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**Research article**

# Existing and Upcoming Challenges for Extending Electric Vehicle Battery Lifetime Through 2nd Life Applications

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## Abstract

Climate-neutrality targets and clean energy transition rapidly drive the increasing demand for batteries, making the market increasingly strategic at a global scale. Material efficiency, prolonging lifetime and circular economy are seen as key strategies to secure supply to critical raw materials. The European Commission sees that storing energy allows flexibility to adjust demand and supply, which is key to increase renewable energy production and utilisation, energy efficiency and security. Batteries are urgently needed to meet the EU's objectives on climate neutrality, replacing fossil fuel dependency and increase use of renewable energy. The utilisation of end-of-life electric vehicle batteries in 2nd life applications is currently a poorly exploited field with limited legislative support in the EU. There is untapped potential with 2nd life applications and implementing higher circular business models prior to recycling may help reach several of EU's key strategic targets. Although reusing electric vehicle batteries will lead to nearly exclusively positive impacts, there are many challenges for successful scale up. The current work presents the findings of a thorough literature review on existing technology for reuse and repurposing, identified different circular business models, and an overview of the relevant legislative landscape in the EU, Norway and Finland. Interviews have been conducted to understand how various stakeholder groups perceive the possibilities within this business segment and what they see as the main barriers for implementation of 2nd life batteries. In total, 10 challenges and barriers were identified in four different categories: technical, legislative, eco-design, and safety/reliability. Technical challenges are related to restricted access to historical data, lack of standardization in battery design, and rapid development of the battery technology. Safety/reliability are hampered by limited standards and legislation as well as being affected by the technical challenges. Although new standards are under development and the new EU Battery Regulation will address some of the identified challenges, it will take time before these changes becomes effective. Additionally, the EU Battery Regulation prioritizes material recycling of batteries over activities aimed at extending their lifespan in a circular manner, as it mandates a minimum proportion of materials in new batteries to be sourced from recycled materials.

**Keywords**: Electric Vehicle Battery, Energy Storage, Stationary Energy Storage, Circular Economy, Reuse, Repurposing, Second Life, Legislation

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# 1. INTRODUCTION AND BACKGROUND

Driven by the ongoing climate-neutrality targets and clean energy transition, demand for batteries is rapidly growing, making this market increasingly strategic at a global scale. The European Commission (EC) estimated (2020) that to reach its climate neutrality target by 2050, the European Union (EU) would need up to 60 times more lithium and 15 times more cobalt (S. Bobba, 2020). The European market potential for batteries is predicted to be worth EUR 600 billion annually from 2025 onwards (Ivar Valstad, 2020). However, until now, more than 95% of the global Li-ion battery (LIB) cell production, and corresponding IP and knowledge, has taken place in Asia (mostly China, Japan, and South Korea). Additionally, not only are many of the materials required for LIB production, such as cobalt, nickel, lithium and graphite sourced and produced in politically unstable and unpredictable regions of the world, but their extraction often involves the exploitation of both workers' rights and the natural environment. The EC has identified securing and diversifying supply of critical raw materials as one of the top 10 strategic issues to ensure EU's freedom and operational capacity in the future (European Commission, Secretariat-General, 2021). Material efficiency, prolonging lifetimes of products and circular economy are seen as key strategies to secure access and reduce demand. The win-win-win potential of circular economy for sustainable development defined by Korhonen et al. (2018) is that successful circular economy would contribute to sustainable economic, environmental, and social development (Korhonen ym., 2018) . There are however tensions that are brought by the circular disruption to the existing markets and impacts on the industry, technology, and systems. Especially the automobile industry is faced with structural tensions due to the transformative pressure with the transition to electric vehicles using lithium-ion batteries. By adopting a holistic view, the study illustrates the interconnectedness among sustainability transition, circular economy, and the key role of actors in managing structural tensions. It argues that analysing strategies pursued by actors across the value chain is crucial for understanding the complexity of managing these tensions, revealing interconnected levels, potential conflicts, and the significant influence of weakest and passive actors on the transition's pace and direction in the context of EV lithium-ion batteries. (Chizaryfard ym., 2022).

In 2018, about 68% of the world's graphite production took place in China (Statista, 2023), with only a few percent production originating from European countries. Graphite specific for battery applications is produced nearly exclusively in China, both natural and artificial, with more than 90% market share (Benchmark Mineral Intelligence, 2022). The global market for electric vehicles (EVs) in particular, is thus highly dependent on Asia, and particularly China. In addition to the exponential growth in electrification within mobility, there is also a growing need for stationary energy storage. Electrochemical energy storage such as LIB are currently used mostly in small scale for private homes or small businesses, with a few examples of larger systems at mega- and giga-scale. However, the growth of utility-scale batteries is predicted by Bloomberg NEF to reach 1000 GWh by 2035 and nearly 3500 GWh by 2050 (BloombergNEF, 2021). These values are supported both by the 2022 and 2023 IEA World Energy Outlook as well as a recent report from McKinsey. The IEA reports show an overview of the overall energy needs, but also particularly analysing the power system flexibility needs induced by the propelling adoption of renewable energy sources. According to IEA up to 25% of these flexibility needs may potentially be covered by large battery energy storage systems (BESS) (International Energy Agency, 2023) (International Energy Agency, 2022). The recent report from McKinsey provides insights into the BESS market and its relation to the growing share of renewable energy sources, estimating future needs until 2030 for battery as energy storage. (Gabriella Jarbratt, 2023).

Strategically, the EC also sees that storing energy allows flexibility to adjust demand and supply, which is key to increase renewable energy production and utilisation, energy efficiency and energy security. Modelling studies show an important relation between increasing renewable energy deployment and flexibility of the energy systems. In addition to providing flexibility, energy storage reduces price fluctuations and lower peak prices. It is a way to electrify different economic sectors like buildings and of course also transportation, but also provides a way for consumers to adapt their energy consumption to prices and their needs. According to the ETC CE report (2023) on consumption and the environment in Europe's circular economy, housing is responsible for the largest volume of greenhouse gas (GHG) emissions, contributing to 40 % of total GHG emissions caused by the European households, which is mainly caused by energy consumption for heating, hot water and lighting (Manshoven et al., 2023).

Batteries are seen as an increasingly important technology for energy storage. The main storage reservoir in the EU is pumped-hydro storage (over 90 %) but the expectation is that further new battery projects will come as the battery storage systems become more feasible (European Commission, 2020). The stationary battery market in the EU (EU27) is growing quickly and doubled in 2021, with the cumulative installed capacity reaching 4.6 GW / 7.7 GWh, which is around 14 % of global installed capacity (Bielewski et al., 2022). Currently, most batteries in stationary applications are provided new from the battery cell manufacturers. Afterall, limited focus is paid to utilising 2nd life batteries, which is also seen in amended updated legislation. There is a large unexploited potential in batteries that have spent their first life in EVs or other mobile applications as 2nd life batteries in stationary energy storage. An EV battery (EVB) usually has a warranty of 8 to 10 years (or 100 000 miles/160 000 km) (Nichols, 2023). When EVBs have reached 70-80% of their original energy capacity, they are often considered to be inadequate for use in EVs. With the less stringent requirements set for stationary applications, these batteries can still be used for anywhere between 5 to 15 years, depending on the application. Extending the lifetime of EVBs before they are sent to recycling can thus contribute to lowering the demand for critical minerals and virgin raw materials as well as significantly reducing the environmental footprint over the lifetime of the batteries. With the EV production increasing considerably, the need for a circular strategy for EVBs reaching their end-of-life (EoL) will become necessary in the next years. In the first quarter of 2024, the electric car sales grew around 25% worldwide, compared to the same time period in 2023. According to the Global EV Outlook 2024, the market share of electric cars for 2024 could reach up to 45% in China, 25% in Europe, and over 11% in the USA (International Energy Agency, 2024).

Although reusing EVBs will lead to nearly exclusively positive impacts, the process is not straightforward and there are many challenges to tackle before this can become mainstream. The current work has conducted a literature review on existing technology for reuse and repurposing, identified different circular business models, and established an overview of the relevant legislative landscape in the EU, and specifically in Norway and Finland. The country-specific scoping was chosen as this work is part of the EU project TREASoURcE, where three battery demonstration units based on 2nd life batteries will be implemented in Norway and Finland as part of the project. Additionally, several stakeholder interviews have been conducted to understand how various stakeholder groups perceive the possibilities within this business segment and what they believe are the main barriers for implementation of 2nd life batteries. The interviews both confirmed findings from literature as well as provided added information particularly regarding public perception, safety concerns, and concerns regarding availability cost of 2nd life EV batteries. Through this work, several challenges and barriers have been identified, which may slow down or hinder further growth in the battery 2nd life market. The challenges are sorted into four different categories: technical, legislative, eco-design, and safety/reliability. The results and findings from this study can inform policymakers in the challenges and limitations related to extending the lifetime of EVBs. Through increased knowledge and better understanding of the practical implications of the current legislative framework and technology status, it will be easier to make informed decisions on how to further improve the circularity in the battery value chain, leading to increased sustainability and reducing the batteries' total environmental footprint.

## 2. METHODOLOGY

Two main methods were chosen for gathering information for this research paper. The first was a literature review, where different reports, data sets, scientific publications and EU, Finnish and Norwegian legislative documents were explored. The literature review started by a thorough search of the EU legislative documents in addition to collecting all relevant reports from International Energy Agency (IEA), EU Joint Research Initiative (JRC), as well as national legislative documents and strategy reports from Norway and Finland. Technical information about battery chemistries, battery system construction, assembly and disassembly processes as well as battery state of health (SoH) diagnostics were found trough mostly searching in peer reviewed scientific journals, but also reports from other EU projects and information from company specific web pages.

The second method was conduction of interviews with a variety of stakeholders to seek in-depth understanding of perceptions about implementation of 2nd life batteries. The focus of the interviews was to identify challenges and barriers for repurposing operations and possible solutions to overcome them. Details on the collected information and questions used for the interviews are provided in supplementary information. Although the interviews followed the structure indicated, the interviewees were also given the opportunity to provide additional information and comments. The interview participants were selected based on criterion sampling, of which one main criterion was that they operate within Europe. Additionally, the participants must belong to at least one of the following four categories:

1. Battery repurposing operator or company
2. Participant of a project(s) focusing on EVB repurposing
3. Participant with knowledge of repurposing EVBs
4. Participant is either an end-user of repurposed EVBs or is considering becoming one

A total of 18 interviews were conducted, including 22 participants from four different countries, of which twelve were from Finland, seven from Norway, two from Germany, and one from Sweden. All interviews were conducted via online video calls and were recorded and transcribed for data analysis. The interview questions were sent out a week in advance for the interviewees to familiarize with the topics. In order to avoid unintentionally leading questions, the wording was neutrally phrased. All the questions were open-ended and close-ended, grouped into different themes: background, technology, economy, regulatory, environmental, consumers, and final considerations. One exception is the questions used for the end-user group, which did not include the technology theme. This topic requires specific knowledge of the batteries, which is not expected from the end-users. Thus, a slightly different questionnaire was used for this stakeholder group (see supplementary information). Various stakeholder groups participated in the interviews, see Figure 1. 33% of the participants were researchers, representing research areas such as LIB recycling, energy efficiency and process modelling, battery and thermal energy storage, battery cell manufacturing, and EV charging. Repurposing operator companies that repurpose and sell EVBs as well as other entities that have participated in repurposing projects, represented 28% of the participants. End-users represented 17% of the participants and included consumer groups participating in demo projects and considering procuring 2nd life battery systems. The other 22%, consisted in equal shares of members of cluster management, supply chain service, government, and operators of battery assembly for machines.

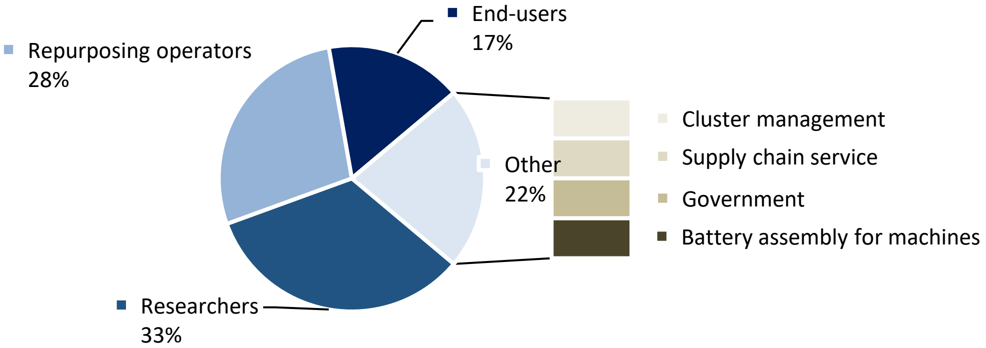

*Figure 1. The Different Stakeholder Groups in the Research Sample*

## 2.1 Data Analysis

A thematic analysis method with a deductive approach was used to identify, analyse and report the data collected from the interviews. The six-step thematic analysis method by Braun and Clarke (Virginia Braun, 2006) was used (M. E. Kiger, 2020). The process included familiarisation of the interview data, generating initial codes from the data, searching for themes, reviewing the themes, defining and naming themes, and producing the report. In this research, the focus was on the challenges and solutions for repurposing EVBs, thus codes were generated and sorted under these two categories. For qualitative data analysis, the software NVivo was used for coding the interview data.

Coding of the data was done through naming or tagging sections of interview transcripts that appear relevant to the research objectives, in this case identifying challenges and solutions for repurposing operations. New codes were created whenever a new aspect occurred for the first time, and reoccurring aspects were included in already-made codes. The codes were placed under two categories, namely “challenges” and “solutions”. This facilitated the next step, in which the codes were grouped into the themes previously listed (background, technology, economy, regulatory, environmental, consumers, and final considerations). The process of coding and arranging in themes was done in multiple steps to ensure that the codes within each theme were relevant. Thus, codes were rearranged, and themes were modified to better illustrate the coded data. The process also involved adding, combining, and discarding themes and eventually reviewing the entire interview data set to validate the identified themes and recode data that fit under the modified themes.

## 3. FINDINGS

## 3.1 Circular Business Models

Based on the search query employed in this research, along with various refinements, a total of 181 articles were meticulously chosen to constitute the dataset, representing the scientific literature within the interdisciplinary field of circular economy and tourism. Figure (2) provides an overview of the primary characteristics of these articles, revealing a notable growth rate of 6.42%, which signifies a positive indication of the interconnectedness between the circular economy and tourism domains, particularly during the study period covering the last three years. These articles were collectively authored by 633 researchers and were published across 115 different journals and sources. Furthermore, they collectively featured approximately 754 keywords, serving as essential bibliographic information to decipher the research directions and prevailing thematic areas within this scientific domain. Until just a few years ago, when EVBs started to reach EoL in the EU, the battery value chain for EVBs would go straight from EV use to recycling, recovery, and landfill. However, many companies have discovered the potential of circular businesses within EVB repairing, refurbishing, remanufacturing, and repurposing. Repairing considers activities like repair and maintenance of a product to keep it in the original function, refurbishing is where an old product is restored and updated, remanufacturing is where parts of a new product is used in the same function and repurposing is where product or its parts are used in a new product in a different function (J. Potting, 2017). In recent years the number of companies offering solutions based on used EVBs has multiplied.

Repair of EVBs is a business model that is closely related to already established businesses repairing other vehicles and will likely not give rise to new businesses. However, established businesses need to develop new knowledge and expertise specific to EVBs. Remanufacturing of EVBs is potentially a profitable business model, where for example several faulty battery packs are collected and disassembled. The faulty components are discarded, and the functional components in the battery pack are reassembled using the original casing and electronics. Refurbishing of EVs can be done by retrofitting additional battery packs or by replacing the battery pack with a new one, which increases the range and subsequently the lifetime of the EV. BATTKOMP AS is an example of a company targeting a circular business model in the battery value chain (BATTKOMP, 2023). They are a small-scale battery production company in Norway, specializing in producing and designing Li-ion batteries for small mobility applications, such as bicycles, forklifts, and scooters. Their goal is to increase the lifetime of battery-driven products by replacing old batteries with new batteries.

An EVB can be repurposed in various ways. A battery system or battery pack is typically built from single cells into modules, which are further assembled into a battery pack (illustrated in Figure 2). Battery cells come in different shapes and sizes, but the three most common form factors for EVs are cylindrical, pouch or prismatic. The latter two both have a rectangular shape, but with different sizes and casing. A battery module can contain anywhere from only a few battery cells up to several hundred or several thousand cells, based on the manufacturer and final application. The total size (energy storage capacity) of the battery pack will then be determined by how many modules make up the whole system. The battery pack is controlled by a battery management system (BMS), which ensures safe operation of the battery through monitoring and control of essential parameters such as state of charge, voltage, and temperature. The BMS also provides essential information on state of health (SoH).

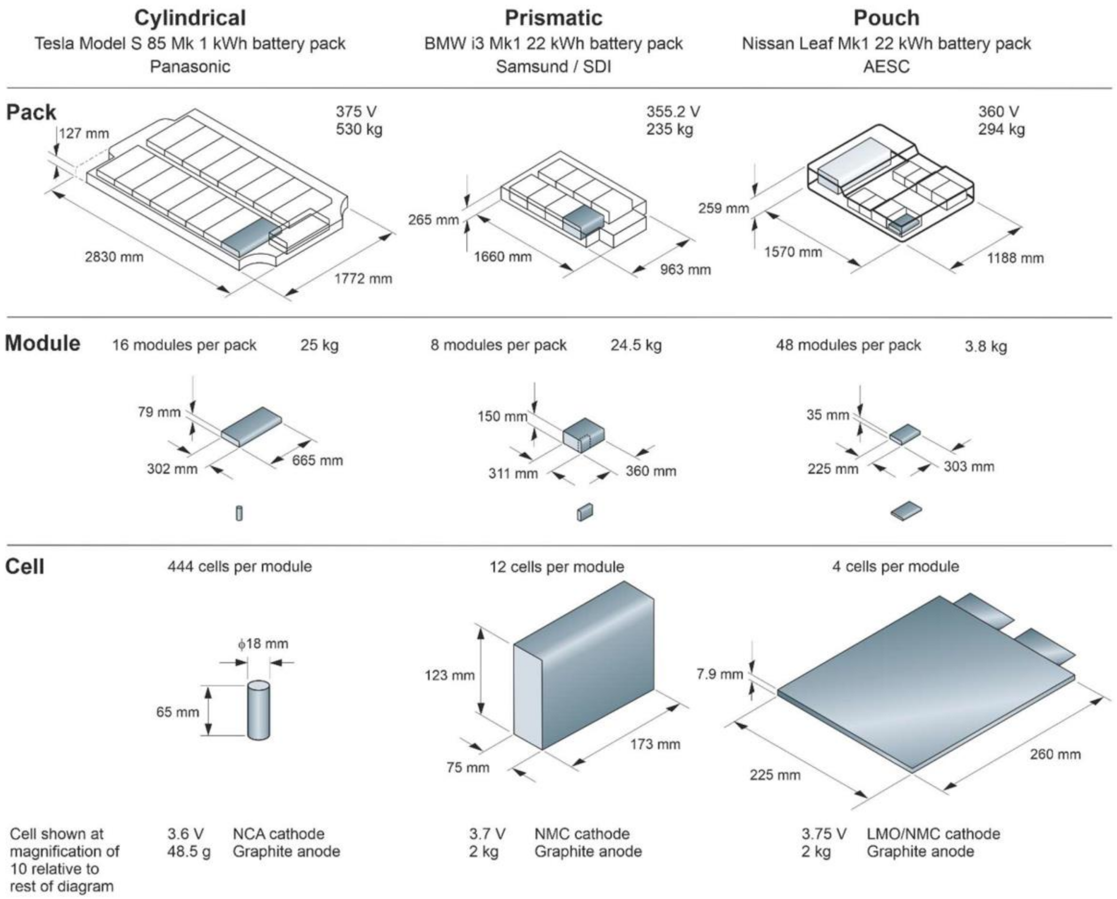

*Figure 2. Illustration of How Battery Packs Are Assembled From Cells and Modules, Redrawn From (Harper G, 2019)*

Repurposing EVBs is still a new market and emerging process, and there are no standardized operations for repurposing. Due to the large variations in EV pack designs, it is challenging to automate the process, and much of the work is done manually. The cost and time of disassembly of pack, module, and cell is shown in Table 1 (Rallo H, 2020). Independent of battery pack design, the repurposing business models for used EV batteries can be split into three main categories based on the level of disassembly of the battery system before it is repurposed into a new battery pack:

1. Reuse the whole battery pack without disassembly.
2. Disassembly of battery pack to module level and reassembly of usable modules into a new battery pack, or even reuse of single modules.
3. Disassembly of the battery system down to cell level and reassemble usable cells into a new battery pack.

*Table 1. The cost and time of disassembly of pack, module, and cell (Rallo H, 2020)*

| | Pack | Module | Cell |
|---|---|---|---|
| **Time** | 500 min | 800 min | 965 min |
| **Cost** | 52 €/kWh | 60 €/kWh | 76 €/kWh |

The most practical solution for disassembly depends on a variety of factors such as model, batch, reasons for retirement, operation history, etc. Companies that build energy storage systems from used EVBs normally base their technology on one of these three business models. Common for most of these companies is that they currently specialize in one specific EV manufacturer or model. However, it is likely that with a growing market, each company will expand to include several types and makes.

## 3.2 Availability and Economic Viability of 2nd Life Batteries

For the use of 2nd life batteries to become economically viable, sufficient volumes of used batteries need to become available on the markets. Additionally, the process of disassembly and reassembly of the batteries must be efficient and low cost to keep the market price of the used batteries as low as possible. From the stakeholder interviews, both availability and cost were major concerns. EVs are still not dominant in most countries, and it will take some time before a larger scale implementation of used EVBs is a reality. Used batteries have shorter lifetime and are seen as less reliable compared to new batteries. The availability of used EVBs is expected to increase rapidly over the next few years. However, there is still some reluctance from EV manufacturers to provide the used batteries, which could delay and/or reduce the availability. Furthermore, there is currently no mandating legislation directing batteries for 2nd life use. The technical challenges, which are currently the main cost drivers, may therefore be the most important factor for the future economic viability of 2nd life battery systems. These will be discussed in more detail in section 3.3.

However, there was particularly one major positive impact highlighted by the stakeholders during the interviews. Purchasing used batteries is considered more sustainable due to the climate and environmental footprint advantage. Thus, even if used batteries are only marginally less expensive than new batteries, consumers may chose used batteries due to their beneficial environmental impact. From the stakeholder interviews it is quite clear that there are large variations in how the potential market growth is perceived. The different responses even amongst repurposing operators suggests that economic viability currently remains uncertain and is very case dependent.

## 3.3 Technical Challenges

The rapid development in battery technologies during the last decade, has resulted in a variety of different chemistries, particularly on the battery cathode side. Form factors of the battery and battery pack design vary significantly, both between the different EV manufacturers as well as between different models from the same manufacturer. In general, EVBs are not designed for being reused in another application, which contributes to driving up the cost of disassembly and reassembly of the batteries. This section will explore and elucidate the challenges tied to the design and structure of EVBs, the prevalent cell chemistries employed, and the methods used to assess the state of health (SoH), reliability, and safety of used EVBs.

### *3.3.1 Battery Pack Design*

EVB packs are built from single battery cells which are assembled into modules, which in turn are assembled into battery packs (illustrated in Figure 2). In addition, a battery management system (BMS), battery thermal management system (BTMS), power converter, sensors, and high-voltage wiring are required for a fully functional battery system. The modules contain cells with a nominal voltage between 3 and 4.5 volts, depending on the cell chemistry. The cells and modules are stacked in parallel and series to provide the necessary voltage to drive the electric motor, to quickly charge the battery, and to maximize the total battery capacity. The BMS is the brain of the battery pack and handles the charging and discharging of the battery. Through communication between various sensors and the EV, the BMS ensures safe and optimal operation of the battery.

When repurposing EV batteries, the BMS can be used as it is with an energy management system (EMS) communicating with several EV battery packs each with its own BMS. This is a suitable approach when the EV battery packs are repurposed without pack disassembly. If the battery pack is disassembled to module or cell level, the BMS can also be replaced. The BMS contains historical data of all the onboard sensors. However, this information is not always available for other actors than the original equipment manufacturer (OEM). This data can be used to rapidly diagnose the SoH and state of safety, as well as the remaining useful lifetime (RUL) of the individual battery cells. It will require advanced algorithms, typically hybrid physical-based and data-driven models, to accurately diagnose the batteries. With the

EU Battery Regulation and battery passport, described in section 3.5, this data will be made available in the future.

The BTMS ensures the temperature of the battery cells to be within the safe operating window. This is done by employing a cooling and heating system and with thermal insulation. The BTMS in EVs vary depending on the manufacturer. The first hybrid EVs (HEVs) such as Honda Insight and Toyota Prius used preconditioned cabin air for heating/cooling of the battery. The Nissan Leaf is dependent on air-cooling of the battery (J. Jaguemont, 2018). Due to issues with overheating in hot conditions when only air was used as cooling, several EV manufacturers started implementing liquid cooling. Both Tesla and GM use liquid glycol as coolant where heat transfer occurs via a refrigeration cycle. Tesla Model S use a cooling design with a zig-zag pattern through the cylindrical cells (Inside EVs, 2015). GM on the other hand, which uses prismatic battery cells, have chosen to use cooling plates situated between the cells (Inside EVs, 2015). The cooling effect is dependent both on the geometry and the choice of cooling liquid (Lu et al., 2020). Efficient cooling is necessary to avoid thermal runaway and facilitate fast charging while limiting degradation and ensuring optimum lifetime of the batteries. The large differences in cooling technology, and more generally the manufacture of different kinds of battery packs using distinct modules, will make both the combination of battery packs and the standardization of the disassembly process very difficult. Reusing modules from different EVs, even from the same manufacturer, could prove itself challenging.

### *3.3.2 Cathode Chemistries*

The most common EV cathode chemistries are NMC (lithium nickel manganese cobalt oxide), LFP (lithium iron phosphate), and NCA (lithium nickel cobalt aluminium oxide) (Man, 2023). LMO (lithium manganese oxide) was also used in the first-generation Nissan Leaf. (Nissan Motor Corporation, n.d.) Due to issues with cycle life, these were replaced by the more stable NMC chemistries. New developments with the LMO structure and particle engineering are however, making both LMO and LMNO (lithium manganese nickel oxide) interesting candidates for future LIBs. Still, there will be some time before we see significant amounts of second life LMO or LMNO batteries on the market. There are also variations of the NMC cathode chemistries with various fractions of the elements, like NMC111 (1/3 Ni, 1/3 Mn, 1/3 Co), NMC532, NMC622, NMC721, and NMC811, in order of increasing nickel content. NMC111 is the only material deviating from the regular nomenclature, where “1” refers to 1/3. There is less variation in materials selection on the anode side, where graphite is the dominating choice. The third major component of the battery is the electrolyte, which is typically lithium hexafluorophosphate ($LiPF_6$) dissolved in an organic solvent containing linear and cyclic carbonates. However, the exact composition and different additives used, vary greatly, and can significantly alter the battery’s properties and degradation behaviour.

The properties of the cathode chemistries mentioned above can vary quite significantly. While NMC has higher specific energy density compared to LFP, it suffers from shorter lifetime and lower thermal stability. (J. Jyoti, 2021) In addition, the materials in LFP cells are both cheaper and less toxic than substances such as cobalt and (J. Jyoti, 2021) In addition, the materials in LFP cells are both cheaper and less toxic than substances such as cobalt and nickel in NMC cells (Sun et al., 2020). NMC cathodes on the other hand, contain higher concentrations of valuable metals (nickel, cobalt, manganese), making them more profitable to recycle than LFP cathodes where the amount of valuable materials is low (Baum et al., 2022). However, fluctuating market prices for nickel and cobalt cause large variations in battery cell production costs. In 2021, the EV cathode market sales shares of nickel-based cathodes (NMC and NCA) were 85%, while the sales shares for LFP was 24% (IEA, 2022). In September 2022, the LFP sales share has increased to 33%, and it is expected to grow (IEA, 2022). Tesla has used LFP cathode chemistries for some of their models since October 2021. Before that, Tesla used $LiCoO_2$ (lithium cobalt oxide), NMC, and NCA cathode chemistries for their EVs. BYD also uses LFP cathode chemistries. Audi, Ford, Chevrolet, Hyundai, Jaguar, Nissan, Renault, and VW all currently use NMC cathodes.

### 3.3.3 Battery Cell From Factors

There are three battery cell form factors used in EVs: pouch, prismatic, and cylindrical (Arar, 2020). The pouch and prismatic cells have a higher packing density than cylindrical cells, allowing for high energy density. Pouch cells require a mechanical structure to apply pressure to the cell. The cooling systems are more difficult for larger and thicker cells. This affects how batteries can be assembled and how thermal management systems are designed for optimal use based on the given application. The three different types of battery cells used in EVs contribute to an expanded range of requirements for BMS, BTMS, and fastening techniques, thereby necessitating specialized equipment for disassembly and specialized models and techniques for evaluating battery state of health, safety, reliability, and remaining useful lifetime. Between the three main form factors utilized, there does not seem to be one cell form factor which is more easily repurposed compared to the others. The difficulty with regards to repurposing is rather connected to the large variability in shape and size, even for the same type of cell. For example, cylindrical cells come in different diameters and lengths, with the most common being the 18650 (18 mm diameter, 65 mm length) and the 21700 (21 mm diameter, 70 mm length). The newest cells from Tesla are even larger with a 4680 format (46 mm diameter, 80 mm length). (Baazouzi et al., 2023) All these three different cylindrical cells would require different designs for cooling systems, as well as module and pack design, making streamlined repurposing processes even more challenging.

### 3.3.4 Procedures Required for 2nd Life Use

EV batteries are very diverse, and the new anode, cathode, and electrolytes are being researched and developed at a fast pace. Additionally, completely new battery technologies such as all-solid-state batteries, are expected to reach the market in the near future. This makes it challenging to repair, remanufacture, repurpose, and recycle EV batteries, and this technology must follow at the same pace. Zhu et al. have established a general overview of the repurposing procedure, which includes 5 main steps (Zhu J, 2021):

1. Incoming assessment
2. Disassembly
3. Mechanical, electrochemical and safety performance evaluation
4. Sorting and regrouping
5. Developing control strategies for second life applications

For step 1 in the process the historical battery information is essential. For OEMs, 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, and time-consuming physical testing must be performed to assess the RUL (Zhu J, 2021). The uptake of data-centric approaches, such as the battery passport, electronic exchange system, and QR code labelling introduced by the EU 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 (Shahjalal M, 2022).

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 (Harper G, 2019). Battery modules are typically not designed to be detachable, with their joints glued or welded, which requires forceful opening. Currently, the disassembly process is done manually and, thus, relies heavily on human labour, which is expensive and time-consuming compared to an automated process (Haram MHSM, 2021). Therefore, the maximum level of disassembly, i.e., cell-level, typically results in greater costs and takes more time. This was also the result of a study where a Smart For-Four battery was manually disassembled in 2019 at the Polytechnic University of Catalonia (Rallo H, 2020). Even if it is preferable to repurpose either the EVB packs or modules to minimize costs (Zhu J, 2021), dismantling is typically required due to the variation of the battery cell capacity and performance (Shahjalal M, 2022).

The greatest challenge for disassembly stems from the various EVB pack designs (Harper G, 2019). 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 (Haram MHSM, 2021). Thus, standardization of the EV 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 notmeet specific criteria and are unsuitable for 2nd-life applications. In the first screening (step 3.1), the mechanical integrity of the cells is evaluated by visual inspection. Cells with mechanical deformation and leakage are a safety risk for internal short circuits, thermal runaway, and fire and are sent directly to recycling. Currently, visual inspection is done by human workers, which makes it expensive, unreliable, and un-safe. Digital image-based approaches, X-ray-based techniques, and acoustic tools are promising alternatives for overcoming the shortcomings of manual labour (Zhu J, 2021).

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.

The three main strategies for evaluating battery degradation are post-mortem examination, charge-discharge testing, and electrochemical impedance spectroscopy (EIS) with equivalent circuit model (ECM) analysis (Zhu J, 2021). Post-mortem examination is typically destructive and includes opening the battery and is thus not suitable for commercial operations. It is however, used extensively in research and is required to fully understand and correlate data from non-destructive methods with degradation mechanisms. Non-destructive techniques include X-ray computed tomography (XCT) or methods based on acoustic signals. The most used methods currently comprise differential voltage and incremental capacity (DV-IC) analysis in addition to EIS combined with ECM analysis. The key in the latter two strategies 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 (Zhu J, 2021). 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 (Shahjalal M, 2022). 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 (Haram MHSM, 2021). Another problem with inaccurate SoH and RUL assessments is that EoL batteries might not find the optimal 2nd life application. RUL assessments also face the challenge of the non-linear aging processes of LIBs, as 2nd life batteries are more likely to face the knee point, after which the capacity will undergo accelerated degradation (Hua Y, 2021). Historical operation data could ease the SoH and RUL assessments, but this information is not easily available. However, as previously mentioned, the new EU 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 (Hua Y, 2021). 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 (Zhu J, 2021). After the screening processes, the eligible cells are sorted and regrouped with cells of similar quality to ensure pack homogeneity (step 4). The first challenge is selecting appropriate indicators, which depend highly on cell type, battery chemistry, and demands of the 2nd life application. Some typical indicators include SoH, SoC, the voltage of pulse discharge, ECM fitting parameters, and thermal behaviour. 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 (Zhu J, 2021). 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 (Hossain E, 2019).

Second-life applications require control and management strategies (step 5). First, as repurposed batteries have reduced energy and power capabilities compared to virgin batteries, optimal battery sizing and appropriate control are necessary for smoothing power output, avoiding overcharge or over- discharge, and extending life cycle. Secondly, once 2nd 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. Lastly, 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 (Zhu J, 2021).

In section 3.3, we have identified three main technical challenges hindering large-scale implementation of second life batteries. Firstly, the restricted accessibility of historical data stored on the BMS, limited to the original equipment manufacturer, hinders other stakeholders from utilizing valuable information about the battery's past performance. Secondly, due to the wide variety of cell chemistries, cell form factors, and battery pack designs, coupled with rapid technological advancements, life-extending circular activities need to be customized for each battery manufacturer and constantly evolve to keep up with the fast pace of innovation. Finally, evaluating EVBs involves time-consuming and therefore costly procedures that necessitate advanced diagnostic and prognostic algorithms to assess battery state of health, safety, and remaining useful lifetime.

## 3.4 Eco-Design

Eco-design is a holistic design approach to consider the environmental impacts of a product throughout its entire lifetime. The goal is to design products that have as little impact on the environment as possible. The **Eco-design Directive 2009/125/EC** has aimed at improving energy efficiency by integrating environmental issues and life cycle thinking in the product design phase. In March 2022, the EU Commission established a proposal for a new regulation **Eco-design for Sustainable Products Regulation** to repeal the Directive 2009/125/EC. Regulations have binding legal force in every EU Member State and enters into force on a set date, when directives lay down results that must be achieved, but each Member State can freely decide how they transpose them into the national law. The new regulation will apply also to electric vehicle batteries (EVBs) and emphasises circular economy more thoroughly. It aims to provide products that have less environmental impacts, use less energy and natural resources, have long lifetime, as well as being easy to repair and recycle. Current EVBs are not made with eco-design in mind, and quite a few modifications would have to be implemented for EVBs to meet the criteria set in the Eco-design for Sustainable Products Regulation. The technical and eco-design challenges are strongly related and are to a large extent centred around the battery chemistry, variations in battery design, and access to historical user data for the EVBs. Disassembly of EVBs is a time consuming and costly procedure. Depending on its design, it could be complex or impossible to disassemble the EVB to replace or reuse the battery components. This is caused by EV manufacturers aiming for lighter and cheaper battery packs, prioritizing the reduction of the upfront cost, performance, and safety of EVs. The extension of the life of EVBs after reaching the end of their first life is hence not the main concern. However, EVBs are designed to be easily repairable and serviceable during 1st life. Most EVBs are modular, in the sense that the battery cells are stacked into modules. The purpose of this is to ensure the battery pack meets the required current and voltage specifications, and to improve its repairability and serviceability.

Adhesives are typically used in battery packs to ensure that the components remain securely in place and to ensure that the battery pack is watertight. Adhesion bonding is typically lighter and cheaper than mechanical fastening with bolts, nuts, and screws. One of the major challenges of adhesion bonding in EVB packs is that it complicates the ability to repair and repurpose the battery pack. Unlike mechanical fastening, which can be easily undone, adhesion bonding often requires specialized tools and techniques to disassemble the pack without damaging its components. This can make repairs and maintenance more challenging and expensive, as well as limiting the ability to reuse or even recycle the battery pack. In addition, the use of adhesion bonding can make it more difficult to identify and isolate faults or defects in the pack, which can lead to longer diagnostic times and increased downtime for repairs. Structural batteries are becoming increasingly popular among EV manufacturers. Type 1 structural batteries are conventional batteries designed to integrate the battery into the structure of the vehicle, providing both energy storage and structural support. This approach has been pioneered by Tesla and has since been adopted by other manufacturers in the industry. Structural batteries reduce the total weight of the EV, but are more difficult to repair, service and repurpose, as the EVB packs are more difficult to access and remove. In addition, the complexity of the design is higher, making it necessary to have specialized procedures for disassembly.

As described in section 3.3, the repurposing process includes several steps for measuring and evaluating the battery health and condition. The number of tests carried out could be reduced if the company handling the used batteries for repurposing was provided easy access to the first life user data stored in the battery management system (BMS). It is, however, not trivial to access historical data for the batteries. Additionally, current BMSs are not designed for optimizing use in both first and second life, nor providing estimation of degradation rates in second life use (MARBEL, 2021). The precise estimation of battery SoH and development of BMS algorithms for estimating RUL are challenging. Batteries have a limited number of measurable parameters and EVs are used in various conditions and changing temperatures that makes modelling difficult (Xjong, 2020). Batteries are closed systems with complex chemistries and a simple SoH measurement cannot necessarily provide information on the degradation mechanisms leading to the decreased capacity. Based on a study by Wei et. al. (W. Liu, 2022), there is extensive ongoing research into integrating artificial intelligence (AI) techniques into BMS for battery diagnosis and prognosis. However, AI techniques are computationally demanding, often necessitating the use of cloud computing. Additionally, incorporating blockchain technology to maintain traceable and immutable battery historical records can pave the way for the creation of accurate digital twins. These digital models could provide a more precise estimation of the battery's state through its complete lifetime (W. Liu, 2022). Some companies have already released control solutions that are based on algorithms and AI powered software functions. A Dutch company called NXP Semiconductors has developed solutions for EVs where the BMS is connected to the cloud to leverage an AI powered digital twin. Digital twin enables better control and monitoring of the battery and thus extends the battery lifespan and performance. The solution can provide more precise estimation of RUL (NXP Semiconductors, 2022). The company Eatron has a solution where AI based functions are used to run diagnostics in real time in vehicle and in large scale in the cloud. Software can for example be used for predictive cell diagnostics and RUL estimations (Eatron Technologies, 2023).

From an environmental point of view the major impact from the second life use phase is related to charging of the battery. Thus, environmental impacts depend highly on the production method of the used electricity (L. Ahmadi, 2015). Smart charging is technology that is used for grid connected batteries and makes it possible to adjust how much energy is used by the battery based on the grid performance. For example, the battery can be charged at the right time when the production of renewable energy is the highest. The battery can also provide electricity to the grid to achieve peak shaving and therefore reduce the need for building new electric grid infrastructure (MARBEL, 2021). If the battery system is connected to solar panels and to the electricity grid, an increasing share of solar energy can reduce the impacts in the reuse phase. For example, using solar energy instead of electricity grid mix is usually a more environmentally friendly option. Thus, the battery size should be dimensioned so that the usage of solar energy is optimised. However, the bigger battery would also mean bigger impacts on sustainability during the battery first life manufacturing as well as recycling phases (J. Thakur, 2022). Product digital passport is a tool to support the traceability and transition to more sustainable and circular products. It will not automatically make repurposing more environmentally friendly, but it can offer information that enables the systematic development work. EU's new Battery Regulation, approved in June 2023 and reappealing the Battery Directive 2006/66/EC, requires that EVBs have a digital passport that includes information about the battery model, chemistry, where the materials are sourced, production site, user data, etc. All EVBs placed on the market or put into service from 42 months after the regulation entered into force need to have a battery passport (European Parliament, 2023).

The battery passport should enhance transparency along the supply and value chains for all stakeholders through providing information including carbon footprint, battery chemistry, origin of materials, state of health, hazardous chemicals, about repair, repurposing, and dismantling operations to name a few things. Several stakeholders in the EV battery value chain will be able to utilize the information stored in the passport. OEMs can use the data to minimize the battery's environmental impacts and improve the value chain performance. Users can use it to select the product that best fits their purposes. The passport could make the recycling process significantly less complex as the battery chemistry and design would be known. Also, regulatory bodies could better follow-up products' circular performance and adjust the current legislation as needed (K. Berger, 2022).

Research has identified several categories where information is needed. These include battery chemistry and system, application type, sustainability and circularity, diagnostics, performance, and maintenance, as well as value chain actors. Sustainability and circularity mean information about environmental and social impacts, lifespan, and practicability of battery disassembly. Diagnostics, maintenance, and performance include information about the battery health, maintenance history and delivered performance. The value chain actor's category contains data on those who have been involved at any point in the EV battery's life cycle (K. Berger, 2022). The new EU Battery Regulation's requirements supports these research findings. According to the regulation, the battery passport should include information related to product technical features and structures, environmental impacts, dismantling and battery health, to name a few. Some information will be available for all, while some information will have a limited access (European Parliament, 2023). The main challenge related to eco- design identified in this section, is a consequence from the emphasis on low cost and weight for battery systems. This focus causes certain EVBs to be designed and manufactured in a manner that that presents difficulties when it comes to disassembly, making the process difficult and potentially time-consuming.

## 3.5 Legislative Framework

This section will provide an overview of the legislative environment affecting repurposing operations in the EU, and a snapshot of the national case studies in Norway and Finland. The focus was on identifying potential obstacles and enablers affecting repurposing of used EVBs. Until recently the **Batteries Directive 2006/66/EC** has been the primary EU legislation concerning batteries. This directive included requirements for waste management and recycling targets for EoL batteries for portable, automotive, and industrial batteries. The Batteries Directive had no requirements or targets regarding repurposing EVBs for other applications. Instead, the focus was on recycling (S. Roschier, 2020) (European Commission) (Hoarau Q, 2022). With the rapid adoption of LIBs in the automotive sector, the EU Commission saw an urgent need for an update to the Batteries Directive, and a first draft of the new battery regulation was published in December 2020. The new Battery regulation was adopted in plenary by the European Parliament on June 14th, while it was announced in a press release on July 10th, 2023, that the new regulation was also adopted by the European Council (European Council, 2023). The new regulation covers the entire life cycle of the batteries, including production, use, reuse and recycling, ensuring safe, sustainable and competitive batteries. All types of batteries are covered by the new regulation, including all chemistries and from small portable applications to medium and large size stationary energy storage applications.

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 the following actions:

- Separate battery classification category for EVBs.
- Requirement for recycled content in new batteries with mandatory minimum levels.
- Safety requirements for stationary battery energy storage system (BESS).
- Increased recycling efficiencies, and specific material recovery targets for cobalt, copper, lead, nickel, and lithium.
- Requirements for repurposing industrial batteries and EVBs for a second life.
- Requirements for labelling and information.
- BMS, electronic battery passport and a QR code.

Article 12 considers the safety aspects of stationary BESS a typical application for repurposed EVBs. Stationary BESS 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 set out 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 (European Parliament, 2023). Article 13 requires that 42 months after the date of entry into force of the Battery Regulation, batteries should be labelled with a QR code to provide information such as battery type, model, chemistry, and contained critical raw materials (CRMs). Article 14 requires that EVBs shall include a BMS that stores parameters relevant for assessing the SoH and RUL of EVBs, and that repurposing operators can access the BMS. The parameters for determining SoH include remaining capacity, overall capacity fade, remaining power capability, 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. Article 14 also states that the BMS shall include a software reset function to enable uploading of different BMS software in the event that used batteries require it. If then the reset function is used, the original battery manufacturer shall not be held liable for any breach of safety or functionality of the battery occurring during 2nd life use (European Parliament, 2023). This latter addition relating to a shift in producer responsibility could potentially make it easier for the OEMs to provide used EVBs for the 2nd life BESS market.

Article 56 on Extended Producer Responsibility (EPR) further elaborates on the responsibility of battery producers and economic operators. This article states that economic operators who make batteries or battery systems available for the first time within the EU, based on reused, repurposed, or remanufactured batteries, will be responsible for these products' EPR. (European Parliament, 2023). Obligations of economic operators providing 2nd life battery solutions are detailed in Article 45. This article describes the responsibilities with regards to performance testing, safe packing, and shipment, and that the companies selling the batteries must ensure that the batteries comply with all the requirements of the Battery Regulation. The remanufacturing company must also upon request be able to document that the battery has been subject to remanufacturing in accordance with the Battery Regulation (European Parliament, 2023). Article 73 also concerns obligations with regards to documentation of SoH and general condition of the battery to prove that it is suitable for reuse or repurposing. It also requires evidence and documentation of safe handling and transportation of the used batteries.

Article 74 has requirements for handling waste batteries and repurposing EVBs. Paragraph 3 describes the information which must be made available to waste management operators or companies preparing batteries for reuse or repurposing. This includes battery model specific information regarding proper and environmentally sound treatment of the batteries. More specifically, information must be available on dismantling and safe removal of the battery as well as protective measures regarding safety and fire protection during storage, transport, and handling. Perhaps one of the most important chapters in the Battery Regulation concerns the digital battery passport, which is described in Article 77 and 78. All batteries larger than 2 kWh placed on the market from 42 months after the date of entry into force of the Battery Regulation shall have an electronic record containing all the information described in Article 77. Some information will be available to the general public, while certain sensitive information will only be accessible to notified bodies, market surveillance authorities and the European Commission. Information regarding dismantling, safety measures, detailed composition of the battery, historical user data and SoH should be available to companies performing repairs, remanufacturing, and 2nd life operations as well as recycling. Details of information that should be available is listed in Annex XIII (European Parliament, 2023).

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. Article 71 and Annex XII sets targets for recycling efficiency of all batteries. For Li-based batteries, the target is 65% by 2025, and will be further increased to 70% by 2030. Additionally, materials recovery targets for Co, Cu, Pb, Li and Ni are provided, as shown in Table 2. For industrial batteries, EVBs, and light mobility 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 described in Article 8 (European Parliament, 2023).

*Table 2. Recycling Targets set in the Battery Regulation*

| | Year | Cobalt | Copper | Lead | Lithium | Nickel |
|---|---|---|---|---|---|---|
| **Minimum recovered content in new batteries** | 2031 | 16 % | - | 85 % | 6 % | 6% |
| | 2036 | 26 % | - | 85 % | 12 % | 15% |
| **Material recovery targets for waste batteries** | 2027 | 90 % | 90 % | 90 % | 50 % | 90% |
| | 2031 | 95 % | 95 % | 95 % | 80 % | 95% |

In addition to the Battery Regulation, there are quite a few other directives and regulations that are also relevant for the storage, transportation, handling, and operation of stationary batteries. A brief summary of these is provided here. **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). Reuse is here 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" (European Parliament, 2008). 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.

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 battery standards info website (S. Roschier, 2020). There are also various legislations related to the transportation of EoL EV LIBs. **Directive on the inland transport of dangerous goods 2008/68/EC,** the **IATA Dangerous Goods Regulations (DGR)** 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. The IATA DGR, which describes the requirements related to transportation of lithium batteries by air, also has limitations on size of the battery to be transported in terms of energy stored. 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 point 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 (S. Roschier, 2020).

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 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 is no existing legislation 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 (S. Roschier, 2020). Although specific legislation does not exist that cover repurposed battery systems, several are under development and there are some international standards in place which cover installation of both new and 2nd life BESS. There are also several international standards under development specifically for safe installation of large BESS. The German standard **DIN VDE V 0510-100: 2023-04 Safety of lithium-ion batteries from the vehicle sector for use in stationary applications** considers the safety of traction batteries during their complete life cycle, including storage, transportation, installation, operation, maintenance, disassembly and feeding for recycling. This standard is expected to form the basis for other European standards on the subject. However, the document does not cover the requirements for BESS that use the traction batteries described here. These requirements are defined in other codes. The document focuses on industrial applications that are not accessible to non-experts, while home storage systems are not considered in this edition.

Several standards from the International Electrotechnical Commission (IEC) are to a greater or smaller extent relevant for 2nd life BESS. **IEC EN 62281 Safety of primary and secondary lithium cells and batteries during transport** covers standards for packaging of batteries during transport and is closely linked to UN38.3. IEC 62933-5-3 **Performing unplanned modification of electrochemical based system** provides safety requirements, considerations, and process steps when unplanned modifications of the BESS are to be carried out. It is, however, only relevant if an existing BESS is getting re-used/repurposed batteries installed. For new BESS using re-used/repurposed batteries, it does not apply. **IEC 61427-2 Secondary cells and batteries for renewable energy storage** describes test criteria for performance of batteries. However, it is not specific for reuse or repurposing and provides no specific requirements for 2nd life batteries. **IEC 62485 Safety requirements for secondary batteries and battery installations** can be used for installation of both new and 2nd life BESS, but it does not cover 2nd life batteries specifically. The same is true for **IEC 62619:2022 CMV Safety requirements for secondary lithium cells and batteries, for use in industrial applications**, which addresses new (1st life) batteries, but does not cover reused or repurposed batteries for 2nd life BESS. In addition to these already existing IEC standards, two other standards are under development: **IEC TC 21: IEC 63330 Requirements of reuse of secondary batteries**, and **IEC 63338 General guidance for reuse of secondary cells and batteries**. The first of these two will be one of the central standards for reuse and repurposing of LIBs. It will still be very general, including information regarding test requirements, safety assessments, and some required information necessary for repurposing. The latter is expected to be an important part of the guidelines for reuse and repurposing of LIB. It will cover guidance for safety risks, agreements between original producer and the manufacturer of the repurposed battery systems. Additionally, it is expected to cover guidance for repurposing, mainly intended for original manufacturers as well as qualified manufacturers of reused and repurposed battery systems.

With all the legislation and standards mentioned above, there is still one area not covered by any of the existing or upcoming documents, which is the recommended standards for battery rooms and procedures for risk assessment of large BESS installations. Both are vital for safe implementation and operation of BESS and are a major hindrance for building owners and real estate developers considering energy storage solutions. The safety aspect and lack of documentation and regulation in this area were also pointed out as weaknesses by many of the stakeholders participating in the interview process.

### 3.5.1 Legislative Landscape in Finland and Norway

As Finland is part of the EU, it currently follows the Batteries Directive. The **Finnish Government Act on batteries**, **Valtioneuvoston asetus paristo-ista ja akuista (2014/520)**, has incorporated requirements of the Batteries Directive (Finnish Government). 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 (Finnish Government). Therefore, operators other than battery manufacturers should have the opportunity to establish reuse or repurpose services for EoL batteries.

Norway along with Iceland, Liechtenstein, and Switzerland are not members of the EU. Instead, they are the four members of the European Free Trade Association (EFTA). 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 (EFTA, n.d.). 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 (Brick Court Chambers, 2016). 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 (Lovdata, 2004).

An unregulated market for EoL EVBs is growing in Norway due to the absence of a legislative 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 (Grudzień, 2022). This is problematic because EVBs unsuitable for reuse or repurpose applications may be used due to the absence of safety protocols and standardized procedures. Also, since anyone in principle can buy and assemble used EVBs, the knowledge of the people handling the batteries is not necessarily sufficient for ensuring proper and safe use. Thus, it is crucial to include the safety aspects of both reuse and repurpose in the legislative framework to avoid accidents when working with EVBs and to ensure adequate safety of 2nd life applications (S. Roschier, 2020).

In section 3.5, we have discussed challenges related to the current legislative framework. Two main challenges were identified; the first being the absence of a regulatory framework, adequate testing protocols, and established safety standards, which hinders the repurposing of electric vehicle batteries. A second challenge comes from the forthcoming EU battery directive. While promising ways to mitigate some of the challenges that EoL EV batteries are facing, it prioritizes material recycling of batteries over activities aimed at extending their lifespan in a circular manner, by mandating a minimum proportion of materials in new batteries to be sourced from recycled materials.

## 3.6 Safety/Reliability

Lithium-ion batteries in general perform extremely well and are very reliable. They have high energy and power density, high cycling stability, and long cycle and calendar life[3]. However, aged LIBs present a significant safety hazard. From the stakeholder interviews, four main challenges relating to safety/reliability were identified. These are a combination of technical and societal barriers. The lack of knowledge on how 2nd life batteries behave, the concerns related to sudden loss of capacity, as well as the increased risk of fire and lack of efficient fire-suppression systems, are all significant factors contributing to a negative public perception. Battery room standards and sufficient knowledge of proper construction materials are also a significant reason as to why many entrepreneurs and real estate developers are hesitant to installing stationary LIBs. In this section, more detailed descriptions of these major barriers are provided.

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[3] The cycle life of a battery refers to the total number of charge-discharge cycles it can undergo throughout its lifespan, while the calendar life represents the duration it can endure without requiring charging or discharging.

LIBs, while generally reliable, can unexpectedly fail before their projected EoL. In EVs, batteries are designed to last between 8-10 years and can undergo 1000-3000 cycles before their SoH degrades to 80%. Nevertheless, batteries may reach a knee point, also referred to as 'rollover failure' or 'sudden death,' characterized by a sudden decrease in energy capacity. This unpredictable event can be triggered by several factors such as electrolyte drying, significant alterations to the solid electrolyte interface (SEI), lithium metal dendrites formation, or lithium plating. The complex and varied nature of these causes makes predicting rollover failure a challenging task. Moreover, as the calendar and cycle life of the LIBs increase, so does the likelihood of experiencing rollover failure. Consequently, batteries repurposed for a second life inherently exhibit reduced reliability. Ongoing research and development are actively seeking solutions to extend the life and reliability of lithium-ion batteries, aiming to mitigate the occurrence of rollover failure. Breakthroughs in areas such as solid-state batteries, improved battery management systems, and advanced electrode materials promise a future where battery cycle life and safety are significantly enhanced.

Thermal runaway can lead to catastrophic battery failure such as fire, explosion, release of toxic and flammable gases, and jet flames. Although rather unlikely, thermal runaway is the most common catastrophic failure mode of LIBs. According to Feng et al. (X. Feng, 2018), the estimated probability of self-induced thermal runaway in EVBs is estimated to be approximately 1 in 10,000, whereas the corresponding statistic for all vehicle types in the US is 7.6 in 10,000. However, it is important to note that the consequences of a thermal runaway event can be significant. In addition to releasing large amounts of energy, the heat leads to decomposition reactions, releasing toxic gases. For example, a 2011 Nissan Leaf 24 kWh EV battery pack (battery and plastics) has a peak heat release rate (PHRR) of 6.3 kW (Watanabe et al., 2012). The PHRR is proportional to $E^{0.6}$, where E is the storage capacity of the battery. Sun et al. (2020) estimate that a 5 MWh battery energy storage system (BESS) has a PHRR of 25 kW (Sun et al., 2020). In addition, toxic gases such as hydrogen fluoride (HF), hydrogen cyanide (HCN), and carbon monoxide (CO), and flammable gases such as hydrogen ($H_2$) and methane ($CH_4$) can be released.

On average, EV fires produce a similar amount of PHRR compared to internal combustion engine vehicles (ICEV) (Sun 2019). However, it can be more difficult to suppress EV fires compared to ICEV fires, due to both the battery pack accessibility for fire suppression and the reignition risk if the battery is not sufficiently cooled down. It is thus equally important to cool down the battery as it is to extinguish the fire. This makes EV fires unique, and different to ICEV fires. As a result of this, EV fires have attracted a considerable amount of negative media attention, which in turn negatively affects the public opinion of the safety of EVs as well as the public acceptance of EV battery repurposing for BESS.

Battery failure is caused by mechanical, electrical, and/or thermal abuse of the battery. Mechanical abuse may cause a short circuit to occur, leading to large amounts of energy being released rapidly. This can happen by piercing of the battery cells, creating an internal short circuit, by damage to the battery pack or module in such a way that it creates an external short circuit, in the event of a car crash or other external effects such as external fire or natural disasters. EVBs repurposed for BESS might have undetected mechanical damage from 1st life. Additionally, damage can occur during transport to the installation site. However, mechanical abuse is less likely for BESS as they will remain in the same place for the duration of their operation.

Electrical and thermal abuse can promote the aging of the battery component materials. Battery ageing reduces the energy storage capacity and increases the risk of thermal runaway. Electrical abuse, such as overcharging and over-discharging, and thermal abuse can lead to internal short circuiting, which is the most common reason for thermal runaway (X. Feng, 2018). Internal short circuiting can for example occur if the separator material is heavily degraded or a lithium dendrite pierces the separator material, so that the anode and cathode materials come in contact. Aged batteries have a higher probability of faults, and consequently a higher risk of thermal runaway. For this reason, it is crucial to evaluate the EoL batteries that are considered for circular activities such as repair, remanufacture, refurbishing, and repurposing.

Batteries at the end of their lifecycle need to be systematically collected, transported, and stored before they can be repurposed. However, during this logistical phase, comprehensive information about the battery often remains scarce. Although batteries are visually inspected for any mechanical damage before collection and receive a more in-depth assessment during storage, potentially hazardous batteries may be handled before more thorough evaluation is performed. A significant challenge in this process lies in the scarcity of data regarding the battery's 1st life. Detailed historical operation information, including charge-discharge rates, operating temperatures, and cell voltages, is not consistently accessible. As discussed in section 3.5, government regulations play a pivotal role in the end-of-life management of lithium-ion batteries, enforcing standards for their safe handling, transportation, and storage to minimize environmental and health risks.

For either new or 2nd life LIB it is essential to plan and design the battery rooms for safe and effective operation of a BESS. Employing fire-retardant construction materials in the enclosures offers enhanced protection against physical damage and can help mitigate potential fire hazards. Incorporating fire suppression systems, designed to promptly detect and extinguish fires, forms an integral part of these precautions. These systems, particularly those equipped with advanced features like automatic activation and targeted extinguishing agents, not only provide an additional layer of safety but also help in mitigating potential damage to surrounding infrastructure, reinforcing the overall security of these repurposed battery systems. Proper ventilation in battery rooms is essential to maintain optimal temperature and prevent the build-up of harmful gases, which can arise from the operation or malfunction of 2nd life batteries. Implementing effective ventilation systems can thus mitigate risks of overheating or potential hazardous situations, ensuring a safer and more stable operational environment for these repurposed battery energy storage systems. External trigger mechanisms for fires in battery rooms can encompass factors like electrical faults, exposure to extreme temperatures, an external fire spreading to the battery room, or even natural disasters such as earthquakes, floods, or lightning strikes. This wide array of potential risks reinforces the need for comprehensive safety precautions, resilient design, robust fire suppression systems, and well-prepared emergency response plans for these facilities.

Greater research and development efforts are crucial to advance the effectiveness of fire-retardant construction materials and fire suppression systems to significantly enhance the safety and resilience of 2nd life BESS. The absence of explicit standards and certifications for 2nd battery installations are a significant issue, leading to uncertainties in defining safety and performance benchmarks. The establishment of comprehensive, stringent, and globally recognized standards and certifications for these installations is thus essential to ensure consistent safety, reliability, and efficiency across the rapidly growing 2nd life battery industry.

We have identified 4 major challenges related to safety/reliability. EoL batteries pose risks of damage and fire hazards, necessitating proper collection and storage protocols that are crucial to mitigate the inherent dangers associated with handling these potentially hazardous batteries. Concerns regarding this safety challenges causes a general negative public perception and heightened apprehension regarding EV battery repurposing for BESS.

The reliability of 2nd life BESS is concerning due to the potential for sudden loss of energy capacity in lithium-ion batteries, making this another important challenge to extending EV battery lifetime through 2nd life applications. Finally, insufficient understanding of battery room construction, including the selection of appropriate construction materials, implementation of effective fire-suppression systems, and adequate ventilation, can lead to critical gaps in ensuring the safety and optimal functioning of battery storage facilities.

## 4. SUMMARY AND CONCLUSION

From the stakeholder interviews and the review of available literature, including regulations and legislation, a set of 10 main challenges were identified. The challenges were categorised under technical, legislative, eco-design, and safety/reliability. These are summarised in Table 1.

*Table 1. Summary of the 10 Main Challenges Identified, Grouped by Category*

| | # | Challenges |
|---|---|---|
| **Technical** | 1 | The restricted accessibility of historical data stored on the battery management system, limited to the original equipment manufacturer, which hinders other stakeholders from utilizing valuable information about the battery's past performance. |
| | 2 | Due to the wide variety of cell chemistries, cell form factors, and battery pack designs in batteries, coupled with rapid technological advancements, life-extending circular activities need to be customized for each battery manufacturer and constantly evolve to keep up with the fast pace of innovation. |
| | 3 | Evaluating EVB involves time-consuming procedures that necessitate advanced diagnostic and prognostic algorithms to assess battery state of health, safety, and remaining useful lifetime. |
| **Legislation** | 4 | The absence of a regulatory framework, adequate testing protocols, and established safety standards hinders the repurposing of electric vehicle batteries. |
| | 5 | The new EU Battery Regulation prioritizes material recycling of batteries over activities aimed at extending their lifespan in a circular manner, as it mandates a minimum proportion of materials in new batteries to be sourced from recycled materials. |
| **Eco-design** | 6 | Due to the emphasis on low cost and weight, certain EVBs are designed and manufactured in a manner that poses challenges when it comes to disassembly, making the process difficult and potentially time-consuming. |
| **Safety & reliability** | 7 | Negative public perception regarding EV battery repurposing for BESS, primarily driven by concerns surrounding perceived high fire risks and associated hazards, leading to heightened public apprehension. |
| | 8 | Reliability of second life BESS is a concern due to the potential for sudden loss of energy capacity in lithium-ion batteries. |
| | 9 | EoL batteries pose risks of damage to people and surroundings, and are a fire hazard, necessitating proper collection and storage protocols that are crucial to mitigate the inherent dangers associated with handling these potentially hazardous batteries. |
| | 10 | Insufficient understanding of battery room construction, including the selection of appropriate construction materials, implementation of effective fire-suppression systems, and adequate ventilation, can lead to critical gaps in ensuring the safety and optimal functioning of battery storage facilities. |

To summarise, the main challenges of the overall repurposing process are costly human labour-based operations, lack of automation, absence of standardized indicators and models, lack of access to historical user data, 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 non-destructive acoustic methods, standardization of EVB pack designs, utilization of EIS-based and IC-DV techniques for modelling battery degradation, and incorporating of data-driven prognostics for determining RUL. The legislative framework review revealed that in general, there is a great lack of laws, policies, and standards on many levels to encourage 2nd life. There are no standard testing protocols or established safety standards for repurposing batteries, which causes great uncertainty both amongst the 2nd life battery providers and the end users. The new EU Battery Regulation repealing Directive 2006/66/EC and amend Regulation (EU) No 2019/1020 will enter into force in 2023. The updated Regulation will to a large extent address recycling with specific targets for collection rates and recycling yields, but no specific targets are set for reuse and 2nd life, which may hamper the acceleration of this circular strategy and market.

Potential solutions to overcome the identified challenges were also identified during the study. In conclusion, legislation should encourage, e.g. via mandates and targets, EVBs to be designed for 2nd life and high circularity. This would require active involvement of car manufacturers as car manufacturers should consider the 2nd life of EVBs already in the design phase. In addition, the standardization of EVB designs should be advanced in the EU. Currently, the variability of battery types and designs is handled by using only same type of EVBs from the same car manufacturers. In this case, the availability of similar EVBs is a limiting factor for market growth.

The primary safety/reliability challenges in extending the lifetime of EVBs revolve around the risks of thermal runaway and sudden energy capacity loss, which can significantly impact public perception of 2nd life use of aged LIBs. By comprehensive safety risk assessments and implementing effective safety measures, reliability and trust in the cycle life, performance, and safe utilization of EVBs can be improved and fostered. Possible solutions to respond to end-users' concerns about safety are 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.

Policy makers and industrial actors may achieve a better understanding of the challenges and barriers that exist, and especially gain insights into how their short- and long-term decisions may affect the possibility to reuse or repurpose an EVB. The identification of these challenges and gaps may help in managing the circular disruption. As Chizaryfard et al (2022) elaborate in their study, different value chain actors must overcome different disruption and structural tensions at different levels, which are furthermore interconnected and influence each other simultaneously; also, in some cases causing conflicts between each other (Chizaryfard ym., 2022). The current EU legislation is causing tensions between the reuse and recycling circular strategies and the value chains operating in those are facing conflicts.

As a conclusion, batteries are urgently needed to meet the objectives of the EU's Green Deal and REPowerEU on climate neutrality, replacing fossil fuel dependency and increase use of renewable energy. Circular economy on the other hand is key to enhance EU's resource independency and increasing security of value chains as well as supply security – especially of valuable and critical battery materials. The utilisation of end-of-life EVBs in 2nd life applications is an underutilised and legislatively under-supported field with untapped potential to help reach several of EU's key strategic targets.

## AUTHOR CONTRIBUTIONS

**Fride Vullum-Bruer**: Collected and summarized a significant part of the literature sited, data analysis, lead and corresponding author in charge of writing the document based on collected data.
**Olav Galteland**: Writing parts of the document, collecting literature, reviewing and editing.
**Margaux Gouis**: Writing parts of the document, collecting literature, reviewing and editing.
**Nina McDougall**: Methodology for interviews, conducted interviews and analysed the collected data, collected and summarized a significant part of the literature sited.
**Anna Tenhunen-Lunkka**: Writing parts of the document, methodology for interviews, analysis of data, review and editing.

## DECLARATIONS

**Competing interests** The authors declare no competing interests.

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# APPENDICES

## 1. APPENDIX A. INTERVIEW QUESTIONS FOR ALL PARTICIPANTS EXCEPT END-USERS

### 1.1 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)

### 1.2 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?

### 1.3 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?

### 1.4 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?

### 1.5 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?

### 1.6 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?

### 1.7 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?

# 2. APPENDIX B. INTERVIEW QUESTIONS FOR END-USERS

## 2.1 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)

## 2.2 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?

## 2.3 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?

## 2.4 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?

## 2.5 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?

## 2.6 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?