitiveness, 4. increase the global recognition of the Finnish battery and electrification sector, 5. responsibility as part of the growth, renewal, and brand of the Finnish battery sector, 6. Finnish actors play a key role in new value chains, and 7. digital solutions will expand the knowledge and business base and speed up the development of the battery sector. Several measures are proposed to achieve these objectives, including creating a national cooperation body for the battery industry, developing competitiveness with graduate and engineering programs, assigning battery ambassadors to promote Finland, and developing legislation to support the responsibility and recycling business. [70]

The strategy identifies that Finland has many strengths to succeed in the battery sector. Among others, these include the reserves of battery metals such as nickel, cobalt, and lithium, expertise in producing and recycling battery metals, cooperation between the public and private sectors, and socially and ecologically sustainable production. In addition, the strategy presents the main Finnish operators in the BVC, as illustrated in Figure 13. The repurpose operators include Merus Power, Wärtsilä, Fortum, and Helen. [70] However, unlike the Norwegian battery strategy, these are not start-ups solely focused on providing second-life battery solutions. Instead, Wärtsilä is collaborating with Hyundai Motor Group to repurpose their EVBs for second-life ESS [71]. Fortum has worked with Volvo Cars and Comsys to pilot second-life solutions for batteries [72]. No information about Merus Power, which offers various ESS, and the energy company Helen, could be found about their involvement in repurposing projects. In addition to those mentioned, there is Cactos, a company founded in 2021 that repurposes EVBs for ESS.

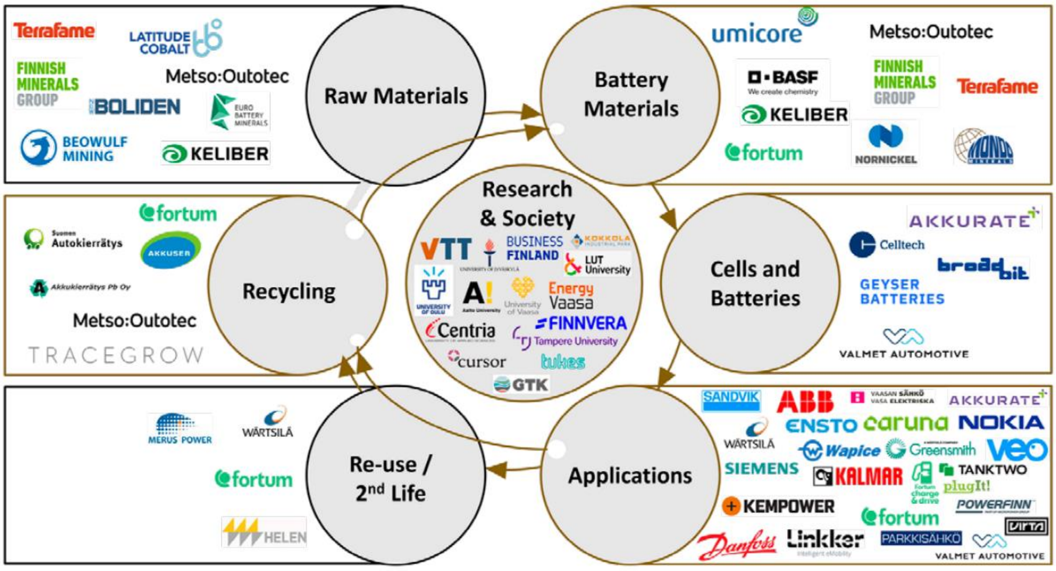

Figure 13. Main operators in the Finnish BVC [73].

The battery strategy also emphasizes that Finland intends to promote the CE of batteries. It states that CE is necessary for the sustainable success of the battery industry. Moreover, it is highlighted that Finland has the know-how, technologies, industrial activities, and research projects in several areas of CE. As an example, the Finland-based circular ecosystem of battery metals consortium (BATCircle) aims to increase the recycling of LIBs. However, it also notes that CE is much more than just recycling, and that one key goal is to extend the battery life cycle through repair, reuse [repurpose], or remanufacturing. It is mentioned that the reuse [repurpose] of batteries provides new opportunities and that Finland has reliable legislation supporting both reuse [repurpose] and recycling. [70]

To conclude, the Finnish battery strategy recognizes the importance of CE. However, despite aiming to promote the CE of batteries, no specific measures or targets are introduced to support the higher-level circular strategies such as repurposing. Instead, the battery strategy focuses on improving Finland's role as a competent, competitive, and sustainable operator in the international battery industry. Therefore, the current and upcoming regulatory environment created by the EU legislation also applies in Finland.

5 State-of-the-art

This chapter reviews the state-of-the-art of repurposing EVBs for energy storage applications. First, the repurposing process and its technical challenges are discussed, and possible solutions are introduced. Then, various second-life energy storage applications and example projects are presented. Finally, other challenges related to repurposing operations are discussed.

5.1 Repurposing process

The repurposing of EVBs is still an emerging technology. Defining a single unified process is challenging due to the various EVB pack designs. There is only one standard, UL 1974, which defines general safety operations and performance tests of EOL batteries but lacks detailed steps and specifics. Furthermore, thorough technical procedure information is typically unavailable in the open literature, despite a few exceptions. Based on the accessible literature, Zhu et al. (2021) have established a general overview of the repurposing procedure, which, among other sources, is the basis for reviewing the status and technical challenges in the repurposing process. The procedure consists of five main steps, 1. incoming assessment, 2. disassembly, 3. evaluation of mechanical, electrochemical, and safety performance, 4. sorting and regrouping, and 5. developing control strategies for second-life applications, see Figure 14. [45] Next, each step is described in more detail.

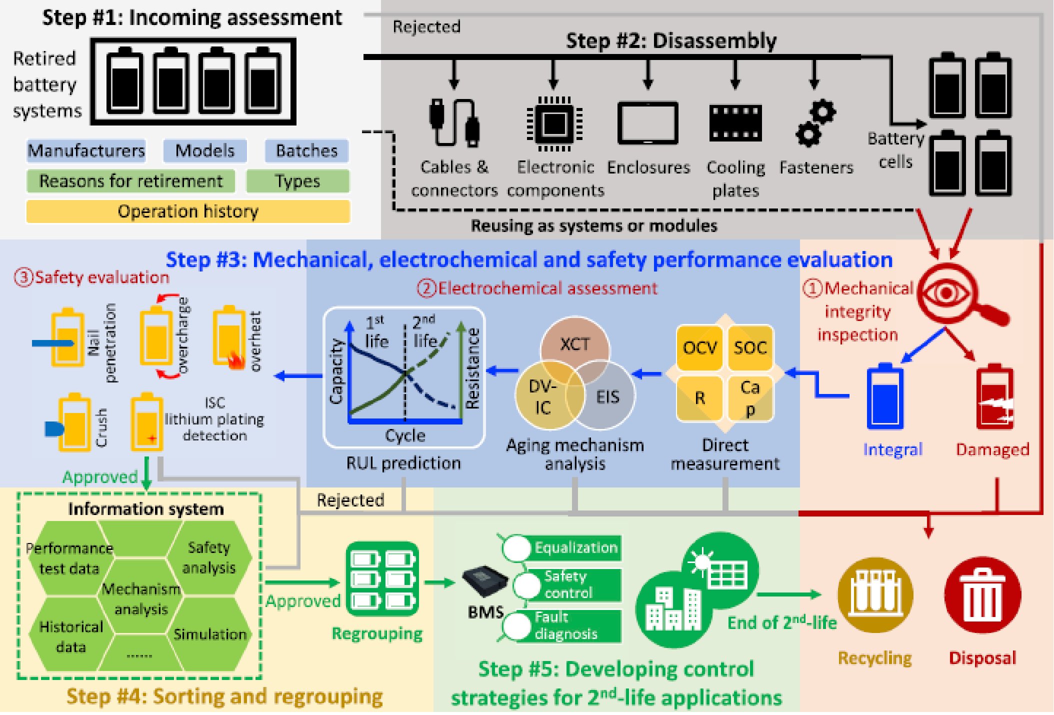

Figure 14. A general overview of the repurposing process and its steps [45].

To understand the condition and remaining potential of EOL EVBs, they must undergo an incoming assessment (step 1), for which historical battery information is essential. Among others, these include manufacturer, model, batch, date of manufacture, battery type, operation history, and reasons for reaching EOL. For EV and battery manufacturers, this information is readily available. However, the lack of battery information is a challenge for third-party operators, as information is typically not provided when EOL batteries are procured. Therefore, costly physical testing must be performed to assess the remaining value. [45] The uptake of data-driven approaches, such as the battery passport, electronic exchange system, and QR code labeling introduced by the Battery Regulation, could help streamline the initial assessment. Furthermore, blockchain technologies also have the potential for tracing battery components through their life cycle and other relevant information like origin, health, and past application [74].

Once it has been determined at which level the EVB is to be repurposed – pack, module, or cell – the disassembly process (step 2) can begin. The procedure includes opening the battery pack casing, removing electrical and mechanical connections between the cells, and removing the auxiliary parts [44]. Currently, the disassembly process is done manually and, thus, relies heavily on human labor, which is expensive and time-consuming compared to an automated process [12]. Therefore, the maximum level of disassembly, i.e., cell-level, typically results in greater costs and takes more time. This was, for example, the result of a study where a Smart ForFour battery was manually disassembled in 2019 at the Polytechnic University of Catalonia [75], see Table 2. This stems from battery modules, which are not designed to be detachable. For example, their joints are glued or welded, which requires forceful opening. Thus, it is preferable to repurpose either the EVB packs or modules to minimize costs. [45] Sometimes EVB packs can be directly repurposed, avoiding the expensive and lengthy disassembly. Still, dismantling is typically required due to the inconsistency of the battery cells [74].

Table 2. The cost and time of disassembly of pack, module, and cell [75].

	Pack	Module	Cell
Time	500 min	800 min	965 min
Cost	32 €/kWh	60 €/kWh	76 €/kWh

The greatest challenge for disassembly stems from the various EVB pack designs [44]. This complicates the current manual and the possibility of an automated disassembly process, as there are no general steps for different battery packs, and each pack requires specific procedures. For instance, cylindrical cells are the most difficult to dismantle in cell-level disassembly, followed by the pouch and then prismatic cells [12]. Thus, standardization of the EVB pack design plays a vital role in facilitating the disassembly process.

After cell-level disassembly comes the mechanical, electrochemical, and safety performance evaluations (step 3). The aim is to screen out cells that do not meet specific criteria and are unsuitable for second-life applications. In the first screening (step 3.1), the mechanical integrity of cells is evaluated by visual inspection. Cells with mechanical deformation are a safety risk for internal short circuits, thermal runaway, and fire. Thus, cells that show leakage or damage are disposed of. Currently, visual inspection is done by human workers, which makes it expensive, unreliable, and unsafe. Digital image-based approaches, X-ray-based techniques, and acoustic tools are promising alternatives for overcoming the shortcomings of manual labor. [45]

In the second screening (step 3.2), battery cells are assessed by their electrochemical performance based on direct measurements such as open circuit voltage, internal resistance, capacity, and temperature. The screening is done according to predefined criteria by the inspector. After that comes the accurate assessment of battery degradation, which is essential for estimating the SOH and predicting the RUL of the EVB. This step is especially challenging due to the complexity of battery degradation and the need for non-destructive assessment techniques to enable commercial repurposing operations.

According to Zhu et al. (2021), there are three methods for evaluating battery degradation 1. post-mortem examination-based, 2. charge-discharge curve-based, and 3. electrochemical impedance spectroscopy (EIS) and equivalent circuit model (ECM) based. However, post-mortem examination is typically related to destructive testing, which includes opening the battery and, thus, is not suitable for commercial operations. Instead, non-destructive X-ray computed tomography (XCT) is more appropriate but not a very established technique. The second category comprises differential voltage and incremental capacity (DV-IC) analysis, and the last method depends on the EIS test results. The key in the latter two methods is to correlate the measured electrical response with internal chemical and physical changes. XCT, DV-IC, and EIS-based techniques are currently only used for research or in the laboratory and are not yet suited for commercial use. [45] Thus, the development of non-destructive assessment methods is important for repurposing.

The SOH assessment differs for the various battery types and chemistries, an additional complication resulting in higher costs [74]. Standardization rises again as a solution for easing the SOH assessment. In addition, currently, there are no standards or reliable guidelines for assessing the SOH and RUL, which creates unreliability that could be an issue for potential customers. [12] Another problem with inaccurate SOH and RUL assessments is that EOL batteries might not find the optimal second-life application. RUL assessments also face the challenge of the non-linear aging process of LIBs, as second-life batteries (SLBs) are more likely to face the knee point, after which the capacity will undergo accelerated degradation [76]. Historical operation data could ease the SOH and RUL assessments, but this information is not easily available. However, the new Battery Regulation will require that repurposing operators can access the BMS of the EVB, which stores relevant parameters for assessing the SOH and RUL. This could facilitate the assessment processes.

Finally, batteries undergo a safety evaluation in the last screening (step 3.3). Currently, conventional safety tests such as thermal, electrical, and mechanical abuse tests for new batteries are also being used for testing EOL batteries. However, after their long operation period of hundreds or even thousands of cycles, the internal and external characteristics of EVBs have changed dramatically, leading to more significant safety risks [76]. Harsh operation conditions can result in minor abuses such as local internal short circuits, gas generation, or lithium plating. The changes in a battery's safety depend highly on the degradation history and mechanism. As batteries undergo complex and varying degradation processes, accurately estimating safety is challenging. Therefore, more advanced tests should be developed to detect minor defects in EOL batteries. In addition, due to the inconsistencies in EOL batteries, sampling algorithms are needed as safety tests should be performed on batteries with the lowest stabilities. [45]

After the screening processes, the eligible cells are sorted and regrouped with similar qualities to ensure pack homogeneity (step 4). During their first life, EVBs experience harsh operating conditions leading to inconsistencies in battery cells and modules. Cell-to-cell and module-to-module variations harm battery life and performance, so sorting is crucial for second-life applications. The first challenge is selecting appropriate indicators, which depend highly on cell type, battery chemistry, and demands of the second-life application. Some typical indicators include SOH, SOC, the voltage of pulse discharge, ECM fitting parameters, and thermal behavior. The other challenge is finding an effective and efficient sorting algorithm. There are two types: pursuing simplicity and high efficiency or solving high-dimensional problems with powerful but expensive statistical tools. [45] Moreover, the repurposed EVBs need to meet the physical dimensions of the energy storage applications, which may be challenging due to the various EVB designs [77].

Second-life applications require control and management strategies (step 5). First, as repurposed batteries have low energy and power capabilities, optimal battery sizing and appropriate control are necessary for smoothing power output, avoiding overcharge or over-discharge, and extending life cycle. Second, once second-life ESS is in operation, the emerging inconsistencies in cell-to-cell or module-to-module require active equalization strategies to ensure adequate and safe performance. Third, in addition to voltage, current, and temperature controlled by the BMS, repurposed battery systems also need advanced fault-diagnosis algorithms to rapidly detect internal short circuits, lithium plating, and gas generation. Multi-sensor-based algorithms combining data from voltage, current, temperature, and gas sensors are promising solutions. [45]

In conclusion, the main challenges of the overall repurposing process are costly human labor-based operations, lack of automation, absence of standardized indicators and models, and lack of high-efficiency algorithms. Solutions to improve the repurposing process include automation of battery disassembly and inspection, using advanced statistical algorithms for fast screening and sorting, assessing SOH with nondestructive acoustic waves, standardization of EVB pack designs, utilization of EIS-based and IC-DV techniques for modeling battery degradation, and incorporating of data-driven prognostics for determining RUL. However, further technological advancements are required until these solutions can be implemented. [45]

5.2 Second-life energy storage applications

Repurposed energy storage applications can be categorized by different criteria such as application area (residential, commercial, and industrial) and usage (grid stationary, off-grid stationary, and mobile), or mobility (stationary, quasi-stationary, and mobile) and user (grid operators and utilities or behind-the-meter customers) [12, 74, 76]. For this review, the categorization by usage is chosen for introducing various energy storage applications.

Grid stationary applications are typically large, in the MWh range. With the penetration of intermittent renewable energy sources (RES) like solar and wind energy, grid stability and integrity are at risk. Therefore, SLBs can be used for renewable energy farming, i.e., reducing the adverse effects of RES by storing excess energy when renewable generation ramps up and vice versa, providing energy when renewable generation ramps down. Another application for SLBs is generation-side asset management, in which the battery provides energy when the main power generation is momentarily suspended due to maintenance or other reasons. Third, SLBs can be utilized for energy arbitrage, i.e., storing electricity during off-peak hours and consuming stored electricity during peak hours. This includes peak shaving and load leveling applications, which reduce the need for peaking units and postpone investments in additional generation capacity [78]. Finally, SLBs are suitable for frequency regulation, which is about maintaining the nominal grid frequency in an acceptable range, and for real and reactive power injection that both help ensure grid stability. However, these applications are deemed potential, assuming SLBs cost less than new batteries. [77]

Off-grid stationary refers to isolated grids like microgrids that are small-scale electricity networks of consumers and local electric supply. Microgrids can be connected to the national electric grid and/or operate in standalone mode. When microgrids operate independently, the system stability and integrity face a challenge, especially with intermittent renewable production. Thus, SLBs can improve power quality and reliability with accurate and rapid responses by which short-duration disturbances can be prevented. In addition, repurposed batteries can be used for load following, where they are discharged and charged to alleviate demand fluctuations, and as spinning reserves, which in the case of a generation outage, can supply power to maintain grid stability. Again, the lower cost of SLBs is essential for the feasibility of these applications. Finally, regarding mobile applications, SLBs can be used as EV charging stations and for short-range vehicles such as delivery vehicles, forklifts, and e-scooters. [77, 78]

5.3 Examples of second-life energy storage projects

The first large-scale industrial projects for SLBs started only in the early 2010s. Since then, the number of projects has increased rapidly. For instance, all major automotive OEMs have initiated or are planning to launch SLB projects with their battery supplier or a third-party operator. [45] However, most activities are still relatively small-scale, including piloting, demonstration, and research and development. The volumes of EOL EVBs are still low, so large-scale activities are not yet feasible. [7] Below, a few real-life SLB projects are introduced.

Since 2018, the Johan Cruyff Arena in Amsterdam has been utilizing a 3 MW/2.8 MWh ESS consisting of new and repurposed batteries. Specifically, there are 590 battery packs, of which 250 are SLBs. The ESS provides additional backup power, peak shaving, and grid stabilization services. The ESS stores energy from the 4,200 solar panels or the grid during low-demand periods. During an outage, the ESS supplies sustainable power, reducing the use of diesel generators. In addition, the ESS is discharged during high peak consumption, such as concerts and football matches, which reduces the load on the electric grid. This project is a collaboration between The Mobility House, Eaton, Nissan, and BAM. [79]

Connected Energy collaborated with Groupe Renault to establish a 1.2 MW/720 kWh battery ESS, the E-STOR, for Umicore's industrial site in Belgium, see Figure 15. The ESS unit started its operations at the beginning of 2020. The ESS utilizes batteries that were used to power Renault Kangaroo Z.E. vehicles. The SLBs are expected to last another seven years. The E-STOR unit provides a firm frequency response that leads to revenue generation and maintains the power quality for Umicore's operations. [80]

Figure 15. The E-STOR battery ESS by Connected Energy. Reprinted with permission by [81].

In March 2022, a 4 MW/1.7 MWh backup ESS began operating in Melilla, a Spanish enclave in North Africa. As Melilla is isolated from the national grid of mainland Spain, the electricity needs of the 90,000 habitants are covered by a local microgrid. If a power plant is disconnected from the microgrid, the ESS can supply electricity for 15 minutes, allowing the plant to reset and restart power production. Thus, the second-life ESS helps to avoid situations of load shedding and improves the reliability and security of Melilla's grid. The backup ESS consists of 48 repurposed Nissan LEAF and 30 new ones. The EVB packs are used directly in the storage system, and no disassembly was required. The second-life project is a result of the partnership between Enel and Nissan. [82]

Jaguar and Pramac have collaborated to develop an off-grid battery ESS powered by Jaguar Land Rover's EOL I-PACE batteries. However, the current units utilize I-PACE batteries from test and prototype vehicles. Each ESS unit consists of 50 modules coming from the I-PACE batteries. The mobile and self-sufficient ESS, charged by solar panels, delivers zero-emission electricity in places without access to the grid. The flagship ESS system has a capacity of 125 kWh, see Figure 16. The unit proved successful in testing in the UK and Spain in the 2022 ABB FIA Formula E World Championship, where it was used to power the Jaguar team's diagnostic equipment to analyze the race car's performance and supply auxiliary electricity to the pit garage. [83]

Figure 16. Jaguar I-PACE batteries power the battery ESS. Reprinted with permission by [83].

In the previous examples, only LIBs were used in the second-life applications. However, in October 2022, Toyota and JERA introduced a 485 kW/1,260 kWh second-life battery ESS utilizing different battery types (lithium-ion, nickel-metal hydride, and lead acid), which is novel to the sector of repurposing. The so-called Sweep Energy Storage System is located at Yokkaichi Thermal Power Station in Nagoya, Japan, and is used for recharging and discharging operations. In addition, the ESS is equipped with a function called sweep, which enables the existence of differences in battery performance and capacity. The sweep function also allows series-connected batteries to be bypassed in microseconds. [84] This technological advance could solve the challenges arising from the high variability of EVB packs while also enabling the use of different battery technologies, which typically is not the focus of repurposing operators.

5.4 Challenges

In addition to the challenges of the repurposing process, there are other challenges to consider. The main recurring challenge relates to the uncertainty about the economic viability of SLBs [12, 30, 74, 76]. Economic feasibility is regarded as the most challenging issue for the widespread adoption of SLBs. The industry and individuals are still determining whether SLBs are cost-effective solutions [12]. Some suggest that without government subsidies, the economic viability of many SLB projects is unlikely [76]. However, before discussing the economic uncertainty in more detail, the cost breakdown of an SLB is introduced. The most significant factor affecting the cost of an SLB is the procurement of EOL batteries accounting for 56% of the total cost, as illustrated in Figure 17. The cost of labor and general administration share second place, accounting for 13% of the overall costs. Fourth is the cost of packaging materials for reassembling repurposed EV modules into a battery pack for the second-life application, accounting for 7% of the entire cost. [85]

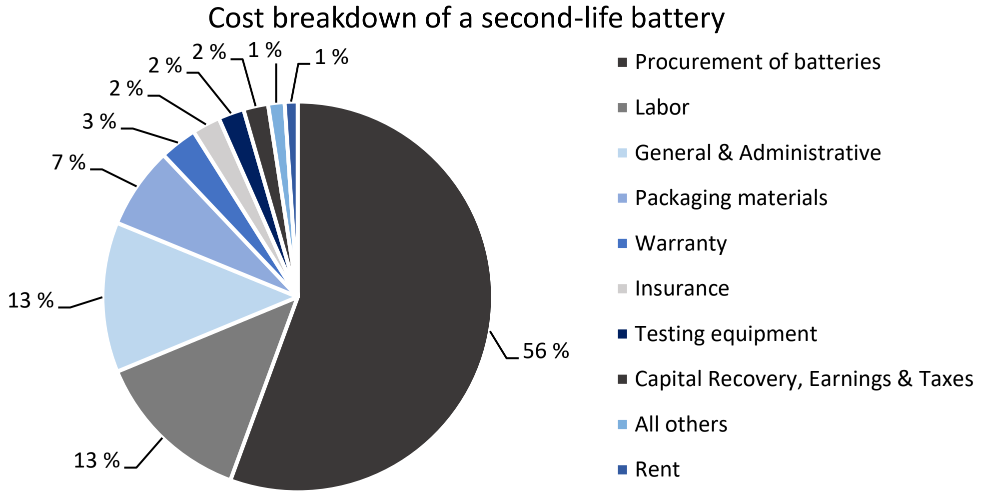

Figure 17. Cost factors of a second-life battery. Adapted from [85].

The sale price of an SLB is based on the purchase price of the EOL battery, the cost of repurposing, and a profit margin [74]. Thus, the expenses related to the repurposing process should be minimized to ensure the competitiveness of SLBs. The main cost factors of repurposing relate to the logistics of collecting EOL batteries, manual human labor, and the degree of disassembly [45]. Therefore, the aim is to procure EOL batteries as near as possible to either reduce the time technicians spend on each battery or transition to a more automated process and minimize the degree of disassembly. Nevertheless, the current estimations of SLB selling prices range widely between optimistic, reasonable, and high [12]. This suggests that there is still much uncertainty related to the cost factors of SLBs. Below, other issues affecting the cost competitiveness of SLBs are introduced.

First, repurposed EVBs compete with the cost of new LIBs [12, 30, 74]. Due to technological advancements and economies of scale in the battery manufacturing process, the cost of new LIBs is expected to decline further in the upcoming years. It is estimated that the cost of new LIBs will go below $100/kWh by 2026 [86]. This a challenge for SLBs as their sales price competes with the constantly evolving cost of new batteries. However, the highly fluctuating price of raw materials significantly impacts the cost development of new LIBs. For instance, according to BloombergNEF (2022), after a decade of decline, the price of new LIBs increased by 7% from 2021 to 2022 due to rising raw material and battery component prices [86]. Second, new technologies such as flow batteries are continuously being developed, which could eventually become more cost-efficient or provide better technical performance, resulting in a declined demand for SLBs [45]. Third, the shorter lifespan of repurposed batteries compared to new batteries also affects the economics of SLBs [12, 74]. Recent studies have shown that SLBs with a remaining capacity of 70-80% could have an extended lifetime of more than ten years. However, issues related to minor degradation inconsistencies, their impact on battery performance, and potential issues affecting module or pack performance due to sudden individual cell failure remain unsolved. [45] In addition, the shorter lifetime of SLBs results in system replacement, installation, logistics, and system downtime costs. Therefore, product certification and warranty must be comparable with new batteries to build consumer confidence in SLBs. [87]

The ownership of the EVB could affect the cost competitiveness of SLBs. There are two ownership models. First, the EVB is sold with the EV, so the car owner owns the EVB. Second, the EVB is leased so that the car manufacturer or importer retains the ownership of the EVB. In general, the ownership of EVBs is challenging because it is not always clear who owns a particular EVB, and ownership can even change during the car's lifetime, for example, after the warranty period. [7]

Battery availability is also a challenge for repurposing operations. It is commonly suggested that once an EVB has a remaining capacity of 70-80%, it reaches its EOL. However, this might be more applicable for first-generation EVs with shorter driving ranges, typically 100-200 km. Modern EVs have longer ranges, so a SOH of 70-80% could still be sufficient to supply the less demanding needs of other users. Thus, second-life operators will likely face competition with the used car market. [87] In addition, the repurposing industry aims to create homogenous batteries, as it improves the performance and lifetime of SLBs. Therefore, the availability of similar battery types might be a challenge. [12, 74] However, innovations such as the sweep function of Toyota could overcome the requirements for similar battery types.

Another challenge is the mismatch between the requirements of EVBs and specific energy storage applications. EVBs are designed for high energy density and fast charging rather than cyclic lifetime. The requirements for energy storage applications such as load leveling or home storage systems are the opposite: low C-rates, optimized for one full cycle per day, and high cyclic life. Similarly, according to another source, the C-rate is large for EVBs, while energy storage applications usually operate with a small C-rate [88]. Instead, electric long- and medium-haul trucks operate in conditions closer to these two applications. However, other storage applications with a typically low number of cycles, such as grid-level operating reserves and emergency power supplies, are deemed more suitable for EVBs. [87]

Repurposing also competes with recycling, a common practice for managing EOL EVBs. However, the market will likely decide whether the EOL EVB is repurposed or recycled: the highest bidding party gets the EVB. Repurposing operators should be able to pay a higher price because EOL EVBs have a greater value as SLBs compared to recovered metals. Also, the financial profitability of repurposing seems to be better than recycling. The cost of recycling an EVB is €450-1,300, while repurposing an EVB can generate at least €45/kWh in return. [7]

Safety is also a risk and challenge for SLBs [76]. Ensuring the safety of even new battery storage systems can be challenging. Battery accidents can have severe consequences and, in the worst case, lead to casualties. A single catastrophic accident could ruin consumer confidence in SLBs. This is particularly challenging for repurposing operators who are often new start-ups. A severe accident can make it difficult for a new business to regain consumer confidence. [87]

The final challenge is the lack of awareness. In general, recycling is a better-known circular strategy than repurposing. Even within the industry, repurposing is sometimes overlooked in BVC illustrations [88]. Another example is the European Battery Alliance's BVC, where recycling and second-life applications are placed in the same segment, despite the clear hierarchy between the two strategies [89]. Thus, more awareness about the environmental benefits of repurposing EVBs is needed to guide consumers and industry toward sustainable products and ensure enough demand for SLBs [74].

6 Methodology

The experimental part of the thesis aims to find answers to the research questions. The focus is on discovering challenges and barriers for repurposing operations and possible solutions to overcome them. The research methodology, key stakeholder interviews, was predefined by the TREASoURcE EU project. Interviews typically seek an in-depth understanding of perceptions about a focused topic. Since non-numerical data is collected in the interviews, the research is qualitative. Qualitative research methods are generally most suitable when little is known about a phenomenon or when attempts are made to generate new theories [89].

There are different interview types: structured, unstructured, and semi-structured. Of these three, semi-structured interviews blend the former two, combining the advantages of both: comparable, reliable data and flexibility in follow-up questions. [90] Semi-structured interviews usually consist of a limited number of predetermined closed-ended questions and many open-ended questions to elicit discussion on a topic [91]. Regarding the research objectives, the characteristics of semi-structured interviews are considered more suitable compared to the other two interview options. However, despite its strengths, a semi-structured interview also has its weaknesses. There is a risk of the Hawthorne effect, i.e., some participants tend to change behavior due to their awareness of being observed, observer bias, recall bias, and social desirability, which can be challenging to avoid entirely. In addition, there is a risk of interviewer effect in all interview types. [92]

6.1 Data collection

The interview participants were selected with purposeful sampling, which is widely used in qualitative research to select information-rich candidates related to the phenomenon of interest. Specifically, a purposeful sampling strategy called criterion sampling was utilized to ensure that the invited candidates met the predefined criteria. [93] Since the geographical scope of the thesis is the EU, participants must operate within Europe, which excludes participants from other geographical areas. Moreover, participants must meet at least one of the following criteria:

1. Participant represents a repurposing operator or a company
2. Participant has participated in a repurposing EVB project
3. Participant has knowledge of repurposing EVBs
4. Participant is or is considering being an end-user of repurposed EVBs

Based on these criteria, 51 candidates were invited to participate in the interview by email request, which described the research's purpose and the thesis's objective. Participation in the study was voluntary and could have been interrupted at any time. The interview questions were sent out a week before the interview to ensure participants had enough time to familiarize themselves with the topics. Despite the interviews being in both Finnish and English, the questions were only in English to avoid terminological misunderstandings due to translation.

The interview questions were worded neutrally to avoid the interviewer effect that could have resulted from unintentionally leading questions [92]. The questions were open-ended and close-ended, grouped into different themes: background, technology, economy, regulatory, environmental, consumers, and final considerations, see Appendix A. However, as an exception, the questions for end-users were slightly modified to be more suitable for exploring the same themes from their perspective, see Appendix B. Similarly, the technology theme questions were not included for end-users due to their lack of knowledge on the topic. Moreover, the questions were not numbered, but they were in a precise order under the themes, so all participants were asked the questions in the same order. The interview setting was also relaxed to stimulate open discussion of other related topics and to enable additional follow-up questions, both of which were successfully achieved.

A total of 18 interviews were conducted, of which 14 were one-on-one, while the other four sessions had two interviewees participating simultaneously. The 22 participants were from four countries, 12 from Finland, seven from Norway, two from Germany, and one from Sweden. All interviews were conducted via online video calls via Microsoft Teams and were recorded and transcribed for data analysis. During the interview, the interviewer shared their screen to ensure clear communication and understanding between the interviewer and interviewee. Therefore, in addition to listening to the questions, the interviewees could also read them themselves. The interviewees also had the opportunity to correct misinterpretations when the interviewer wrote down the answers. In addition, all interview answers were collected so that no aspect was overlooked due to the risk of observer bias.

Various stakeholder groups participated in the interviews, see Figure 18. The largest group was researchers, who represented 33% of participants. The research areas of these participants included LIB recycling, energy efficiency and process modeling, battery and thermal energy storage, battery cell manufacturing, and EV charging. Second were repurposing operators, who represented 28% of participants. The repurposing operators included companies that repurpose EVBs and sell them and other entities that have participated in repurposing projects. Third were end-users representing 17% of participants. The end-users included consumer groups participating in demo projects and considering procuring SLBs. Last were other stakeholder groups, including cluster management, supply chain service, government, and battery assembly for machines, each representing 5.5% of participants.

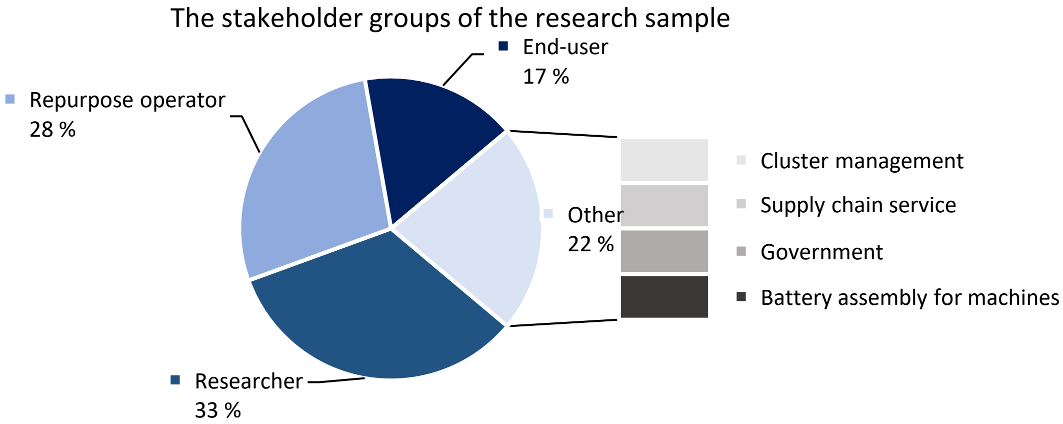

Figure 18. The different stakeholder groups in the research sample.

6.2 Data analysis

Thematic analysis is a suitable and effective method to understand experiences, thoughts, or behaviors across qualitative research data, such as interviews and survey responses. Thematic analysis is designed to search for common and shared meanings, and it has been suggested as a good first analytic method for novice qualitative researchers. [94] Based on the research objectives, thematic analysis was deemed suitable for analyzing the interview data.

In practice, thematic analysis is a method for identifying, analyzing, and reporting themes: topics, ideas, and patterns that come up repeatedly in the data [95]. Themes can be identified either with an inductive or deductive approach. Deductive can be described as a “top-down” approach, where the data is approached with preconceived themes expected to be present [95]. Whereas inductive is a “bottom-up” approach in which data determines the themes [95]. A deductive approach was deemed more suitable for this research, as challenges and solutions were expected to be found from the data. In addition, themes can be identified at a semantic or latent level. With a semantic approach, the themes are analyzed with the explicit meaning of the data, and nothing other than what the interviewee has said is sought. While a latent approach involves reading into the underlying ideas and assumptions of the data. [96] In this research, a semantic approach was deemed adequate.

The six-step thematic analysis method by Braun and Clarke (2006) was chosen because it is the most widely accepted framework for conducting thematic analysis [94]. Next, the different steps are introduced, focusing on how each step was conducted in this research. Step one is about the familiarization of the interview data [96]. Because the interviewer listened to and wrote down the interviewee's answers simultaneously, possible misunderstandings and points missed by the interviewer probably occurred. Therefore, the recorded interview sessions were relistened to complement and clarify the interview transcriptions. After this, the Finnish interview transcriptions were translated into English, and then all the English transcriptions were transferred to an Excel file to facilitate the next step.

Step two regards generating initial codes from the data. Coding refers to tagging or naming sections of interview transcriptions that appear relevant to the research objectives. As a deductive approach was chosen for this analysis, the data is approached with specific questions in mind. [96] In this case, the focus is on the challenges and solutions for repurposing operations. Therefore, everything in the data that could be a challenge, or a solution was coded. New codes were created whenever an aspect occurred for the first time, and reoccurring aspects were included in already-made codes. The codes were placed under two categories: the codes relating to challenges were placed under the challenges category, and the codes relating to solutions were placed under the solutions category. This facilitated the next step, in which the codes were grouped into themes. The qualitative data analysis software NVivo was utilized for coding the interview data.

After coding the data, themes were searched from the codes. This involved sorting the codes into possible themes and including all relevant codes under identified themes. Within each category (challenges and solutions), the codes were combined to form overarching themes. In the following step, the identified themes were reviewed in two phases. First, the aim was to ensure that the codes within the theme were relevant. Thus, codes were rearranged, and themes were modified to illustrate the coded data better. Themes were also added, combined, and discarded. In the second phase, the entire interview data was reviewed again to validate the found themes and recode data that fit under the modified themes. In the last step, the themes were defined and named. A definition and narrative description of each theme was created, including why it is important to the research. [96] The results of the thematic analysis, i.e., identified themes, are presented in the findings chapter.

6.3 Reliability and validity

Reliability and validity are used to evaluate the quality of research. According to Guba, the reliability and validity of qualitative research can be ensured by four criteria: credibility, transferability, dependability, and confirmability [97, 98]. Each of these criteria and the measures taken to ensure the trustworthiness of this research are briefly presented below.

Credibility relates to the truth value of the research findings. Various actions were taken to ensure the credibility of this research. First, well-established research methods were used to e.g., collect the research sample and analyze the interview data. Second, triangulation was implemented by having multiple and diverse data sources, i.e., the various stakeholder groups. Third, the honesty of the interviewees was ensured by having voluntary participation that could have been interrupted anytime without any specific reason. In addition, participants were informed that the interview data is anonymized, so answers cannot be traced back to the participants. Fourth, peer scrutiny was implemented by a public online webinar in which the result findings were presented to a broad audience, including some interview participants. The attendees were encouraged to provide feedback on the findings. Fifth, members check, i.e., ensuring the data's accuracy, were conducted during the interview by writing down the answers so that the participants could correct misunderstandings. Similarly, some participants were asked to elaborate on the meaning of certain answers after the interviews.

Transferability refers to how applicable the research findings are to other situations. In this research, the question relies on whether the research findings can be applied to a broader scope. However, to ensure transferability, the boundaries of the research have been clearly defined by the purposeful sampling, and information that does not compromise confidentiality has been provided about the interviewees, such as the number of participants, nationalities, stakeholder groups, and their share. In addition, the data collection process and data analysis method have been described in detail. Furthermore, the interview questions are available in the Appendices.

Dependability refers to the consistency and stability of the research findings. First, to address the dependability of this research, the research methodology, design, and process have been described thoroughly. In addition, the research process has been planned and discussed together with the thesis advisor and two other master's thesis workers who are conducting similar research studies. Finally, confirmability refers to the neutrality of the data and its interpretation. Before conducting the study, the researcher internalized the importance of a neutral approach to the research and conducted the interviews with an open mind to minimize confirmation bias. Triangulating data was also helpful in reducing investigator bias.

6.4 Methodological limitations

The methodological approach for this research has some limitations. First, due to the time constraint of the thesis, a limited number of candidates were requested to participate in the research. Second, the defined sampling criteria excluded other relevant stakeholder groups in the EV BVC, such as car manufacturers and LIB recyclers. Third, in a few instances, two or three questions were asked simultaneously from the participants. This was found to be unfavorable as sometimes all the questions were not answered. Thus, some perceptions of the interview topics were not obtained. Finally, confirmation bias may have occurred in interpreting the interview data as only one person conducted the research, and no peer review was performed. This kind of bias could affect the research findings.

7 Findings

This chapter presents the findings of the key stakeholder interviews. These are the found themes, i.e., challenges affecting repurposing operations and solutions suggested to overcome these issues. However, potential solutions were only found for some of the challenges.

7.1 Uncertain economic viability of second-life batteries

There was a strong consensus among the interviewees that the sales price is the decisive factor when choosing a battery. If the sales price of SLBs is the same as that of new batteries, new batteries are usually chosen. However, there were two exceptions. Considering climate goals and if the price difference is small, SLBs can be chosen instead of new batteries. In addition, new battery technologies were seen as a challenge if they become cheaper than SLBs. Examples from the interviews (researchers, end-users, and cluster management) elaborating on these topics:

> No one wants to pay the same price for SLBs, which are not manufactured and optimized for the storage application if you can get a new battery that is optimized for the application for the same price.
>
> I would not choose repurposed batteries if they were more expensive. The repurposed batteries are supposed to have a lower remaining lifetime than new batteries.
>
> If the costs are close to each other, then new batteries are certainly more popular. The sales price is the deciding factor.
>
> Based on climate goals and guidelines, repurposed batteries could be chosen even if they were more expensive. But the decision also depends on the price difference and the performance of the new battery compared to the repurposed battery.
>
> The cheapest battery would be chosen, financials are the main driver. However, if you don’t lose too many margins, the more expensive option could also be okay.
>
> Sodium-ion batteries [...] and flow batteries may be cheaper [...] than SLBs, which can be an economic challenge for SLBs.

Some participants also considered that SLBs need to have a clear cost advantage over new batteries. This was because SLBs have already degraded and have a shorter life than new batteries. Examples from the interviews (repurposing operators and researcher) on this topic:

> A significant "discount" e.g., 25% less than the first-life battery is needed to have the competitiveness of SLBs.
>
> Economic aspects are the fundamental driving force in all businesses. It must be central when discussing these matters. Half the price of new batteries could make SLBs feasible.
>
> An SLB can be, for example, 50% cheaper than a new battery, and it should be considerably cheaper than a first-life battery.

The economic competitiveness of SLBs with new batteries is still being determined based on the significant differences in the answers of the interview participants, see Figure 19. This can partially be explained by the different degrees of knowledge of the participants. Naturally, the repurposing operators have a better understanding of the costs of SLBs. However, as they only represent 28% of the interview participants, other answers may be based on assumptions or research studies. Nevertheless, even among the repurposing operators, there were different responses, suggesting that the economic viability of SLBs remains uncertain and case-dependent.

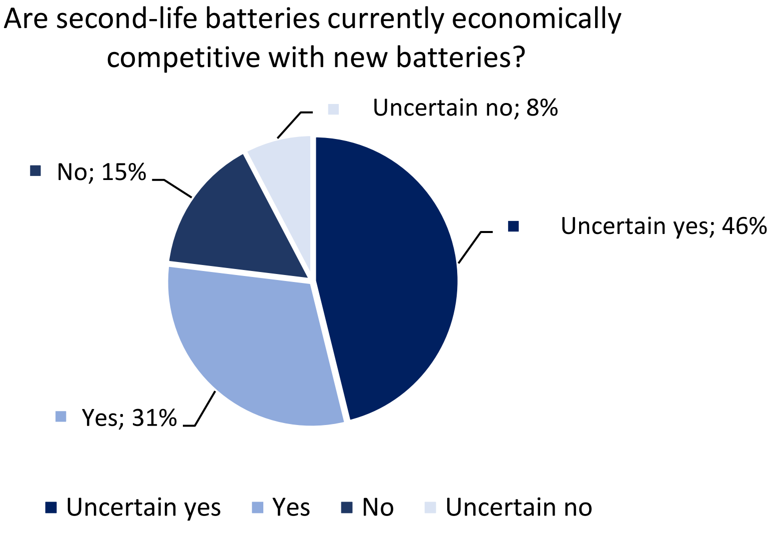

Figure 19. Answers to the cost competitiveness of SLBs.

In summary, the sales price of SLBs is currently competing with new batteries, and some consumers expect a significant cost advantage for choosing SLBs. In particular, the requirement to be cheaper than new batteries is a challenge for repurposing operations because the economic competitiveness of SLBs is still uncertain and varies from case to case. The solutions proposed by the participants to support the economic viability of SLBs included: tax removal, tax rebates, incentives, and paying for the carbon footprint.

7.2 Low availability of electric vehicle batteries

According to many participants, the low availability of EVBs is currently the biggest challenge for repurposing operations. However, participants expected the volumes to increase in the future. Another reason behind the low availability is that car manufacturers want their EVBs back. The reluctance of car manufacturers to provide EVBs is challenging because it could prevent repurposing operations. Examples from the interviews (government, researcher, and repurposing operators) on this topic:

> The biggest challenge is that there are no batteries.
>
> The scarcity of used EVBs now, but the amount will increase in the future.
>
> Supply and availability of EVBs but could change when the volume of old EVBs increase.
>
> Our biggest problem is having enough EVBs to complete our projects.
>
> Car manufacturers are not excited that old batteries are in circulation. If accidents happen it could negatively affect their brand image.
>
> The biggest challenge is being able to agree with the manufacturer about the EVBs.
>
> To build a business, the availability of similar batteries is essential.

7.3 Lack of battery information

The lack of battery information exchange with car manufacturers was also deemed a challenge for repurposing operations. Historical battery information exists but is not easily available for repurposing operators. This is because car manufacturers are typically reluctant to provide historical battery data. Examples from the interviews (repurposing operators) on this topic:

> There is always an information gap that comes from the battery manufacturer, all information is not generally available.

> Historical battery data is important information. However, automakers don't want to share this information.
>
> We often do not know how the batteries were used in their first life. Charging C-rates, DOD, and temperature data are often unknown and have a huge impact on how the batteries operate and when they could potentially fail. This information is not known to us.

Repurposing operators typically aim to access the BMS, which includes relevant technical information about the EVB. However, accessing the BMS is challenging as there is no common interface. There are different battery interfaces, making it challenging to work with different EVBs. In addition, extra testing is needed if there is no access to the BMS. Examples of interviews (repurposing operator, supply chain service, and researcher) on this topic:

> The main problem we face is the connection to the BMS. There is no standard connection interface for batteries, so each battery module needs a specifically designed plug.
>
> There is no uniform interface for the BMS where you can read the battery's condition. They are closed interfaces of car manufacturers that cannot be accessed.
>
> Repurposing an EVB without BMS access requires separate technical assessments to acquire relevant information.

The more historical information available, the easier it is to repurpose EVBs. Many procedures in the repurposing process, such as the SOH assessments, are already challenging, even with historical battery data. Without historical battery information, many of these procedures become more challenging. Examples of interviews (researcher and repurposing operators) on this topic:

> Performance evaluation is challenging because there is no way to know how the battery will degrade if we don't have historical data.
>
> The more information you get from the OEM, the easier it is to repurpose the batteries.
>
> The assessment of the batteries is not easy. [...] The reason for battery capacity loss can differ, the same SOH could result from different degradation mechanisms (different location and how has the EV been driven and charged). [...] Fast charging also affects degradation. It is not easy to find out this information.

In summary, the lack of battery information complicates the repurposing process from different aspects. A common practice is to access the BMS to acquire historical battery data. However, accessing the BMS is not straightforward, and special plugs are needed for different interfaces. In addition, the lack of battery data makes the performance evaluation of EVBs more difficult and may require additional testing. Thus, the lack of battery information increases the workload, which directly affects the sales price of SLBs.

The battery passport and the requirement to provide BMS data, proposed by the EU Battery Regulation, were seen as possible solutions to obtain relevant information. Another solution suggested was a blockchain tracking tool with different information access levels. In addition, paying the car manufacturers for battery data was also seen as a possible way forward.

7.4 Electric vehicle battery designs

Many technical challenges in the repurposing process stem from EVBs not being designed for a second life. For instance, the mechanical shape of EVBs is horizontal, while energy storage applications are built vertically, which requires altering the shape of the EVBs. In addition, there are also other technical mismatches between EVBs and energy storage applications, such as battery chemistries, voltage, and C-rates. These technical mismatches arising from the EVB designs are manageable. However, the challenge is more related to the additional costs of solving these technical mismatches, which directly affect the sales price of SLBs. Examples from the interviews (repurposing operators and government) on this topic:

> Today’s EVBs are not built for reuse [repurpose] (or even recycling). EV companies are 100% focused on EV costs and not considering the value that might be useable in reuse [repurpose].
>
> Repurpose is probably a nice dream, EVBs are not designed for a second life.
>
> The challenge is to disassemble the EVB, which hasn’t been designed to be disassembled.
>
> SLBs are probably not economically competitive with new batteries due to the extra cost of cooling, special mechanical structures, special cabling, and high C-rating compared to many demands in the market.
>
> Certain chemistries are poorly suited to second life, such as NCA with a short cyclic lifetime of 500 cycles, compared to LFP with 3000-5000

> cycles. NMC is in intermediate terrain. LTO has a long cycle life and is very suitable for SLBs.

A few participants also pointed out that there are new types of EVB designs that could prevent repurposing. Examples from the interviews (repurposing operator and researcher) elaborating on this issue:

> The new Tesla Model Y structural battery pack 4680 is part of the car's rear frame. The cells are glued to the car's frame. Second life is not considered in the design phase as the car likely needs to be recycled as it is difficult to remove the battery. In the worst case, if this design becomes popular, second-life applications can be prevented.
>
> Blade cell technology, possibly used in a new Tesla Model, cannot be dismantled.

Another challenge is the large and growing variability of EVB designs, which makes it difficult to automate the repurposing process. Manual labor is a significant cost factor that affects the sales price of SLBs. Thus, manually repurposed SLBs face price competition with new batteries manufactured by automated processes. Examples of interviews (repurposing operators, supply chain service, researchers) on this topic:

> The variability of EVBs is growing exponentially [...].
>
> The variety of EVBs makes it difficult to automate the disassembly process.
>
> Automation would be nice, but there are too many variables to make it work.
>
> Automated disassembly is a challenge without standardization – high variability even for one EV manufacturer.
>
> Repurposing will be too expensive if it cannot be done in an automated process.
>
> Disassembly takes a lot of time and money if EVB packs are not designed to be repurposed. Testing methods must be fast and automated, especially in large volumes, if done manually, it will be expensive, and can be more expensive than manufacturing new batteries.
>
> Labor is a big part of the price of an SLB — a new battery made by robots versus a manually repurposed battery.

Solutions for the above challenges are as follows. Car manufacturers should consider the second life of EVBs already in the design phase. Legislation should encourage EVBs to be designed as repurposable. Active intervention in the activities of car manufacturers is needed if the possibility of repurposing wants to be kept. The EU should promote the standardization of EVB designs. Currently, the variability issue is overcome using EVBs from the same car manufacturers. In this case, the availability of similar EVBs is essential.

7.5 Safety concerns

The safety aspects of EVBs were a recurring topic in the interviews. According to the interviewees, the risk of safety-endangering phenomena increases with degraded EVBs. It was deemed important to manage the increased safety risks so that accidents do not harm the reputation of SLBs. However, two participants considered that the safety of SLBs is on par with new batteries. Safety aspects were considered one of the main focus areas for repurposing. Examples from the interviews (repurposing operators and researchers) elaborating on this topic:

> The battery is already old, safety problems might occur more likely, e.g., thermal runaway.
>
> The longer the battery is in use, the greater the risk of dendrites, which can cause short circuits leading to thermal runaway.
>
> When the repurposing is done correctly, the battery is as good as new.
>
> SLBs are as safe as new batteries.
>
> Safety issues are the biggest problems of all. Reputation [of SLBs] could suffer, which would ruin the business opportunity and lead to the direct recycling of EOL EVBs.
>
> The safe operation of SLBs is important because there is a risk of ruining the reputation [of SLBs] with an accident.

Various solutions were proposed to ensure the adequate safety of SLBs. These included sensors to detect thermal runaway, control and management systems with automatic shutdown when limits are exceeded, temperature monitoring, extinguishing systems integrated into SLBs, advanced fault detection systems, local control for internet outages, self-healing methods, and cloud service monitoring. In addition, proper assessment of EVBs and quality assurance of SLBs were considered factors that increase safety.

According to nearly all participants, fire safety is the main concern of consumers. The increased safety risks of SLBs and the safety concerns of consumers are a challenge, as consumers may prefer to choose new batteries with lower safety risks. Examples from the interviews (repurpose operators and end-users) elaborating on this issue:

> Accidents have occurred even with new batteries, how will the safety of SLBs be ensured? How is safety monitored?
>
> The safe operation of repurposed batteries is important for consumers to be interested.
>
> Customers are most concerned about fire safety.
>
> The biggest safety concern is the risk of fire.

A possible solution to consumers' concerns is to place the SLBs outside in a separate or fireproofed room. In addition, discussing safety matters with consumers and addressing that adequate security measures are in place was seen as helpful. Furthermore, according to a few participants leasing an SLB could be less of a concern than buying an SLB.

7.6 Regulatory shortcomings

Regarding the current regulatory environment, the participants assessed that the regulatory framework is nearly non-existent due to a lack of standards and regulations for repurposing. Thus, EVBs can currently be repurposed by anyone, and DIY projects are already occurring, which could also harm the reputation of SLBs. Examples of interviews (cluster management, repurposing operator, government, and researchers) on this topic:

> The current regulation is almost non-existent for second-life applications. This [...] does not give our customers peace of mind regarding safety and longevity of the used batteries. There are, e.g., no certification standards for second-life systems, only validation standards.
>
> No standards for the repurposing process. Currently, anyone could start a repurposing business.
>
> Lack of standards. The whole repurposing process needs clear and adequate operating procedures.
>
> Home battery systems, especially if DIY are not safe.

> The lack of standards and regulations is causing dangerous situations. People are assembling batteries in their basements. There is no law prohibiting this kind of activity.

The EPR of EVBs was also seen as a possible challenge for repurposing. There was uncertainty about the practical implementation of the EPR. To enable repurposing, the EPR should be transferred from the EVB manufacturer to the repurposing operator, who will ensure the SLBs are recycled after reaching their EOL. This was the case with one repurposing operator. However, if the EVB manufacturer pays for recycling, they are entitled to the EVB before recycling, which may affect the availability of EVBs. Examples of interviews (repurposing operator and government) on this issue:

> The original producer responsibility must end with repurposing.
>
> Producer responsibility requires that batteries must be offered free recycling, the producer is responsible (paying) for recycling. The repurposing operators must participate in the recycling and collection after the second-life application.
>
> The producer responsibility side, if the producers pay for the recycling, they have the right to the battery when it reaches the end of its life cycle. How to ensure [the repurposing] step before recycling?
>
> We have a recycling agreement for our SLBs.

As for the upcoming regulatory environment, the recycling targets introduced by the Battery Regulation were a controversial topic. Some considered them negative for repurposing as they could steer EVBs toward recycling. Alternatively, repurposing was seen as a possible way for the car manufacturers to avoid the recycling targets and fees. Also, it was noted that the recovered content in new batteries does not have to come from batteries, and the recycled materials are typically not pure enough to be used in batteries. Examples from the interviews (repurposing operators and researchers) on this issue:

> The EU Battery Regulation's recycling targets are the biggest threat for the second-life industry. All batteries must/might undergo recycling to meet these recycling targets.
>
> The Battery Regulation's recycling targets could hinder repurposing.
>
> Recycling targets are not a very good thing.
>
> Recycling targets could be an issue.

> If the manufacturers can avoid these [recycling] targets by sending the batteries to companies like us for second-life applications, it could be very helpful. We offer auto companies a solution to sell their batteries to us, rather than pay for recycling.
>
> The purity of recycled materials (nickel, cobalt) is difficult to achieve. Therefore, recovered materials are typically downgraded and used elsewhere. The purity of the recycling processes is not enough to return [materials] to battery applications. Instead, recovered materials go to other applications like the production of steel. [...] The recycled material in new batteries does not have to be from an old battery.

Regarding regulation, participants suggested additional measures, support, and targets for repurposing. However, the practical implementation of repurposing targets was unclear because repurposing was considered to be at a level that is challenging to describe at the regulatory level.

7.7 Competition with recycling

Nearly all participants considered that repurposing and recycling strategies complement each other. The common reasoning behind this was that extending a battery's life cycle does not prevent recycling. Repurposing was considered an additional step; eventually, all batteries would be recycled. Examples from the interviews (researchers and repurposing operator) on this issue:

> A repurposed battery's life cycle is extended, which reduces [the battery's] carbon footprint. Eventually, the battery will face recycling.
>
> Waste hierarchy: always repurpose with as little energy as possible before recycling. As long as the battery can be used, it is worth more than recycling, only finally recycling.
>
> First, remanufacture, then repurpose, and finally, recycle.

Despite the complementary nature of repurposing and recycling, recycling was seen as a competing strategy with repurposing for several reasons. First, recycling frees valuable materials from EOL EVBs based on older battery technology, and the recovered materials could be used to manufacture new, more efficient batteries. Second, there is a lot of development in recycling, and recycling was considered more easily scalable to mass production, potentially making recycling cheaper than repurposing. Third, Tesla's new EVB designs were seen as a push toward recycling. Fourth, there are a lot of future-oriented recycling facilities. Fifth, there is a strong lobby for recycling.

Examples from the interviews (battery assembly for machines, researchers, repurposing operators, supply chain service, and government) on this issue:

> Battery technology is constantly developing. Would it make more sense to take the materials from used batteries into new and better batteries, on the long run, it can also become cheaper.
>
> The technical properties of batteries change faster than the batteries wear out in use. The technology of a ten-year-old EVB is very old compared to new batteries, so recycling could make more sense.
>
> Recycling is being developed a lot; it will probably become cheaper.
>
> It is easier to scale recycling into mass production.
>
> Recycling could be a challenge in the future if it is more cost-effective. Tesla's actions [new EVB design that could prevent repurposing] push in the direction of recycling.
>
> Direct recycling [of EVBs] without second life will be mainstream.
>
> A lot of future-oriented recycling projects are being built.
>
> The lobby for recycling is way bigger.

The EPR requires EVB manufacturers to pay for recycling EVBs, but the price of metals can change the status quo. High metal prices encourage the recovery of valuable metals. Specific battery chemistries, such as NMC, are so valuable that recyclers pay to receive them during times of high commodity prices. However, other battery chemistries, such as LFP, do not contain as valuable metals, and thus, the EVB manufacturers must pay for their recycling. Still, there is a risk that recyclers are willing to pay more for EOL EVBs than repurposing operators. Examples from the interviews (repurposing operators and researcher) on this topic:

> The increase in the price of metals encourages the recovery of materials that were not recovered before.
>
> The value of the metals in the battery is worth more than repurposing for second-life applications. There is a huge demand for metals (nickel, cobalt) on the market, and batteries contain them.
>
> LFP is not that valuable for recycling, you may have to pay to get rid of it. NMC has such a great value that it is paid for (the recycler pays).

> If recyclers would pay more for EOL EVB than repurposing operators, it could affect business by making the price of SLBs very high.

7.8 Consumer preferences

The last challenge is related to consumer preferences. Even if SLBs have a significant cost advantage, not all consumers would necessarily choose them. This is because some consumers prefer new products over old ones. Consumers may be concerned about the shorter lifetime or increased safety risks of SLBs. These concerns can lead to reduced demand and, thus, challenge the repurposing business. Examples from the interviews (end-user, repurposing operator, and supply chain service) on this issue:

> Some people don't want to have a used thing that needs to be trusted. People want the best and newest model [...] instead of the old one, especially if it doesn't cost much more.
>
> The masses of consumers prefer new materials compared to old ones.
>
> There is always a bias towards new products as they are bound to last longer, have cheaper ongoing costs, and are less likely to fail.
>
> There is a greater worry about used products than for new products.

In contrast, SLBs were found more appealing than new batteries due to their environmental benefits, such as the lower carbon footprint. Therefore, some consumers could choose SLBs over new batteries, increasing demand for SLBs. Examples of the interviews (end-user, researchers, and repurposing operator) on this topic:

> Customers are indeed interested in repurposed batteries because they are cheaper and have a lower environmental footprint.
>
> Consumers could choose to repurposed batteries for ethical reasons. SLBs do not require new raw materials.
>
> Any company that has environmentally friendly goals would choose second-life batteries.
>
> Repurposed batteries are more attractive because they are in line with climate plans and goals.
>
> Repurposed batteries have a lower carbon footprint.

8 Discussion

This chapter scrutinizes and compares the research findings to the reviewed literature. The following eight challenges for repurposing were found in the interviews: the uncertain economic viability of SLBs, low availability of EVBs, lack of battery information, EVB designs, safety concerns, regulatory shortcomings, competition with recycling, and consumer preferences. These challenges are also further explored to identify their common drivers.

The uncertain economic feasibility of SLBs was a reoccurring topic in the interviews and literature review. According to Shahjalal et al. (2022), consumers would choose new LIBs over SLBs if they cost the same and the environmental effect is neglected [74]. Similarly, Haram et al. (2021) stated that if the price of new LIBs is the same as for SLBs, consumers would prefer the new LIBs if the environmental benefit were overlooked [12]. Likewise, the interview findings suggest that if the sales price of SLBs is the same as that of new batteries, new batteries are usually chosen. This can be explained by the great importance of price in the purchase decision. SLBs have a lower lifetime and increased safety risks compared to new batteries, so it is understandable why there should be a financial inducement.

Based on the interview findings, the economic viability of SLBs is still uncertain and case-dependent. Similarly, Haram et al. (2021) concluded that the cost aspects of SLBs require further investigation due to the significant variations of SLB selling prices in conducted studies [12]. The uncertain economic viability can be explained by the different approaches for repurposing, e.g., repurposing on a pack or a module level, and varying labor costs. According to the reviewed literature and the interview results, achieving a competitive sales price for SLBs is crucial for the repurposing business. Therefore, everything increasing the sales price of SLBs can be considered an issue, such as the variability of EVB designs that prevents automation, additional testing due to the lack of battery information, and measures to resolve technical mismatches. Without a financial inducement, the repurposing business may struggle to thrive. Therefore, cost minimization is essential.

The low availability of EVBs was deemed the biggest challenge for repurposing in the interviews. This is partially explained by the novelty of EVs, which have become common only in recent years, and by the long lifetime of EVBs. Data suggests that larger volumes of EVBs will come to the market already in the next few years [1, 7]. However, a more significant challenge was the reluctance of car manufacturers to provide EVBs. The different ownership models of EVBs could be a potential solution. Some EVBs are owned by car owners that could be open to selling the EOL EVBs for repurposing operators.

However, more information about the different EVB ownership models and their prevalence would be needed to be certain.

According to Börner et al. (2022), the used car market will also affect the availability of EVBs. It was found that the lower technical capabilities of EVBs could supply the needs of other consumers. Thus, instead of being repurposed, the EVB would continue its life cycle in the car with another consumer. This way, the repurposing step may be missed for some EVBs. [87] In fact, according to the 9R framework, this would be desirable because reuse is a higher-level circular strategy than repurposing. This perspective did not come up in the interviews, probably due to the used car market that has not yet widely emerged for EVs.

The interviews also found that the availability of similar EVBs is important for a repurposing business. Typically, repurposing operators tend to use similar EVBs to facilitate the repurposing process. According to Haram et al. (2021), the availability of similar EVBs is challenging due to the various types, shapes, and chemistries. However, it was considered that matching similar batteries is important for better performance and longer lifespan of the SLBs. [12] Despite different perspectives, the availability of similar EVBs is especially challenging due to the large and growing variability of EVBs.

In summary, several aspects affect the availability of EVBs. Nevertheless, some EVBs are likely to become available for repurposing. However, this volume may not be sufficient for the second-life business, or without a sufficient supply of similar EVBs, repurposing may become unviable. Since no solutions to the EVB availability were found, this issue should be further investigated if the repurposing opportunity wants to be preserved.

The lack of battery information is a cost factor and a safety risk. The interview findings revealed that repurposing operators often do not have all relevant data about the EVBs. This leads to the need for additional testing, which directly affects the economic viability of SLBs. Similarly, Zhu et al. (2021) discussed that the scarcity of battery data results in costly additional tests [45]. However, it should be noted that further tests and assessments do not replace missing first-life battery data. Without appropriate historical information determining the safety of EVBs can be difficult. According to Roschier et al. (2020), various first-life experiences can increase the risk of thermal runaway. Thus, without relevant first-life data, ensuring safety can be challenging. The battery passport and access to BMS data introduced by the EU Battery Regulation were found as possible solutions in the interviews and the regulatory review. However, the practical implementation of these measures could take some time, e.g., the battery passport should only be in use by 1 January 2026 [58]. This is problematic because the information is already needed today. Therefore, in the meanwhile, partnerships between car manufacturers and repurposing operators become increasingly important.

The interviews revealed that EVB designs are a cost factor as they prevent the automation of the repurposing process and require additional measures to resolve technical mismatches. Likewise, according to Harper et al. (2019), the various EVB designs of car manufacturers make it challenging to automate the disassembly process for repurposing [44]. However, a more alarming finding in the interviews was the new EVB designs that could potentially prevent repurposing, as the EVB cannot be removed from the car. Such actions should be urgently addressed if the possibility of repurposing is to be preserved. It was also found that the second life of EVBs has not been considered in their design phase. This is problematic because large volumes of EVs are already entering the market. The proposed solutions, such as standardization and design for repurposable, should have been considered already before the commercialization of EVs. Implementing the proposed solutions will take time; thus, it is unlikely that the challenges resulting from EVBs designs will be avoidable in the near future. Still, EU legislation should support EVB designs to be repurposable and encourage some level of standardization.

Safety concerns came up in the interviews and the literature review. Accidents have occurred even with new batteries, so it is reasonable why consumers are concerned about the fire safety of SLBs, which have increased safety risks. In the past, various companies have had to recall even new batteries. For instance, in 2021, Hyundai recalled 82,000 EVs to replace the EVBs after 15 fires [101], and around 7,200 LG solar energy storage batteries were recalled after nine incidents [102]. Thus, concerns about harming the reputation of SLBs are not unfounded. Recurring or fatal accidents could damage the reputation of SLBs and create fear or stigma that could suppress the demand for SLBs. According to Börner et al. (2022), even a single accident can weaken customer confidence in SLBs, and that new repurposing businesses may not be able to rebuild customer trust [87]. Similarly, accidents that could harm the reputation of SLBs were also noted in the interviews. Therefore, safety aspects should never be compromised with SLBs because even one mishap could hurt the second-life business opportunity.

The regulatory shortcomings in the interviews are similar to those found in the regulatory review. For instance, the inadequacy of the current regulatory environment was considered negative due to DIY projects that could harm the reputation of SLBs. Fortunately, the upcoming Battery Regulation sets requirements for repurposing, i.e., to ensure that examination, performance testing, packing, and shipment are carried out following adequate quality control and safety instructions. While these requirements do not directly prohibit DIY projects, they introduce obligations. In addition, the recycling targets of the Battery Regulation were seen as a threat for repurposing.

New perspectives on regulatory matters also emerged from the interviews. First, repurposing could be a way for car manufacturers to avoid the recycling targets. Second, the recycled materials in new batteries do not need to come from used batteries. Third, the EPR could affect the availability of EVBs. The first two findings suggest that the recycling targets might not steer EVBs toward recycling. Instead, they could encourage car manufacturers to sell their EVBs for repurposing operators. Also, EVBs do not need to be recycled to meet the recycled battery content targets in new batteries, as recycled materials can originate from other sources. Regarding this topic, a new perspective emerged: the purity of recycled battery materials is insufficient to manufacture new batteries. This is interesting because it would challenge the common ideology of using recycled battery materials for manufacturing new batteries. However, this perspective would require more research, especially as recycling processes constantly develop. Finally, the uncertain EPR matters are somewhat clarified by the official draft negotiation text of the Battery Regulation, which states that the EPR will apply to repurposing operators:

> An economic operator making available on the market for the first time within the territory of a Member State a battery that results from preparing for reuse, preparing for repurpose, repurposing or remanufacturing operations shall be considered as the producer of such battery [...] and shall have an extended producer responsibility [53].

According to the 9R framework and the interview findings, repurposing and recycling are complementary circular strategies. However, many factors creating competition between repurposing and recycling were found in the interviews. Roschier et al. (2020) stated that the market will likely decide whether the EVB is repurposed or recycled, as the highest bidding party gets the EVB. They assumed that repurposing operators should be able to pay a higher price because SLBs are more valuable than recovered metals. [7] However, in the interviews, it was noted that during high metal prices, recyclers might also compete for EVBs, which could increase the sales price of SLBs. Despite all the aspects inducing competition, repurposing will occur if it is market-based. It should also be noted that the LIB recycling technology is not very well developed, it is still costly to recycle, and the yield from large-scale recycling is relatively low. So, recycling still has a way to go before it can meet the recycling targets of the upcoming EU Battery Regulation.

While the sales price of SLBs is the main factor affecting purchase decisions, consumer preferences also matter. It was found in the interviews that even if a significant cost advantage was achieved, not all consumers choose SLBs.

Some consumers simply prefer new products over old ones. Such a consumption habit represents linear economy, “take-make-waste,” that is not sustainable. The transition to CE requires the implementation of higher-level circular strategies and a change in consumption habits. Thus, incentives and willingness to buy used products should be supported. However, it was also found that some consumers are willing to pay even a bit more to choose the more environmentally friendly option. Many consumers consider SLBs more appealing than new batteries due to their lower carbon footprint. Such consumer preferences support the second-life business and contribute to transitioning to CE. Despite some consumers preferring new batteries, there will likely be sufficient demand for SLBs due to their environmental benefits, especially as environmental aspects have become increasingly important in recent years. Consumer preferences were not assessed in the reviewed literature, which could indicate a possible knowledge gap.

Various common drivers can be found in the eight challenges that point to essential factors for repurposing. The common drivers include the financial aspects, actions of car manufacturers, factors steering EOL EVBs toward recycling, reputational harm to SLBs, and role of consumers. The main driver was the financial aspects, as four (7.1, 7.3, 7.4, and 7.7) of the eight challenges somehow touched upon the sales price of SLBs. The actions of car manufacturers emerged in three challenges (7.2, 7.3, and 7.4). These actions relate to car manufacturers’ unwillingness to provide EOL EVBs, battery information, and designs of EVBs. Similarly, various factors steering EOL EVBs towards recycling were noted in three challenges (7.4, 7.6, and 7.7). These factors include the new EVB designs preventing repurposing, EU Battery Regulation’s recycling targets, and high metal prices. Accidents that could cause reputational harm to SLBs were discussed in three challenges (7.2, 7.5, and 7.6). The last driver is the role of consumers which occurred in two challenges (7.5 and 7.8). Consumers can impact the uptake of SLBs positively or negatively. For example, battery accidents could frighten consumers and, thus, reduce demand. Alternatively, consumers could choose SLBs over new batteries even if they were more expensive due to their environmental benefits.

9 Conclusions

This thesis aimed to assess the operational environment for repurposing EV LIBs for energy storage applications in the EU. For this purpose, an extensive literature review and key stakeholder interviews were conducted. This chapter concludes the thesis by answering the research questions and drawing the research findings into more general perspectives. It also discusses the research limitations and proposes recommendations for further research.

The first research question concerns assessing the EU regulatory environment for repurposing operations. The research findings indicate that the current regulatory environment is practically non-existed due to a lack of standards and legislation for repurposing. This has resulted, e.g., in unsafe DIY projects that could harm the reputation of SLBs. Thus, it can be concluded that the current regulatory environment is poorly regulated for repurposing. Whereas for the upcoming regulatory environment, which relates to the new EU Battery Regulation repealing the Batteries Directive, the research findings suggest that the recycling targets are negative for repurposing as they could steer EVBs toward recycling. However, the findings also suggest that the new requirements for repurposing provide a small legal framework. Thus, it can be concluded that although the upcoming regulatory environment should be more appropriate for repurposing, it may come with factors that steer EVBs toward recycling. However, the practical implications of the Battery Regulation may become apparent only after it has entered into force.

The second research question regards the challenges and barriers for repurposing operations. A total of eight challenges were discovered from the key stakeholder interviews, which suggests that there is a diverse variety of challenges affecting repurposing operations. These findings were supported by the extensive literature review. In addition, the found challenges are quite complex as various factors typically influence them. For instance, the reluctance of car manufacturers to provide battery data, the difficulty to access the BMS, and the additional testing procedures make the lack of battery information a challenge. Thus, it can be stated that a diverse variety of complex challenges affect repurposing operations.

The eight challenges were further explored, and five common drivers were found pointing to the essential factors for repurposing. The main driver was the financial aspects, which occurred in half of the challenges. This indicates that the economic aspects have a pivotal role in the feasibility of the second-life business. Another important driver was the actions of car manufacturers. These include the EVB designs, and unwillingness to provide battery information and EVBs that directly affect repurposing. Thus, it can be stated that the actions of car manufacturers strongly influence repurposing operations.

Apart from two issues, the research findings indicated that the challenges should be manageable by different means. For example, the economic viability of SLBs can be achieved with financial incentives, the lack of battery information can be solved with additional testing, safety can be ensured with adequate measures, and regulations can be updated. However, no solution was found for the sufficient supply of similar EVBs, which is essential for the second-life business. Similarly, no solution was found for the new EVB designs that prevent repurposing. The repurposing business opportunity can be lost with very low or no availability of EVBs. Therefore, it can be concluded that the low availability of EVBs and new EVB designs are potential barriers for repurposing operations.

The last research question concerns actions and measures that could support repurposing operations. Due to the diverse variety of complex challenges, no single universal solution was discovered from the research findings. Instead, for each challenge, various solutions were proposed. For instance, tax removal, tax rebates, incentives, and paying for the carbon footprint were proposed as possible solutions for achieving the economic viability of SLBs. Similarly, sensors, extinguishing systems, and self-healing methods were suggested as potential solutions to overcome safety concerns. Since the actions and measures supporting repurposing vary depending on the challenge, it can be stated that the solutions are case-specific.

9.1 Limitations of the research

Although one interview study gives an indication of the factors affecting repurposing operations, the findings cannot be considered a broadly researched and accepted overview. In addition, the research mainly focused on the national perspectives of Finland and Norway, despite the geographical scope of the EU. Of the 22 interview participants, 19 were from Finland and Norway, and only three of the 27 EU member states participated in the research. Hence, the research findings represent perspectives from a relatively limited geographical area. Therefore, the research findings are not transferable to the entire EU or other geographies where the challenges could differ due to varying legislation or other aspects.

Despite the various key stakeholder groups that participated in the research, other relevant stakeholders, such as car manufacturers and EV LIB recyclers, were not involved. Both have a significant role in the EV BVC, and thus their input would be beneficial for answering the research questions. In addition, only 38% of those invited participated in the research. Due to these reasons, it is possible that some important aspect was overlooked, and thus the research findings might represent the challenges from a limited point of view. For example, it was found that the actions of car manufacturers strongly influence repurposing. Since car manufacturers were not involved in the research, exploring issues from their perspective was impossible.

Another limitation relates to the nature of research methodology. Interview participants typically answer according to their understanding of the topic, and therefore, achieving entirely objective answers is challenging. In addition, it can be difficult to eliminate and notice the Hawthorne effect and social desirability bias, which can undermine the validity of the research. Furthermore, it is also possible that interviewees might pursue their interests with certain answers. Also, some reservedness was observed as participants did not want to disclose confidential business information. Thus, some relevant information could have been lost.

9.2 Suggestions for further research

As these research findings provide limited insight into the challenges for repurposing, it is advised to study this topic with a greater geographical research sample e.g., including a wider representation of the EU member states. Since the research process is described in detail, this study is easily replicated in other regions. In addition, the participation of other key stakeholder groups, such as car manufacturers, is pivotal for defining a holistic overview of the operational environment, challenges, and possible solutions. Furthermore, as the EU participates in international trade, the challenges for repurposing could be researched with a much broader geographical scope. For instance, the effect of different regulations could be important to understand when importing or exporting SLBs between trade areas.

Another further research area relates to the low availability of EVBs and new EVB designs that were determined as potential barriers for repurposing. Adequate volumes of EVBs are pivotal for the second-life business. Thus, more research is needed to estimate the sufficiency of EVB volumes. In addition, if the repurposing possibility is to be preserved, further research is required to address the new EVBs designs preventing repurposing.

References

[1] International Energy Agency (IEA). Global EV Outlook 2022. Paris: IEA, 2022. Available from: https://www.iea.org/reports/global-ev-outlook-2022.

[2] Norsk elbildforening. Norwegian EV policy [Online]. Available from: https://elbil.no/english/norwegian-ev-policy/ (Accessed 28.10.2022).

[3] Norsk elbildforening. Personbilbestanden i Norge fordelt på drivstoff [Online]. 2022. Available from: https://elbil.no/om-elbil/elbilstatistikk/elbilbestand/ (Accessed 15.9.2022).

[4] Autoalan Tiedotuskeskus. Passenger car fleet by fuel type [Online]. 2022. Available from: https://www.aut.fi/en/statistics/vehicle_fleet/vehicle_fleet_by_fuel_type/passenger_cars (Accessed 18.10.2022).

[5] Norsk elbildforening. Elbilsalg [Online]. 2022. Available from: https://elbil.no/om-elbil/elbilstatistikk/elbilsalg/ (Accessed 8.12.2022).

[6] Autoalan Tiedotuskeskus. Ensirekisteröityjen henkilöautojen käyttövoimatilastot [Online]. 2022. Available from: https://www.aut.fi/tilastot/ensirekisteroinnit/ensirekisteroinnit_kayttovoimittain/henkiloautojen_kayttovoimatilastot (Accessed 8.12.2022).

[7] Roschier S, Pitkämäki A, Jonsson H, Gaia Consulting Oy. Business Finland: Assessment of Li-ion battery reuse solutions – final report. 2020. Available from: https://www.businessfinland.fi/4974e0/globalassets/finnish-customers/02-build-your-network/bioeconomy--cleantech/batteries-from-finland/assessment-of-li-ion-battery-reuse-solutions.pdf.

[8] European Union: European Commission. Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability. COM/2020/474 final, 2020. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0474&from=EN.

[9] European Parliamentary Research Service. New EU regulatory framework for batteries [Online]. 2022. Available from: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689337/EPRS_BRI(2021)689337_EN.pdf (Accessed 12.10.2022).

[10] Potting J, Hekkert M, Worrell E, Hanemaaijer A. Circular economy: measuring innovation in the product chain. The Hague: Agency PNA, 2017.

[11] Tao Y, Rahn CD, Archer LA, You F. Second life and recycling: Energy and environmental sustainability perspectives for high-performance lithium-ion batteries. Science Advances. 2021;7(45), ISSN 2375-2548. https://doi.org/10.1126/sciadv.abi7633.

[12] Haram MHSM, Lee JW, Ramasamy G, Ngu EE, Thiagarajah SP, Lee YH. Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges. Alexandria Engineering Journal. 2021;60(5): 4517-4536, ISSN 1110-0168. https://doi.org/10.1016/j.aej.2021.03.021.

[13] Miao Y, Hynan P, von Jouanne A, Yokochi A. Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements. Energies. 2019;12(6): 1074, https://doi.org/10.3390/en12061074.

[14] Michaux S. Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels. 2021. https://www.doi.org/10.13140/RG.2.2.34895.00160.

[15] Energy Information Administration (EIA). International Energy Outlook 2021. 2021. Available from: https://www.eia.gov/outlooks/ieo/.

[16] European Commission. Questions and Answers on Sustainable Batteries Regulation [Online]. 2020. Available from: https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_2311 (Accessed 6.10.2022).

[17] McKinsey & Company. Global Energy Perspective 2019: Reference Case [Online]. 2019. Available from: https://www.mckinsey.com/~/media/McKinsey/Industries/Oil%20and%20Gas/Our%20Insights/Global%20Energy%20Perspective%202019/McKinsey-Energy-Insights-Global-Energy-Perspective-2019_Reference-Case-Summary.ashx (Accessed 27.9.2022).

[18] United Nations. Population [Online]. Available from: https://www.un.org/en/global-issues/population (Accessed 23.9.2022).

[19] United Nations. Goal 12: Ensure sustainable consumption and production patterns [Online]. Available from: https://www.un.org/sustainabledevelopment/sustainable-consumption-production/ (Accessed 6.9.2022).

[20] European Environment A. Growth without economic growth. Publications Office, 2021. https://data.europa.eu/doi/10.2800/492717.

[21] Ellen Macarthur Foundation. Circular economy introduction [Online]. 2021. Available from: https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/glossary (Accessed 27.9.2022).

[22] Ellen Macarthur Foundation. Eliminate waste and pollution [Online]. Available from: https://ellenmacarthurfoundation.org/eliminate-waste-and-pollution (Accessed 26.9.2022).

[23] Sariatli F. Linear Economy Versus Circular Economy: A Comparative and Analyzer Study for Optimization of Economy for Sustainability. Visegrad Journal on Bioeconomy and Sustainable Development. 2017;6(1): 31-34, https://doi.org/10.1515/vjbsd-2017-0005.

[24] Ellen Macarthur Foundation. Circulate products and materials [Online]. Available from: https://ellenmacarthurfoundation.org/circulate-products-and-materials (Accessed 26.9.2022).

[25] Ellen Macarthur Foundation. Regenerate nature [Online]. Available from: https://ellenmacarthurfoundation.org/regenerate-nature (Accessed 26.9.2022).

[26] Morseletto P. Targets for a circular economy. Resources, Conservation and Recycling. 2020;153: 104553, ISSN 0921-3449. https://doi.org/10.1016/j.resconrec.2019.104553.

[27] DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives. Official Journal of the European Union, L312, 2008. Available from: https://www.reach-compliance.eu/english/legislation/docs/launchers/waste/launch-2008-98-EC.html.

[28] Suomen Autokierrätys. Sähköauton ajovoima-akkujen kierrätys [Online]. Available from: https://autokierratys.fi/kuluttajille/kierratysjarjestelma/sahkoauton-akkujen-kierratys/ (Accessed 27.10.2022).

[29] European Commission, Joint Research Centre, Boon-Brett L, Lebedeva N, Di Persio F. Lithium ion battery value chain and related opportunities for Europe. Publications Office, 2018. https://data.europa.eu/doi/10.2760/6060.

[30] Hua Y, Zhou S, Huang Y, Liu X, Ling H, Zhou X, et al. Sustainable value chain of retired lithium-ion batteries for electric vehicles. Journal of Power Sources. 2020;478, https://doi.org/10.1016/j.jpowsour.2020.228753.

[31] Richa K, Babbitt CW, Nenadic NG, Gaustad G. Environmental trade-offs across cascading lithium-ion battery life cycles. International Journal of Life Cycle Assessment. 2017;22(1): 66-81, ISSN 0948-3349. https://doi.org/10.1007/s11367-015-0942-3.

[32] International Energy Agency (IEA). Global Supply Chains of EV Batteries. Paris 2022. Available from: https://www.iea.org/reports/global-supply-chains-of-ev-batteries.

[33] BloombergNEF. New Energy Outlook 2020 - Executive Summary. 2020. Available from: https://assets.bbhub.io/professional/sites/24/928908_NEO2020-Executive-Summary.pdf.

[34] IDTechEx. Second-life Electric Vehicle Batteries 2020-2030 [Online]. Available from: https://portal.idtechex.com/en/research-report/second-life-electric-vehicle-batteries-2020-2030/681 (Accessed 18.12.2022).

[35] Ghiji M, Novozhilov V, Moinuddin K, Joseph P, Burch I, Suendermann B, et al. A Review of Lithium-Ion Battery Fire Suppression. Energies. 2020;13(19): 5117, https://doi.org/10.3390/en13195117.

[36] Warner J. Chapter 3 - Basic Terminology. In: Warner J, editor. The Handbook of Lithium-Ion Battery Pack Design. Amsterdam: Elsevier; 2015. p. 23-33. ISBN ISBN 978-0-12-801456-1.

[37] Roy P, Srivastava SK. Nanostructured anode materials for lithium ion batteries. Journal of Materials Chemistry A. 2015;3(6): 2454-2484, ISSN 2050-7488. https://doi.org/10.1039/c4ta04980b.

[38] Zwicker MFR, Moghadam M, Zhang W, Nielsen CV. Automotive battery pack manufacturing - a review of battery to tab joining. Journal of Advanced Joining Processes. 2020;1: 100017, ISSN 2666-3309. https://doi.org/10.1016/j.jajp.2020.100017.

[39] Houache MSE, Yim CH, Karkar Z, Abu-Lebdeh Y. On the Current and Future Outlook of Battery Chemistries for Electric Vehicles-Mini Review. Batteries. 2022;8(7): 70, https://doi.org/10.3390/batteries8070070.

[40] Kampker A, Heimes HH, Ordung M, Lienemann C, Hollah A, Sarovic N. Evaluation of a Remanufacturing for Lithium Ion Batteries from Electric Cars. World Academy of Science, Engineering and Technology, International Journal of Mechanical and Mechatronics Engineering. 2016;10(12): 1929-1935, https://doi.org/10.5281/zenodo.1128215.

[41] Maiser E. Battery Packaging - Technology Review. AIP Conference Proceedings. 2014;1597: 204-218, https://doi.org/10.1063/1.4878489.

[42] Salgado RM, Danzi F, Oliveira JE, El-Azab A, Camanho PP, Braga MH. The Latest Trends in Electric Vehicles Batteries. Molecules. 2021;26(11): 3188, https://doi.org/10.3390/molecules26113188.

[43] McKerracher C, et al., BloombergNEF. Electric Vehicle Outlook 2022. Available from: https://about.bnef.com/electric-vehicle-outlook/.

[44] Harper G, Sommerville R, Kendrick E, Driscoll L, Slater P, Stolkin R, et al. Recycling lithium-ion batteries from electric vehicles. Nature. 2019;575(7781): 75-86, ISSN 0028-0836. https://doi.org/10.1038/s41586-019-1682-5.

[45] Zhu J, Mathews I, Ren D, Li W, Cogswell D, Xing B, et al. End-of-life or second-life options for retired electric vehicle batteries. Cell Reports Physical Science. 2021;2(8): 100537, ISSN 2666-3864. https://doi.org/10.1016/j.xcrp.2021.100537.

[46] Pastor-Fernández C, Yu TF, Widanage WD, Marco J. Critical review of non-invasive diagnosis techniques for quantification of degradation modes in lithium-ion batteries. Renewable and Sustainable Energy Reviews. 2019;109: 138-159, ISSN 1364-0321. https://doi.org/10.1016/j.rser.2019.03.060.

[47] Rallo H, Casals LC, De La Torre D, Reinhardt R, Marchante C, Amante B. Lithium-ion battery 2nd life used as a stationary energy storage system: Ageing and economic analysis in two real cases. Journal of Cleaner Production. 2020;272: 122584, ISSN 0959-6526. https://doi.org/10.1016/j.jclepro.2020.122584.

[48] European Union. Types of legislation [Online]. Available from: https://european-union.europa.eu/institutions-law-budget/law/types-legislation_en#:~:text=A%20%22regulation%22%20is%20a%20binding%20legislative%20act.%20It,outside%20the%20EU%2C%20the%20Council%20adopted%20a%20regulation. (Accessed 6.10.2022).

[49] CENELEC. European Standards [Online]. Available from: https://www.cencenelec.eu/european-standardization/european-standards/ (Accessed 20.1.2023).

[50] European Commission. Batteries and accumulators [Online]. Available from: https://environment.ec.europa.eu/topics/waste-and-recycling/batteries-and-accumulators_en (Accessed 5.10.2022).

[51] Hoarau Q, Lorang E. An assessment of the European regulation on battery recycling for electric vehicles. Energy Policy. 2022;162: 112770, ISSN 0301-4215. https://doi.org/10.1016/j.enpol.2021.112770.

[52] European Union: European Commission. COMMISSION STAFF WORKING DOCUMENT on the evaluation of the Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC. SWD(2019) 1300 final, 2019. Available from: https://ec.europa.eu/environment/pdf/waste/batteries/evaluation_report_batteries_directive.pdf.

[53] Council of the European Union. Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020. 5469/23, 2023. Available from: https://data.consilium.europa.eu/doc/document/ST-5469-2023-INIT/en/pdf.

[54] Take-e-way. EU Battery Regulation coming in 2023? [Online]. 2022. Available from: https://www.take-e-way.com/news/eu-battery-regulation-coming-in-2023/ (Accessed 15.12.2022).

[55] Federal Environment and Consumer Protection Ministry (BMUV). EU Environment Council adopts new rules for more sustainable batteries [Online]. 2022. Available from: https://www.bmuv.de/en/pressrelease/eu-environment-council-adopts-new-rules-for-more-sustainable-batteries (Accessed 12.10.2022).

[56] Paristokierrätys. EU Batteries Regulation processing schedule slightly delayed [Online]. 2022. Available from: https://www.paristokierratys.fi/en/blog/2022/10/10/batteryregulation-eu-batteries-regulation-processing-schedule-slightly-delayed/ (Accessed 12.10.2022).

[57] European Council. Council and Parliament strike provisional deal to create a sustainable life cycle for batteries [Online]. 2022. Available from: https://www.consilium.europa.eu/en/press/press-releases/2022/12/09/council-and-parliament-strike-provisional-deal-to-create-a-sustainable-life-cycle-for-batteries/ (Accessed 15.12.2022).

[58] European Union: European Commission. Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/102. COM/2020/798 final, 2020. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798.

[59] European Commission. Green Deal: New proposals to make sustainable products the norm and boost Europe's resource independence [Online]. 2022. Available from: https://ec.europa.eu/commission/presscorner/detail/en/ip_22_2013 (Accessed 15.1.2023).

[60] CENELEC. CLC/TC 21X - Secondary cells and batteries [Online]. Available from: https://standards.cencenelec.eu/dyn/www/f?p=305:22:381344466831801::::FSP_ORG_ID,FSP_LANG_ID:1257217,25&cs=1713A95D8AC1F4E337203EA2AAEC315B0 (Accessed 20.2.2023).

[61] EFTA. How EU Law becomes EEA Law [Online]. Available from: https://eealaw.efta.int/ (Accessed 20.10.2022).

[62] The Explorer. Doing business: How Norway is integrated into the European single market [Online]. 2020. Available from: https://www.theexplorer.no/stories/other/doing-business-how-norway-is-integrated-into-the-european-single-market/ (Accessed 20.10.2022).

[63] Emily MacKenzie. EFTA and the EEA: What are they? [Online]. 2016. Available from: https://brexit.law/2016/07/06/efta-and-the-eea-what-are-they/ (Accessed 21.10.2022).

[64] Avfallsforskriften. Forskrift om gjenvinning og behandling av avfall (FOR-2004-06-01-930), 2004. Available from: https://lovdata.no/dokument/SF/forskrift/2004-06-01-930.

[65] Grudzień P. Is there life after death for Europe’s lithium-ion batteries? [Online]. 2022. Available from: https://www.energy-storage.news/is-there-life-after-death-for-europes-lithium-ion-batteries/ (Accessed 8.11.2022).

[66] Ministry of Trade, Industry and Fisheries, Office of the Prime Minister. Roadmap - The green industrial initiative. 2022. Available from: https://www.regjeringen.no/contentassets/1c3d3319e6a946f2b57633c0c5fcc25b/roadmap_the-green-industrial-initiative_singlepages_web.pdf.

[67] Ministry of Trade, Industry and Fisheries. Norway's battery strategy. 2022. Available from: https://www.regjeringen.no/contentassets/a894b5594dbf4eccbec0d65f491e4809/norways-battery-strategy_singlepages_web.pdf.

[68] Valtioneuvoston asetus paristoista ja akuista 520/2014. Available from: https://www.finlex.fi/fi/laki/alkup/2014/20140520.

[69] Jätelaki 646/2011. Available from: https://www.finlex.fi/fi/laki/ajantasa/2011/20110646.

[70] Työ- ja elinkeinoministeriö. Kansallinen akkustrategia 2025. 2021. ISBN 978-952-327-635-2.

[71] Wärtsilä Corporation. Wärtsilä and Hyundai Motor Group announce energy storage partnership maximizing second-life electric vehicle batteries [Online]. 2018. Available from: https://www.wartsila.com/media/news/26-06-2018-wartsila-and-hyundai-motor-group-announce-energy-storage-partnership-maximizing-second-life-electric-vehicle-batteries-2216004 (Accessed 27.10.2022).

[72] Fortum Corporation. Second life batteries, expertise and a can-do attitude – innovation boosts hydropower plant [Online]. Available from: https://www.fortum.com/about-us/our-company/strategy/decarbonisation-joint-effort/second-life-batteries-hydropower-plant (Accessed 27.10.2022).

[73] Ministry of Economic Affairs and Employment. National Battery Strategy 2025. 2021. ISBN 978-952-327-725-0.

[74] Shahjalal M, Roy PK, Shams T, Fly A, Chowdhury JI, Ahmed MR, et al. A review on second-life of Li-ion batteries: prospects, challenges, and issues. Energy. 2022;241: 122881, ISSN 0360-5442. https://doi.org/10.1016/j.energy.2021.122881.

[75] Rallo H, Benveniste G, Gestoso I, Amante B. Economic analysis of the disassembling activities to the reuse of electric vehicles Li-ion batteries. Resources, Conservation and Recycling. 2020;159: 104785, ISSN 0921-3449. https://doi.org/10.1016/j.resconrec.2020.104785.

[76] Hua Y, Liu X, Zhou S, Huang Y, Ling H, Yang S. Toward Sustainable Reuse of Retired Lithium-ion Batteries from Electric Vehicles. Resources, Conservation and Recycling. 2021;168: 105249, ISSN 0921-3449. https://doi.org/10.1016/j.resconrec.2020.105249.

[77] Hossain E, Murtaugh D, Mody J, Faruque HMR, Sunny MSH, Mohammad N. A Comprehensive Review on Second-Life Batteries: Current State, Manufacturing Considerations, Applications, Impacts, Barriers & Potential Solutions, Business Strategies, and Policies. IEEE Access. 2019;7: 73215-73252, ISSN 2169-3536. https://doi.org/10.1109/ACCESS.2019.2917859.

[78] Hitachi Energy. e-mesh™ Solutions for utilities [Online]. Available from: https://www.hitachienergy.com/products-and-solutions/grid-edge-solutions/applications/energy-storage-applications (Accessed 5.11.2022).

[79] Eaton Corporation. A sustainable future at the Johan Cruijff ArenA [Online]. Available from: https://www.eaton.com/pt/en-gb/products/energy-storage/amsterdam-arena-success-story.html (Accessed 6.11.2022).

[80] Connected Energy. Harnessing the circular economy to provide industrial scale energy storage [Online]. 2020. Available from: https://c-e-int.com/news/news-

reports/harnessing-the-circular-economy-to-provide-industrial-scale-energy-storage (Accessed 6.11.2022).

[81] Renault Group. A second life for batteries: from energy usage to industrial storage [Online]. 2020. Available from: https://www.renaultgroup.com/en/news-on-air/news/a-second-life-for-batteries-from-energy-usage-to-industrial-storage/ (Accessed 7.12.2022).

[82] Nissan Motor Corporation. Nissan partners with Enel to launch innovative “Second Life” storage system for used electric car batteries [Online]. 2022. Available from: https://europe.nissannews.com/en-GB/releases/release-52ceef740fc0095afb0845bf4030d8c5-nissan-partners-with-enel-to-launch-innovative-second-life-storage-system-for-used-electric-car-batteries (Accessed 6.11.2022).

[83] Jaguar. SECOND LIFE: JAGUAR I-PACE BATTERIES POWER ZERO-EMISSION ENERGY STORAGE UNIT [Online]. 2022. Available from: https://media.jaguar.com/news/2022/03/second-life-jaguar-i-pace-batteries-power-zero-emission-energy-storage-unit (Accessed 6.11.2022).

[84] Toyota Motor Corporation. Construction and Launch of a Large-capacity Sweep Energy Storage System from Reused Electrified Vehicle Batteries Connected to the Electrical Power Grid [Online]. 2022. Available from: https://global.toyota/en/newsroom/corporate/38149071.html (Accessed 6.11.2022).

[85] Cready E, Lippert J, Pihl J, Weinstock I, Symons P. Technical and Economic Feasibility of Applying Used EV Batteries in Stationary Applications. 2003, https://doi.org/10.2172/809607.

[86] BloombergNEF. Lithium-ion Battery Pack Prices Rise for First Time to an Average of $151/kWh [Online]. 2022. Available from: https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/ (Accessed 18.12.2022).

[87] Börner MF, Frieges MH, Späth B, Spütz K, Heimes HH, Sauer DU, et al. Challenges of second-life concepts for retired electric vehicle batteries. Cell Reports Physical Science. 2022;3(10): 101095, ISSN 2666-3864. https://doi.org/10.1016/j.xcrp.2022.101095.

[88] Lih WC, Yen JH, Shieh FH, Liao YM, editors. Second Use of Retired Lithium-ion Battery Packs from Electric Vehicles: Technological Challenges, Cost Analysis and Optimal Business Model. 2012 International Symposium on Computer, Consumer and Control; 2012 4-6 June 2012.

[89] Schonfeld DJ, Dreyer BP. CHAPTER 3 - Research Foundations, Methods, and Issues in Developmental-Behavioral Pediatrics. In: Wolraich ML, Drotar DD, Dworkin PH, Perrin EC, editors. Developmental-Behavioral Pediatrics. Philadelphia: Mosby; 2008. p. 47-56. ISBN 978-0-323-04025-9.

[90] George T. Semi-Structured Interview | Definition, Guide & Examples [Online]. Scribbr; 2022. Available from: https://www.scribbr.co.uk/research-methods/semi-structured-interviews/ (Accessed 31.1.2023).

[91] Zendah K. Examining teachers' role in the promotion of child-friendly environments in Zimbabwean secondary schools: implications for teacher professional development: University of Fort Hare; 2017.

[92] George T. Types of Interviews in Research | Guide & Examples [Online]. Scribbr; 2022. Available from: https://www.scribbr.com/methodology/interviews-research/ (Accessed 31.1.2023).

[93] Palinkas LA, Horwitz SM, Green CA, Wisdom JP, Duan N, Hoagwood K. Purposeful Sampling for Qualitative Data Collection and Analysis in Mixed Method Implementation Research. Adm Policy Ment Health. 2015;42(5): 533-544, ISSN 0894-587x. https://doi.org/10.1007/s10488-013-0528-y.

[94] Kiger ME, Varpio L. Thematic analysis of qualitative data: AMEE Guide No. 131. Medical Teacher. 2020;42(8): 846-854, ISSN 0142-159X. https://doi.org/10.1080/0142159X.2020.1755030.

[95] Caulfield J. How to Do Thematic Analysis | Step-by-Step Guide & Examples [Online]. Scribbr; 2019. Available from: https://www.scribbr.com/methodology/thematic-analysis/ (Accessed 23.1.2023).

[96] Braun V, Clarke V. Using thematic analysis in psychology. Qualitative Research in Psychology. 2006;3: 77-101, https://doi.org/10.1191/1478088706qp063oa.

[97] Guba EG. Criteria for assessing the trustworthiness of naturalistic inquiries. ECTJ. 1981;29(2): 75-91, ISSN 1556-6501. https://doi.org/10.1007/BF02766777.

[98] Shenton A. Strategies for Ensuring Trustworthiness in Qualitative Research Projects. Education for Information. 2004;22: 63-75, https://doi.org/10.3233/EFI-2004-22201.

Appendices

Appendix A. Interview questions for all participants expect end-users

Background questions

- Interviewee name and contact details

- Organization name and location of headquarter. What is your title/position in the organization?

- Which stakeholder group do you represent?
    - Repurpose service provider
        - Briefly specify the main steps of how you repurpose batteries
    - Energy company
        - Briefly specify your connection to repurposed batteries
    - Researcher
        - Briefly specify your research area
    - End-user
        - Briefly specify how are/will you utilize repurposed batteries
    - Other, please specify

- What size of an organization are you?
    - Microenterprise (1 to 9 employees)
    - Small enterprise (10 to 49 employees)
    - Medium size enterprise (50 to 249 employees)
    - Large enterprise (250 employees or more)

Technology questions

- What are the main know-how gaps and/or technical barriers for repurposing electric vehicle batteries for energy storage systems? How could they be resolved?

- Lithium-ion batteries used in electric vehicles vary by size, cell types, and cathode chemistries. Regarding the repurposing process, what kind of challenges arise from this?
    - Service providers: Can your repurposing technology be applied to different battery types?

- What are the main safety issues and/or concerns regarding the repurposing of electric vehicle batteries for energy storage systems? How could they be solved?

- Which energy storage applications do you consider the most suitable for end-of-life electric vehicle batteries?

- When considering the overall repurposing process (assessment – disassembly – performance evaluation – sorting and regrouping – control and management), which of these steps are the most challenging? What technologies are potential for streamlining current practices?

Economy questions

- What are the main factors affecting the cost of second-life (repurposed) batteries? Can the cost factors be further reduced and if yes, by which means?

- Are second-life (repurposed) batteries currently economically competitive with first-life (new) batteries? How about in the future if the cost of new batteries continues to decrease?

- How does the cost of recycling lithium-ion batteries compare to repurposing them? Is it an issue for repurposing operations if recycling is more cost-efficient?

Regulatory related questions

- How does the proposed new EU Battery Regulation support the repurposing of electric vehicle batteries for energy storage systems? Are there any shortcomings and/or is there a need for additional measures?

- Do you think it is justified that the new Battery Regulation has set quantitative targets for recycling but not for repurposing?

- How do you view the current regulatory environment for repurposing electric vehicle batteries? Are there any regulatory obstacles, lack of policies and/or standards that are hindering operations?

- Do you think it is justified that Finland's/Norway's battery strategy aims at business growth and getting new investments? Should these strategies provide more attention to repurposing?

Environmental questions

- In your opinion, is the repurposing of end-of-life batteries better for the environment than recycling? Are recycling and repurposing strategies that complement or exclude each other?

- The sufficiency of battery metals to supply the growing demand for electric vehicle batteries and other lithium-ion battery applications will likely be a challenge in the future. In your opinion, which strategy would be the best for tackling this issue, repurposing or recycling batteries or a combination of both?

Consumer questions

- Who are the main customers/consumers for repurposed battery systems? Do customers/ consumers have any perceived risks and/or concerns about repurposed battery systems?
    - If yes, how could they be overcome?

- Are consumers aware about repurposed batteries? Would consumers choose repurposed batteries over recycled batteries? Is there enough market demand for second-life batteries?

Final considerations

- From your perspective, what are the main enabling and inhibiting factors affecting the feasibility of repurposed electric vehicle batteries for energy storage systems?
    - Enabling factors
    - Inhibiting factors

- How has the current energy crisis affected repurposing operations?

- In your opinion, how well did these questions cover the topic of repurposing electric vehicle batteries for energy storage systems? Was some relevant aspect missing? If yes, what topic/issue?

Appendix B. Interview questions for end-users

Background questions

- Interviewee name and contact details
- Organization name and location of headquarter. What is your title/position in the organization?
- Which stakeholder group do you represent?
    - Repurpose service provider
        - Briefly specify the main steps of how you repurpose batteries
    - Energy company
        - Briefly specify your connection to repurposed batteries
    - Researcher
        - Briefly specify your research area
    - End-user
        - Briefly specify how are/will you utilize repurposed batteries
    - Other, please specify
- What size of an organization are you?
    - Microenterprise (1 to 9 employees)
    - Small enterprise (10 to 49 employees)
    - Medium size enterprise (50 to 249 employees)
    - Large enterprise (250 employees or more)

Consumer questions

- Do you have safety concerns about repurposed electric vehicle battery energy storage systems?
    - If yes, what are your biggest concerns and why?
    - If no, why don't you have concerns?
- Why did you decide to participate in second-life (repurposed) batteries?
- What do you consider as more important the cost or the environmental impact of a battery system?
- How/when did you first become aware of second-life batteries? Are second-life batteries well-known among consumers?

Economy questions

- If second-life (repurposed) batteries were more expensive than first-life (new) batteries, which would you choose and why?

- If recycled batteries were cheaper than second-life (repurposed) batteries, which would you choose and why?

Regulatory questions

- Are there any incentives that support the uptake of second-life (repurposed) batteries? If yes, what kind of incentives are they, how do they support the uptake?

- Do you need special permissions for using second-life (repurposed) battery systems?

- Are there regulatory restrictions affecting the installation or use of second-life (repurposed) battery systems? If yes, what are the restricting regulations and how do they affect?

Environmental questions

- In your opinion, is the repurposing of end-of-life batteries better for the environment than recycling?
  - If yes, why do you consider repurposing better?
  - If no, why do you consider recycling better?

- What do you consider as the main environmental benefits of repurposing end-of-life electric vehicle batteries? List the top three.

- The sufficiency of battery metals to supply the growing demand for electric vehicle batteries and other lithium-ion battery applications will likely be a challenge in the future. In your opinion, which strategy would be the best for tackling this issue, repurposing or recycling batteries or a combination of both?

Final considerations

- From your perspective, what are the main enabling and inhibiting factors affecting the attractiveness of repurposed electric vehicle batteries for energy storage systems?
  - Enabling factors

    - Inhibiting factors

- How is the current energy crisis affecting the upcoming/current usage of repurposing of electric vehicle batteries?

- In your opinion, how well did these questions cover the topic of repurposing electric vehicle batteries for energy storage systems? Was some relevant aspect missing? If yes, what topic/issue?