TREASoURcE

Existing and upcoming challenges for extending electric vehicle battery lifetime

WP no and title	**WP4 Existing and upcoming challenges for battery second life**
Lead Beneficiary	**SINTEF, Viken, EKOF, ECO**
Responsible Author(s)	**Olav Galteland, Margaux Gouis, Fride Vullum-Bruer, Nina McDougall, Mathias Winther Thorsen**
Contributor(s)	**All WP leaders** **All partners**

This document contains the ”Report on existing and upcoming challenges for second life battery use” for the TREASoURcE project (Grant Agreement No. 101059491).

Funded by
the European Union

Project Details			
Project acronym	TREASoURcE	Start / Duration	June 2022 / 48 months
Topic	HORIZON-CL6-2021-CIRCBIO-01-01 – Circular Cities and Regions Initiative (CCRI)’s circular systemic solutions	Grant Agreement No	101059491
Type of Action	Innovation Action (IA)	Coordinator	VTT Technical Research Centre of Finland Ltd
Contact person	Anna Tenhunen-Lunkka, anna.tenhunen-lunkka@vtt.fi		
Website	**https://treasource.eu/**		

Deliverable Details			
Deliverable No	D4.1		
Deliverable Name	Report on existing and upcoming challenges for second life battery use		
Work Package	WP4		
Dissemination level	SEN/PU	Type	Report
Due Date (M)	31.05.2023	Submission date	31.05.2023
Lead Beneficiary	SINTEF	Responsible Author	Olav Galteland

Deliverable Contributors				
	Name	Organisation	Role / Title	E-mail
Deliverable leader	Olav Galteland	SINTEF Energy Research AS	Research Manager	olav.galteland@sintef.no
Contributing Author(s)	Margaux Gouis	SINTEF Energy Research AS	Master of Science	margaux.gouis@sintef.no
	Fride Vullum-Bruer	SINTEF Energy Research AS	Senior Research Scientist	fride.vullum.bruer@sintef.no
	Nina McDougall	VTT	Master Thesis Worker	ext-nina.mcdougall@vtt.fi
	Mathias Winther Thorsen	ECO STOR AS	Battery Systems Engineer	mathias.thorsen@eco-stor.no
Reviewer(s)	Ragnhild Sæterli	SINTEF Energy Research AS	Research Scientist	ragnhild.saterli@sintef.no
Final review and quality approval	Anna Tenhunen-Lunkka	VTT	Project Coordinator / Senior Scientist and Project Manager	anna.tenhunen-lunkka@vtt.fi

Document History		
Date	Version	Comments
30.04.2023	0.1	First draft improved based on work package feedback.
15.05.2023	0.2	Third draft improved based on consortium feedback.
31.05.2023	1.0	Reviewed and final version.

TABLE OF CONTENTS

ACRONYMS AND ABBREVIATIONS 7

EXECUTIVE SUMMARY 8

1. INTRODUCTION 9

2. CIRCULAR VALUE CHAIN AND CIRCULAR BUSINESS MODELS 12

  2.1 Circular business models 13

    2.1.1 Repair, refurbishing, and remanufacturing 14

    2.1.2 Repurposing 14

    2.1.3 Recycling 15

3. TECHNICAL CHALLENGES 16

  3.1 Battery management system (BMS) 16

  3.2 Battery thermal management system (BTMS) 17

  3.3 Battery cell 18

    3.3.1 Form factor 19

  3.4 Battery evaluation 20

4. REGULATIONS & LEGISLATIONS 25

  4.1 European Union 25

    4.1.1 Current regulatory environment 25

    4.1.2 Upcoming regulatory environment 27

  4.2 Norway 31

  4.3 Finland 33

5. ECODESIGN 36

  5.1 Disassembly 36

    5.1.1 Nissan Leaf 37

    5.1.2 Tesla 38

  5.2 Monitoring of the battery state 39

  5.3 Optimized charging 40

  5.4 Digital battery passport 41

6. SAFETY & RELIABILITY 42

  6.1 Thermal runaway 42

  6.2 Sudden loss of energy capacity 43

  6.3 Safety in the logistics phase 44

  6.4 Safety of second life battery energy storage systems 44

7. SUMMARY AND CONCLUSION 46

8. REFERENCES 49

List of Figures

Figure 1: Global cumulative energy storage installations between 2015 and 2030 (BloombergNEF, 2021). (MENA = Middle East & North Africa. Buffer represents markets and use-cases that BloombergNEF were unable to forecast due to lack of visibility.).. 9
Figure 2: The total number of passenger light-duty EVs worldwide has increased rapidly from 2010 to 2021 (IEA, 2022). 10
Figure 3: Categories of challenges for increasing the circularity of the electric vehicle battery value chain. 11
Figure 4: EV battery value chain with a high degree of circularity. EV batteries that have degraded sufficiently, can be repaired, refurbished, or remanufactured for further use in the same EV, repurposed for use in EVs with different usage patterns (forklifts or delivery trucks), or for stationary storage in energy storage systems. If these strategies are not viable, the battery components are recycled or incinerated for energy recovery. Figure adapted from (Lluc Canals Casals, 2017). 12
Figure 5: The assembly from battery cells to a battery pack (A. Kampker, 2016) 14
Figure 6: Illustration of the cooling system used in (left) Tesla Model S battery module and (right) GM's EV battery cooling system 17
Figure 7 : Market share of cathode materials in battery energy storage systems, now and in the future. (Wood Mackenzie, 2020) 18
Figure 8: The three battery cell form factors used in EVs: Cylindrical, pouch, and prismatic battery cells. Source from left to right is (Wikipedia, u.d.), (Lima, 2018) , (Morrow Batteries, u.d.). 19
Figure 9 : A general overview of the repurposing process ant its steps (Zhu J, 2021) 21
Figure 10: Waste hierarchy and retirement options for EVBs (Zhu J, 2021)..................................... 26
Figure 11: BVC in Norway's battery strategy. Reprinted by permission of (Minstry of Trade, Industry and Fisheries, 2022).. 32
Figure 12: Main operators in the Finnish BVC (Ministry of Economic Affairs and Employment, 2021). 34
Figure 13: Cutaway of the 2019 Nissan leaf e+ (left) battery pack and (right) battery module (Nissan Motor Corporation, 2023). 37
Figure 14: Development of Nissan Leaf cathode material and module design (Nissan Motor Corporation, 2023). 38
Figure 15: 2017 Tesla Model S battery pack. The battery pack as 16 modules, and 7104 cells. (Cuma, 2017).. 39

Funded by
the European Union

List of Tables

Table 1: Description of circular strategies. 10
Table 2: The cost and time of disassembly of pack, module, and cell (Rallo H, 2020). 15
Table 3: Recycling targets of the proposal and official draft (in red). (Council of the European Union, 2023) and (European Commission, 2020). 30
Table 4: Summary of upcoming and current challenges for extending EVB lifetime. 46

Funded by
the European Union

Acronyms and abbreviations

Acronym	Full name
BESS	Battery energy storage system
BEV	Battery electric vehicle
BMS	Battery management system
BTMS	Battery thermal management system
BVC	Battery value chain
CE	Circular economy
EoL	End-of-life
EPR	Extended producer responsibility
EV	Electric vehicle
EVB	Electric vehicle battery
ICE	Internal combustion engine
LFP	Lithium iron phosphate
LIB	Lithium-ion battery
NCA	Lithium nickel cobalt aluminium
NMC	Lithium nickel manganese cobalt oxide
PHEV	Plug-in hybrid electric vehicle
RUL	Remaining useful life
SoC	State of charge
SoH	State of health

Executive Summary

This report delves into the challenges associated with extending the lifetime of electric vehicle batteries, focusing on four key categories: technical, regulations & legislations, ecodesign, and safety & reliability. Through thorough analysis, ten challenges have been identified, and their summaries are presented. These challenges are interconnected, highlighting the need for a comprehensive and collaborative approach.

An optimal circular value chain is being examined to maximize the lifetime of batteries. To achieve this, the primary lifecycle of batteries can be prolonged through repair, refurbishing, and remanufacturing processes. These processes involve assessing, restoring, and transforming batteries to restore functionality and extend operational lifespan through maintenance, replacement, and upgrades. Alternatively, batteries can be repurposed for a second life, such as in battery energy storage systems. Finally, at the end of their useful life, recycling processes are employed to recover valuable materials, while any remaining residual energy can be obtained through controlled incineration.

To address these challenges technological advancements in battery materials, manufacturing processes, and battery management systems are crucial. Clear regulations and legislations must be established to create standards and frameworks supporting sustainable battery lifecycle practices. Ecodesign principles should be incorporated into manufacturing processes to minimize environmental impacts and enable efficient repair, refurbishing, remanufacturing, repurposing, and recycling.

Moreover, prioritising safety and reliability through robust design, thorough testing, and continuous monitoring is vital to ensure consumer trust and the safe operation of electric vehicle batteries throughout their extended lifetimes. By collectively addressing these challenges, the full potential of electric vehicle batteries can be realized, promoting sustainability, and accelerating the adoption of electric vehicles, thereby contributing to a greener and more sustainable future.

Funded by
the European Union

1. Introduction

There is a growing need for energy storage systems. To reach a zero-emission future, we must shift away from fossil fuels, and renewable energy should be massively deployed. However, replacing fossil fuels with intermittent renewable energy sources reduces the flexibility of the energy market. The power production of for example wind and solar power does not perfectly overlap with the energy demand. To buffer the supply and demands, energy storage systems are needed (IEA, 2022). The global cumulative energy storage installations are forecasted to reach 358 GW and 1028 GWh by 2030 (BloombergNEF, 2021), of which 55% is suggested to provide energy shifting (i.e., storing energy from intermittent renewable sources for later release). Figure 1: Global cumulative energy storage installations between 2015 and 2030 . (MENA = Middle East & North Africa. Buffer represents markets and use-cases that BloombergNEF were unable to forecast due to lack of visibility.)Figure 1 shows the energy storage from 2015 and forecasted to 2030. End-of-life batteries from mobile applications such as electric vehicles (EV), trucks, ships, and similar, can potentially cover a significant part of this stationary market, extending the lifetime of these batteries before they are recycled.

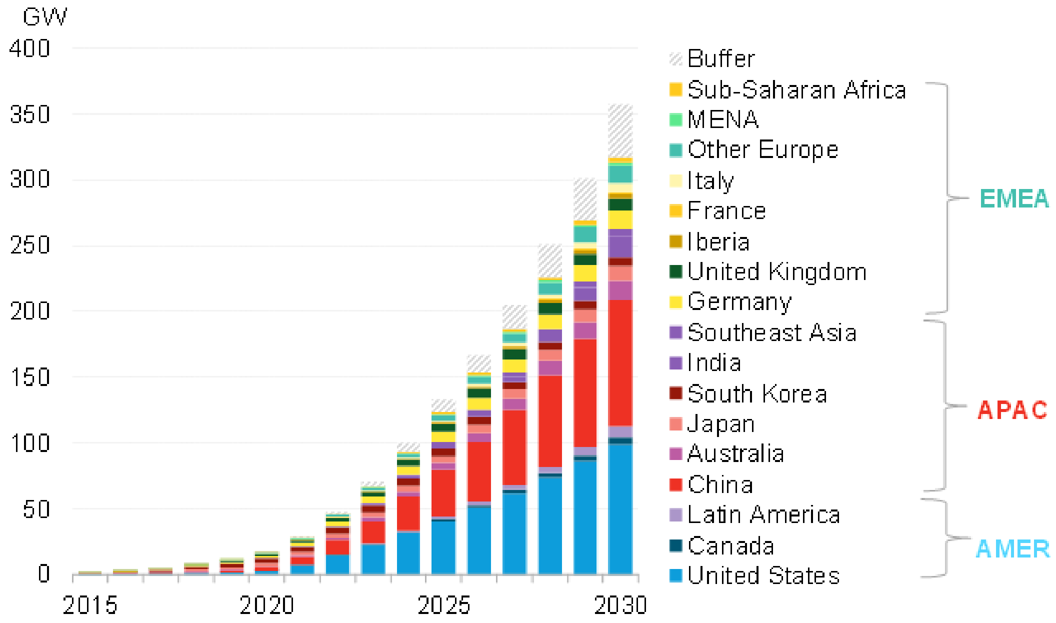
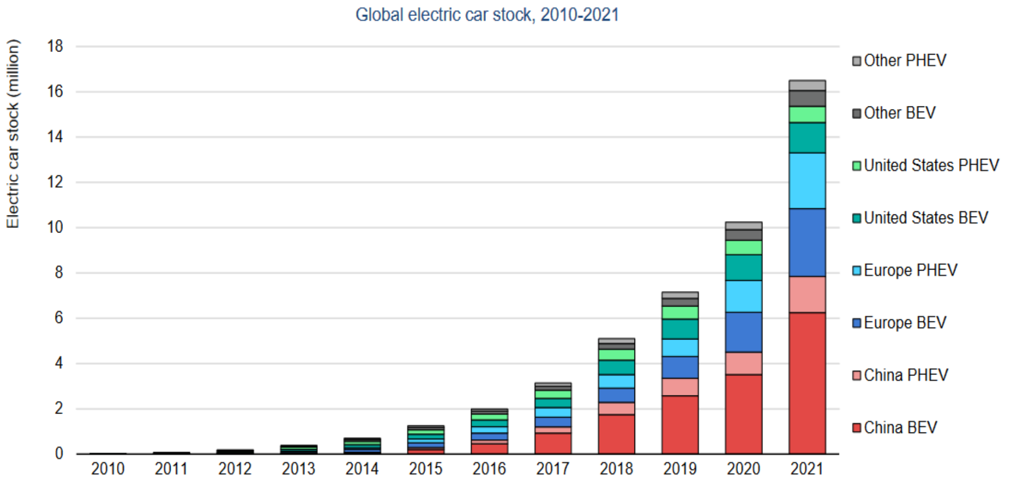


Figure 1: Global cumulative energy storage installations between 2015 and 2030 (BloombergNEF, 2021). (MENA = Middle East & North Africa. Buffer represents markets and use-cases that BloombergNEF were unable to forecast due to lack of visibility.)

An EV battery usually has a warranty of 8 to 10 years (or 100 000 miles/160 000 km) (Nichols, 2023). When EV batteries have reached 70-80% of their original energy capacity, they are often considered to be inadequate for use in EVs. With the EV production increasing considerably, the need for a circular strategy for EV batteries (EVB) reaching their end-of-life (EoL) will become necessary in the next years. In 2019, the worldwide annual sales of EVB reached 20 MWh, and by 2030 it is expected to reach 20 GWh (IEA, 2022). EVs are categorized as plug-in hybrid EVs (PHEV) and battery EVs (BEV).

The total amount of passenger light-duty EVs from 2010 to 2021 are shown in Figure 2. From 2018 to 2021, the total amount of EVs tripled.



IEA. All rights reserved.

Figure 2: The total number of passenger light-duty EVs worldwide has increased rapidly from 2010 to 2021 (IEA, 2022).

Table 1: Description of circular strategies.

Circular strategy		Description
Increasing product lifetime	Repair	Repairing faulty battery components for use in EVs.
	Refurbish	Updating a battery with new technological advances to increase its performance for use in EVs.
	Remanufacture	Combining functional components of several faulty battery packs to produce one functional battery pack for use in EVs.
	Repurpose	Use in battery in a different type of application, such as energy storage systems, ships, or electric bikes.
Useful application of materials	Recycle	Processing to obtain raw material for manufacture of new EV batteries.
	Recover	Incineration of materials for energy recovery.

To reduce the carbon emissions and the environmental footprint of EV batteries, we must increase the lifetime of the products and aim for a circular value chain for EV batteries. To reach a higher degree of circularity, a faulty battery can be *repaired* for continued use in EVs, where the faulty battery components, modules, or cells are replaced. The battery can also be *refurbished* to update an old battery to new technological advances, increasing its performance. Alternatively, functional components of several faulty batteries can be *remanufactured* to produce one functional battery for EVs. The battery can also be *repurposed* in a different type of application, such as energy storage systems (ESS), ships, or electric bikes. If the battery is not suited for either of these circular strategies, the battery is sent for material recycling. Current large scale recycling technologies only allow some parts of the battery to be recycled (approximately 50 %), while the rest is incinerated for energy recovery or stored at a landfill. The new EU Battery Regulation, which will be discussed in detail in chapter 4, will require a significantly larger part of the battery to be recycled. New batteries will also be required to contain a certain amount of recycled materials. Thus, increasing research efforts are accelerating the recycling technology development, leading to greater circularity in the battery value chain. The current circular strategies for batteries are summarized in Table 1. This circular strategy employs six of the ten circular strategies in the 9R framework (José Potting, 2017).

To enhance the circularity through extended battery lifetime, several challenges must be overcome. This report gives an overview of current and upcoming challenges that must be overcome to accelerate growth of the second life battery market. Chapter 2 introduces a detailed description of an EV battery value chain with a high degree of circularity, as well as circular business models. This main part of the report covers current and upcoming challenges for increasing the circularity of the EV battery chain. The challenges are divided into four categories, *technical*, *regulative & legislative, ecodesign*, and *safety & reliability* challenges, as illustrated in Figure 3. This report identified ten main challenges within these four categories.

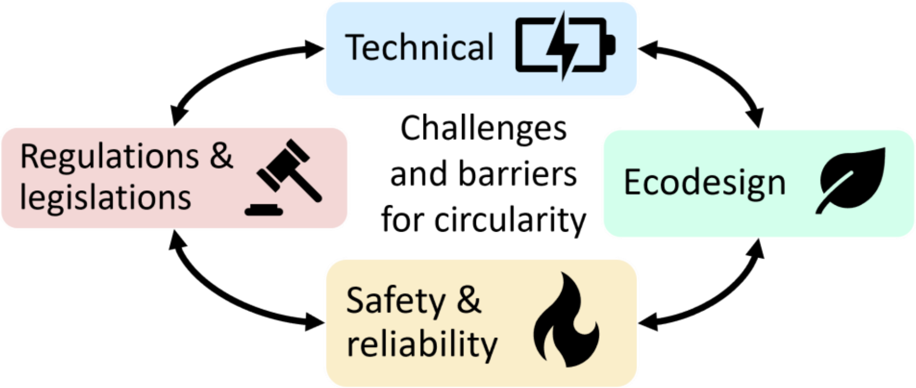


Figure 3: Categories of challenges for increasing the circularity of the electric vehicle battery value chain.

The technical challenges are described in chapter 3, and cover challenges related to the architecture and chemistry of EV battery packs as well as the assessment of EV battery packs, modules, and cells. The regulative & legislative challenges are described in chapter 4 and cover regulations & legislations in the EU, Norway, and Finland. The ecodesign challenges related to environmental design of EVBs will be described in chapter 5. The safety & reliability challenges are described in chapter 6, and cover challenges related to fire safety and expected lifetime of battery energy storage systems (BESS). These four categories of challenges boil down to the cost of circular strategies versus the cost of linear strategies, which is summarized and discussed in chapter 7.

2. Circular value chain and circular business models

Contrary to a linear value chain which describes a linear lifetime from raw materials to production and disposal, a circular value chain is where the raw materials used are circulated back into the manufacturing operation. The individual components or materials can be re-used into the same product or in other products, and potentially very little, if anything, goes to waste (Redwood Logistics, 2023). Figure 4 shows a potential circular value chain for EVBs, from raw materials to fabrication and 1st life use with repairs, refurbishing, and remanufacturing to repurposing in second life, and finally to recycling and recovering of materials and energy, respectively.

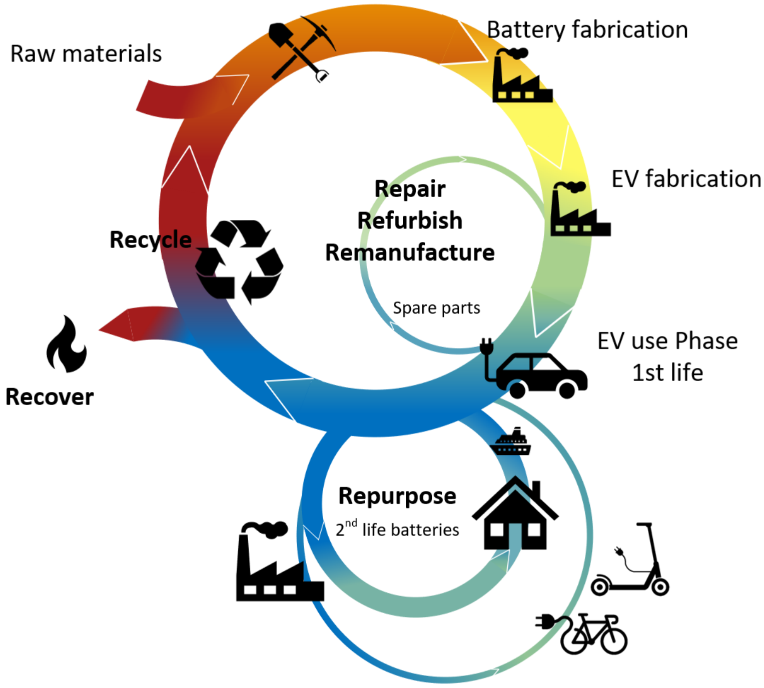


Figure 4: EV battery value chain with a high degree of circularity. EV batteries that have degraded sufficiently, can be repaired, refurbished, or remanufactured for further use in the same EV, repurposed for use in EVs with different usage patterns (forklifts or delivery trucks), or for stationary storage in energy storage systems. If these strategies are not viable, the battery components are recycled or incinerated for energy recovery. Figure adapted from (Lluc Canals Casals, 2017).

The first circular activity in the EVB lifetime is repair, refurbishment, or remanufacturing. In these activities, the battery pack is removed from the EV and either

1. *repaired* with off-the-shelf parts to obtain original performance,
2. *refurbished* with off-the-shelf parts to improve the performance, or
3. *remanufactured* with discarded parts to obtain the original or even improved performance.

With these activities, the 1st life of the EV and parts of the battery pack is extended. Alternatively, the second life of the EVB can be extended by *repurposing* it in other applications, such as BESS in commercial or residential buildings or for propulsion of different means of transportation. If the battery pack performance and safety is good enough, and the application of the EVB is suitable, the whole battery pack may be repurposed without remanufacturing. If the performance or safety of parts of the

EVB is not good enough, the battery pack can be disassembled to replace the faulty components. After second life, the recyclable and valuable materials are recycled for use in new EVBs or in other new products. This value chain is tracing an ideal circularity of the EV batteries. However, some parts of the batteries might be too damaged to reuse into new parts for future battery systems, and those must be sent directly to recycling. To reach a high circular value chain, the cost of the circular activities must be minimized.

EVBs are typically at EoL when they reach approximately 80% state of health (SoH), meaning that the energy storage capacity in the battery has been degraded by 20% compared to the original capacity. The main reason that EVBs are considered at EoL at this stage, is that the remaining lifetime and behaviour becomes much more unpredictable, and EVBs need to be reliable. Many of these batteries can still have a second life in other applications, which do not have equally strict requirements, depending on how they have been degraded. Degradation mechanisms in batteries are quite complex and often difficult to diagnose, which brings a level of complexity and increased cost into the equation. This will be elaborated in chapter 3 on technical challenges. In some cases, EVBs are discarded before they reach 80% SoH, for example EVBs from prototyping, pre-production, batteries with quality defects, or due to EVB overproduction. It may also happen if a car has been involved in a traffic incident or has been damaged by other means, or the owner have upgraded the battery pack to a higher capacity pack. These batteries may be repaired or refurbished, to be reintegrated in another car. If the battery pack is too damaged, the parts that are still usable can be remanufactured into the production of new battery packs. These new battery packs can be implemented in electric cars, but also boats or smaller electricity powered vehicles such as electric scooters or bikes. EVBs can also be repurposed into stationary energy storage systems for a number of applications, such as energy storage for neighbourhoods or as grid support for frequency regulation or voltage support.

2.1 Circular business models

Circular value chains give rise to new circular business models. Until just a few years ago, when EVBs started to reach EoL, the battery value chain for EVBs would go straight from EV use into recycling, recovery, and landfill. However, many businesses discovered the potential for establishing a market within EVB refurbishing, remanufacturing, repair, and repurposing. In recent years the number of companies offering solutions based on used EVBs has multiplied. A significant amount of EoL batteries from EVs can have a second life and provide energy storage for anywhere between 5 to 15 years, depending on the application. EVBs can potentially also be repurposed for use in boats, electrical bikes, and scooters. The recycled materials can either be used in new batteries, or in other products. In chapter 4, we will introduce the upcoming EU Battery Regulation regarding the amounts of materials recycled from EoL batteries, and the amount of recycled materials in new batteries.

2.1.1 Repair, refurbishing, and remanufacturing

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 of the EV and subsequently the lifetime of the EV. MUXSAN is an example of a company which offers refurbishing of Nissan Leafs by mounting an additional battery pack in the luggage space. BATTKOMP AS is another example, who refurbish and design LIB for mobility applications smaller than EVs.

2.1.2 Repurposing

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. 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. Figure 5 shows how pouch cells can be assembled from single cells into modules and further into a battery pack.

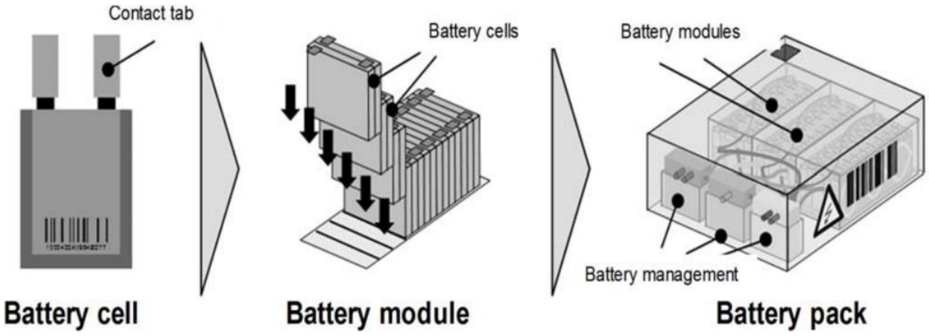


Figure 5: The assembly from battery cells to a battery pack (A. Kampker, 2016)

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).

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 2 (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. Disassemble battery down to module level and reassemble usable modules into a new battery pack, or even reuse single modules.
3. Disassemble the battery system down to cell level and reassemble usable cells into a new battery pack.

Table 2: 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

Which of the three alternatives is the most sensible solution, can depend on a number of factors such as model, batch, reasons for retirement, operation history, etc. In Norway, there are several companies that offer energy storage systems based on used EVBs, including ECO STOR, Hagal, Evyon, Eaton and ChainPro. ECO STOR repurpose EVB packs without disassembly, while Evyon repurpose EVB modules, and Hagal repurpose EVB cells. Each of these companies have specialized in one specific EV manufacturer or model. A more detailed description of technical challenges and cost-driving factors are presented in chapter 3.

2.1.3 Recycling

There are many businesses engaged in the value chain of recycling of EVBs. First, the EoL EVBs are collected, sorted, and disassembled. Contrary to life extending circular activities, disassembly for recycling can be done destructively, *i.e.,* in such a way that the battery components are no longer functional. Furthermore, the battery cells are crushed, processed and refined to make "black mass". The valuable metals, such as nickel, manganese, and cobalt, are extracted from the black mass and further refined into the pure metals. This refinery process is typically done together with refinery of raw materials. The metals can then be used in the manufacturing of EVBs or other useful products. Currently, there are four Norwegian companies involved in the recycling value chain: Batteriretur collect and sort batteries, Hydrovolt produce black mass for battery cells, and Glencore Nikkelverk and ReSiTec refine the black mass to recover valuable materials.

3. Technical challenges

Many of the challenges encountered in the process of extending the lifespan of electric vehicle batteries (EVBs) are rooted in the technical complexities of battery technology. This is further complicated by the rapid development in EVB technology. Innovations are continually pushing the boundaries, with newer chemistries, improved energy densities, and advanced battery management systems (BMSs) being introduced at an unprecedented rate. In this chapter, we aim to 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, reliability, and safety of used EVBs.

EVB packs are built from single battery cells which are assembled into modules, which in turn are assembled into battery packs. 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.

3.1 Battery management system (BMS)

Challenge 1

The restricted accessibility of historical data stored on the battery management system, limited to the original equipment manufacturer, which hinders down stream value chain actors from utilizing valuable information about the battery's past performance.

The BMS is the brain of the battery pack and handles the charging and discharging of the battery. It ensures that the battery pack is operated safely and optimally with information from various sensors in the pack. Typical sensors are temperature, pressure, accelerometers, humidity, and gas sensors in various places of the battery pack, as well as voltage and current sensors in each individual cell. The main purpose of the BMS is to communicate the state of the battery to the EV and ensure safe operation. This is done by:

1. balancing the charge of each individual cell,
2. estimate state of charge (SoC) to determine the remaining range,
3. monitor temperature to reduce damage to the cells,
4. manage current flow to prevent overcharging and over-discharging,
5. fault detection and protection, and
6. logging of data for diagnostic and prognostic purposes.

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 state of health (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 upcoming EU Battery Directive, described in chapter 4, this data will be made available.

3.2 Battery thermal management system (BTMS)

The BTMS ensure 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 car 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 as shown in Figure 6 (Inside EVs, 2015). GM on the other hand, which uses prismatic battery cells, have chosen to use cooling plates situated between the cells as shown in Figure 6 (Inside EVs, 2015). The cooling effect is dependent both on the geometry and the choice of cooling liquid. Efficient cooling is necessary to avoid thermal runaway and facilitate fast-charging while limiting degradation and ensuring optimum lifetime of the batteries.

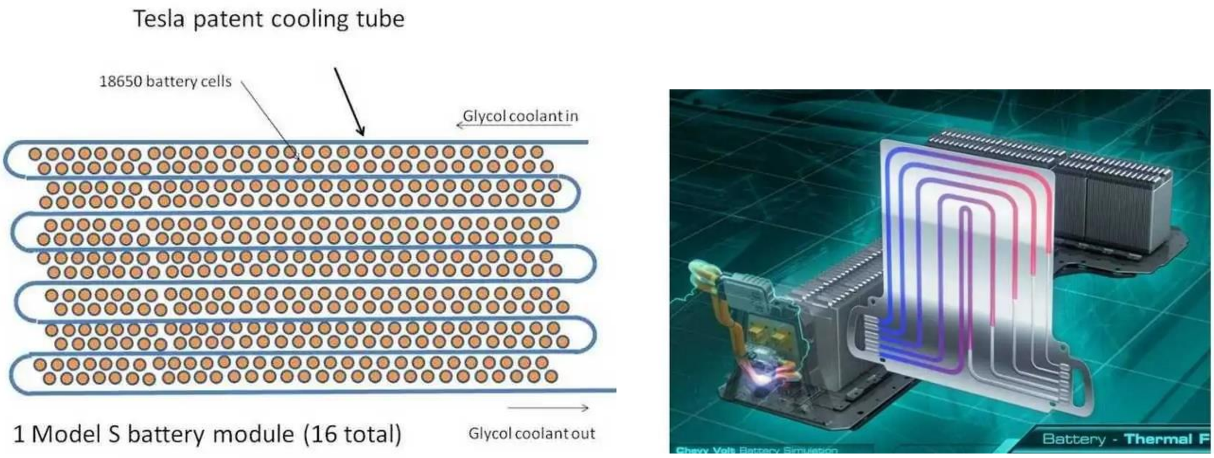


Figure 6: Illustration of the cooling system used in (left) Tesla Model S battery module and (right) GM's EV battery cooling system

3.3 Battery cell

Challenge 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.

The most common EV cathode chemistries are NMC (lithium nickel manganese cobalt oxide), LFP (lithium iron phosphate), and NCA (lithium nickel cobalt aluminium oxide). There are 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. The anode material is typically graphite, which has a high capacity for lithium and a high electrical conductivity. The current collectors are made of thin sheets of copper on the anode side and aluminium on the cathode side. The electrolyte is typically lithium hexafluorophosphate ($LiPF_6$) dissolved in an organic solvent containing linear and cyclic carbonates. The separator separates the anode and cathode and is typically either polyethylene or polypropylene porous film. 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). NMC has inherently higher specific energy density but suffers from shorter lifetime and lower thermal stability. In addition, fluctuating market prices for nickel and cobalt and a desire to reduce or remove the use of cobalt, has caused LFP to gain market shares as EV batteries. The next generation batteries, such as various lithium-ion all-solid-state batteries, are expected to reach the market in the

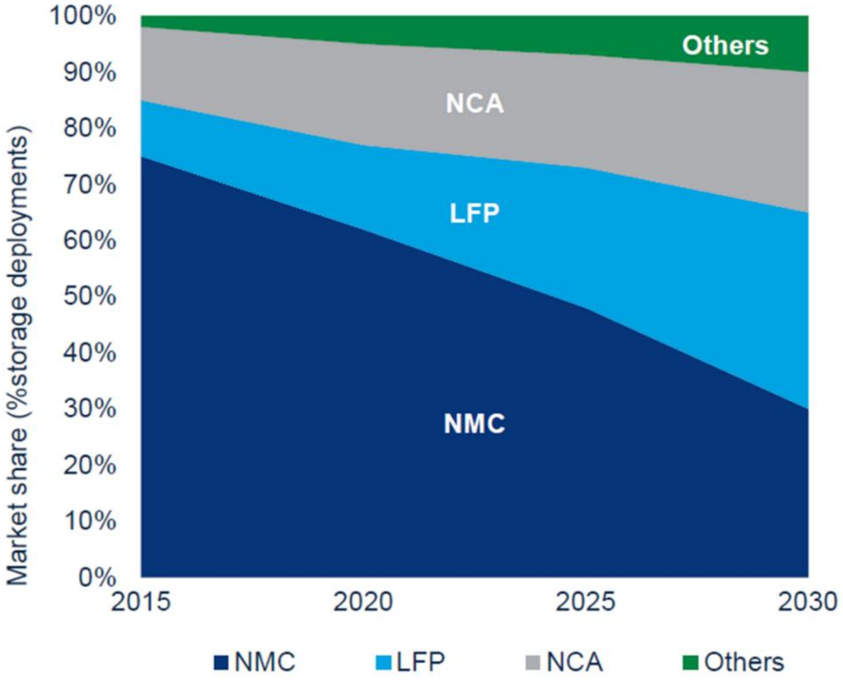


Figure 7 : Market share of cathode materials in battery energy storage systems, now and in the future. (Wood Mackenzie, 2020)

near future. For example, Toyota has unveiled its plans to develop all-solid-state batteries for EVs by 2030 (Toyota, 2021).

The cell voltage of the nickel cathodes is between 3.6-4.5 V, while the cell voltage of LFP is between 3.0-3.3V. As a result, the nickel cathodes have a higher energy and power density than LFP cells. (J. Jyoti, 2021) LFP has a longer cycle lifetime and is significantly cheaper than nickel-based cathodes. The expected cycling lifetime of LFP is between 2000-3000 cycles, while for nickel cathodes the expected cycling lifetime is between 1000 to 2000 cycles. (Battery University, n.d.) The LFP cathodes are considered more stable than nickel-based cathodes, as LFP cells hit thermal runaway around 195 °C, while the NMC cells hit thermal runaway around 170 °C, depending on the specific chemistries and conditions (Duh, et al., 2021). In addition, the materials in LFP cells are less toxic than substances such as cobalt and nickel in NMC cells (Sun, Bisschop, Niu, & Huang, 2020). NMC cathodes contain higher concentrations of valuable metals (nickel, cobalt, manganese), making them more profitable to recycle than LFP cathodes where the amounts of valuable materials is low (Baum, Bird, Yu, & Ma, 2022). In general, the EV sales share of LFP is expected to increase in the coming years.

Tesla has used LFP cathode chemistries for some of their models since October 2021. Before that, Tesla has 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 use NMC cathodes.

3.3.1 Form factor

Figure 8: The three battery cell form factors used in EVs: Cylindrical, pouch, and prismatic battery cells. Source from left to right is *(Wikipedia, u.d.), (Lima, 2018)* , *(Morrow Batteries, u.d.).*

There are three battery cell form factors used in EVs: pouch, prismatic, and cylindrical. These are illustrated in Figure 8. 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 is 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.

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.

3.4 Battery evaluation

Challenge 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.

Zhu et al. have established a general overview of the repurposing procedure (illustrated in Figure 9), 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 EV and battery manufacturers, this information is readily available. However, the lack of battery information is a challenge for third-party operators, as information is typically not provided when EoL batteries are procured. Therefore, costly, and time-consuming physical testing must be performed to assess the RUL (Zhu J, 2021). The uptake of data-driven approaches, such as the battery passport, electronic exchange system, and QR code labelling introduced by the upcoming EU Battery Regulation (explained in chapter 4 of this report), 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).

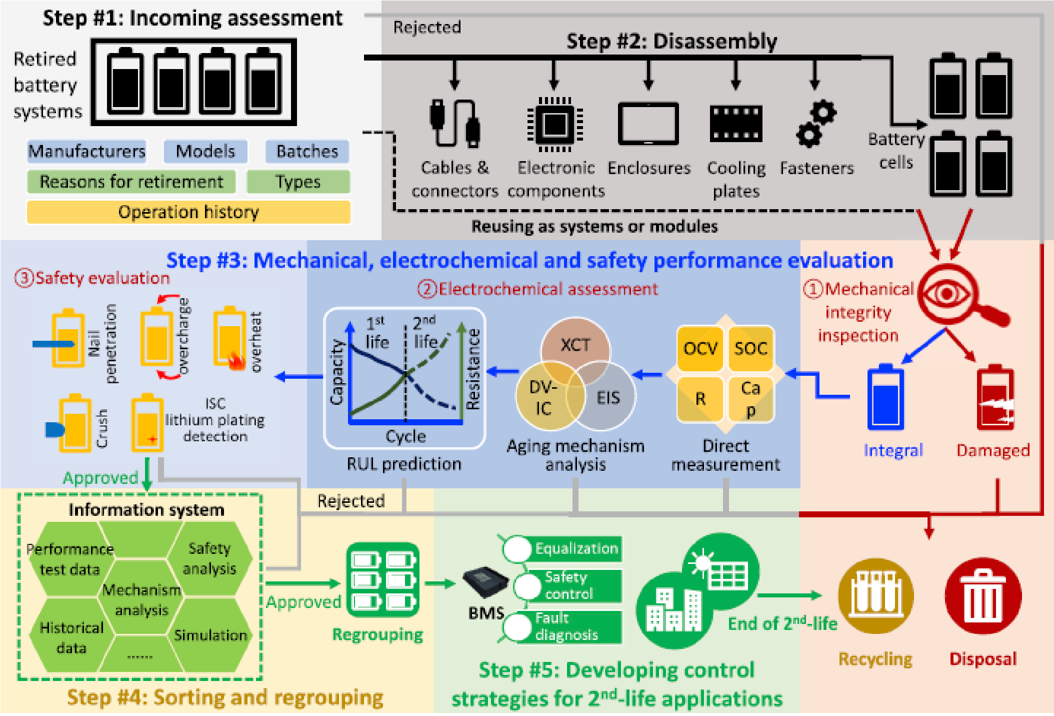


Figure 9 : A general overview of the repurposing process ant its steps (Zhu J, 2021)

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 not meet specific criteria and are unsuitable for 2nd-life applications. In the first screening (step 3.1), the mechanical integrity of cells is evaluated by visual inspection. Cells with mechanical deformation are a safety risk for internal short circuits, thermal runaway, and fire. Thus, cells that show leakage or damage are 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 EV battery. This step is especially challenging due to the complexity of battery degradation and the need for non-destructive assessment techniques to enable commercial repurposing operations.

According to Zhu et al. (Zhu J, 2021), there are three strategies for evaluating battery degradation:

1. Post-mortem examination-based
2. Charge-discharge curve-based, and
3. Electrochemical impedance spectroscopy (EIS) and equivalent circuit model (ECM) based.

Post-mortem examination is typically destructive and includes opening the battery and is thus not suitable for commercial operations. Instead, non-destructive X-ray computed tomography (XCT) is more appropriate but not a very established method. The second strategy comprises differential voltage and incremental capacity (DV-IC) analysis, and the last strategy depends on the EIS test results. 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 process of LIBs, as second-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, 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). During their first life, EVBs experience harsh operating conditions leading to inconsistencies in battery cells and modules. Cell-to-cell and module-to-module variations harm battery life and performance, so sorting is crucial for second-life applications. The first challenge is selecting appropriate indicators, which depend highly on cell type, battery chemistry, and demands of the second-life application. Some typical indicators include SoH, SoC, the voltage of pulse discharge, ECM fitting parameters, and thermal 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 low energy and power capabilities, optimal battery sizing and appropriate control are necessary for smoothing power output, avoiding overcharge or over-discharge, and extending life cycle. Secondly, once second-life ESS is in operation, the emerging inconsistencies in cell-to-cell or module-to-module require active equalization strategies to ensure adequate and safe performance. 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 conclusion, 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 waves, 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. However, further technological advancements are required until these solutions can be implemented (Zhu J, 2021).

4. Regulations & legislations

The text in this chapter is an excerpt from Nina McDougall's thesis titled "The operational environment for repurposing electric vehicle lithium-ion batteries for energy storage applications in the EU" (McDougall, 2023).

This chapter examines the current and upcoming regulatory environment affecting repurposing operations in the EU, Norway, and Finland. Norway and Finland were chosen in particular, as these two countries will host the battery demonstration units implemented through the TREASoURcE project. The focus is on identifying potential obstacles and enablers affecting repurposing operations. First, relevant EU legislation is introduced, after which national legislation and strategies are reviewed for Norway and Finland.

4.1 European Union

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

4.1.1 Current regulatory environment

Challenge 4

The absence of a regulatory framework, adequate testing protocols, and established safety standards hinders the repurposing of electric vehicle batteries.

The Waste Framework Directive 2008/98/EC is relevant because it defines the general definition of waste, introduces the waste hierarchy, and establishes a common framework for the extended producer responsibility (EPR). Article 3 defines waste as "any substance or object which the holder discards or intends or is required to discard" (Parliament). Article 4 sets the foundation for waste management with a five-step waste hierarchy; prevention, preparing for reuse, recycling, other recovery, and disposal. However, reuse is defined as "any operation by which products or components that are not waste are used again for the same purpose for which they were conceived" (Parliament). This would imply that EoL EVBs should be reused for the same purpose, i.e., as the power source for EVs. Although the waste hierarchy does not explicitly mention repurposing, it strives for the best environmental outcome, so repurposing should take place before recycling. This reasoning is supported by an example of the waste hierarchy concept for EoL EVBs, where the reuse segment also includes repurpose applications, see Figure 11. Moreover, EVBs are under EPR, which means that the producer of the EVB (manufacturer or importer of the car) must take care of waste management of EoL EVBs at their own expense; the common practice is to pay for EVB recycling (S. Roschier, 2020).

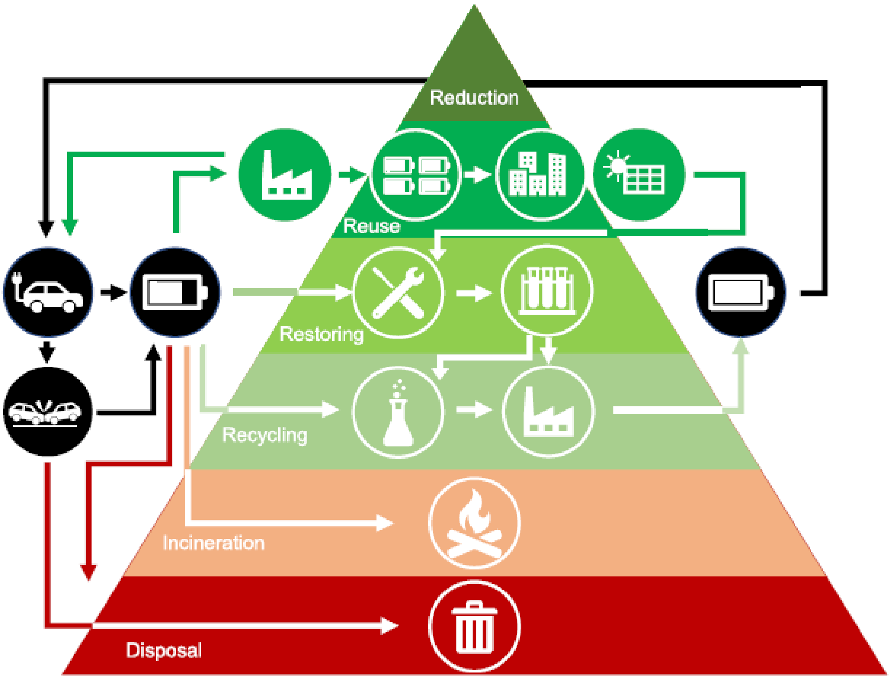


Figure 10: Waste hierarchy and retirement options for EVBs (Zhu J, 2021).

The Batteries Directive 2006/66/EC is the primary EU legislation concerning batteries. It aims to protect and preserve the environment by minimizing the adverse effects of batteries and waste batteries. Thus, it prohibits certain hazardous substances in batteries and sets requirements for waste management and recycling targets for EoL batteries. It also classifies batteries into three categories: portable (electronic devices), automotive (starting, lighting, and ignition power), and industrial (EVs and other industrial applications). It enforces the EPR, which aims to steer EoL batteries to appropriate waste management. It also includes requirements for labeling batteries and their removability from equipment. To achieve a high level of material recovery, it includes recycling efficiency targets of 65% for lead-acid batteries, 75% for nickel-cadmium batteries, and 50% for other waste batteries, including EVBs. However, the collection rates for EoL batteries only apply to portable batteries, excluding EVBs. The Batteries Directive has no requirements or targets regarding repurposing EVBs for other applications. Instead, the focus is on recycling (S. Roschier, 2020) (European Commission) (Hoarau Q, 2022).

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).

Funded by
the European Union

There are also various legislations related to the transportation of EoL EV Lithium-ion batteries (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 thing to note is that if the BMS of the EVB is replaced during the repurposing process, the UN 38.3 test must be redone, which is expensive and results in additional costs. The safety standard **IEC EN 62281: Safety of Primary and Secondary Lithium Cells and Batteries During Transport** is also relevant for repurposing operations (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 are no existing legislations focusing on the safety of ESS. Thus, other existing safety standards related to, e.g., the fire safety of buildings, are applied for ESS. Furthermore, there is currently no legislation concerning the long-term storage of EoL EVBs (S. Roschier, 2020).

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

4.1.2 Upcoming regulatory environment

Challenge 5

The forthcoming EU battery directive 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.

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

In December 2020, the EC proposed a comprehensive new **Battery Regulation** to repeal **Directive 2006/66/EC and amend Regulation (EU) 2019/1020**. The proposal is part of the European Green Deal and other related initiatives, including the Circular Economy Action Plan and the Industrial Strategy. The legislation process has been progressing well. In March 2022, the European Parliament (EP) adopted the amendments, and the European Council (EUCO) agreed on a general approach to the new Regulation. In December 2022, the EUCO and EP reached a provisional political agreement on the content of the Battery Regulation. In January 2023, the official draft negotiation text was published (Council of the European Union, 2023). Next, the EUCO and EP must formally approve the agreement so it can enter into force, which is expected to take effect by Q2 2023 (Take-e-way, 2022). Below, the contents of the Battery Regulation proposal have been reviewed.

The Battery Regulation has three main objectives: 1. strengthen battery sustainability, 2. increase resilience and close material loops, and 3. reduce environmental and social impacts. To achieve these objectives, the proposal introduces new innovations:

- Separate battery classification category for EVBs.
- Requirement for recycled content in new batteries with mandatory minimum levels.
- Safety requirements for stationary 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 and battery passport (Europan Parliamentary Research Service, 2022).

The overall goal is that all batteries on the EU market are sustainable, circular, high-performing, and safe throughout their entire life cycle and that they are collected, repurposed, and recycled, thus becoming a real source of valuable raw materials (European Commission, 2020).

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 laid down in Annex V, for which state-of-the-art testing methodologies should be used. The safety parameters include thermal shock and cycling, external short circuit protection, overcharge protection, over-discharge protection, over-temperature protection, thermal propagation, mechanical damage by external forces, internal short circuits, and thermal abuse (European Commission, 2020).

Article 13 requires that as of 1 January 2027, batteries should be labeled with a QR code to provide information such as battery type, model, chemistry, and contained CRMs. Article 14 requires that

EVBs shall include a BMS that stores parameters relevant for assessing the SoH and remaining useful life (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 (European Commission, 2020).

Article 59 has requirements for repurposing EVBs. First, repurposing operators shall be given access to the BMS to assess the SoH and RUL of the EVB. Second, information relevant to the handling and testing of EVBs, including safety aspects, shall be provided to the repurposing operators. Third, repurposing operators shall ensure that the examination, performance testing, packing, and shipment of EVBs and their components are performed with adequate quality control and safety instructions. Fourth, the repurposing operators shall ensure that the repurposed EVBs comply with the Battery Regulation and other relevant legislation and technical requirements for their specific purpose of use when placed on the market. However, if demonstrated that an EVB subject to repurposing was placed on the market before the specific requirements about carbon footprint, recycled content, performance, durability, and supply chain due diligence was put into force, the obligations under those provisions shall not apply to that EVB when re-purposed. Fifth, to document that a waste EVB, subject to repurposing, is no longer waste, the EVB holder shall demonstrate the following upon a request: 1. evidence of SoH evaluation or testing, 2. certainty of further use with an invoice or sale contract, and 3. appropriate protection against damage during transport, loading, and unloading (European Commission, 2020).

Article 64 concerns the electronic exchange system that contains information about the battery manufacturer, type, model, composition, technical performance, and carbon footprint of EVBs. The information and data shall be sortable and searchable for third-party use. Article 65 discusses the battery passport, an electronic record for EVBs that provides information about the SoH and RUL. The battery passport should enable second-life operators to make business decisions based on data. By 1 January 2026, the electronic exchange system and battery passport should be used for EVBs (European Commission, 2020).

No quantitative requirements are set for repurposing, e.g., X% of EVBs deemed suitable for repurposing should be repurposed before recycling. Instead, the Battery Regulation has introduced several targets for recycling. For instance, Article 8 requires that as of 2030, industrial batteries, EVBs, and automotive batteries that contain cobalt, lead, lithium, or nickel in active materials shall be accompanied by technical documentation demonstrating that those batteries contain the mandatory minimum shares of recovered content, as shown in Table 3. Article 57 sets minimum recycling efficiency targets. For LIBs, the target is 65% by 2025, and will be further increased to 70% by 2030. Article 57 also sets material recovery targets for waste batteries, as presented in Table 3 (European Commission, 2020).

Funded by the European Union

Some of the proposal's recycling targets were updated in the official draft negotiation text, shown by red numbers in Table 3 (Council of the European Union, 2023).

Table 3: Recycling targets of the proposal and official draft (in red). (Council of the European Union, 2023) and (European Commission, 2020).

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

The proposal for a **Regulation on Ecodesign for Sustainable Products** sets new requirements to make products more durable, reliable, reusable, up-gradable, reparable, easier to maintain, refurbish and recycle, and energy and resource efficient (European Commission, 2022). Thus, introducing several circular strategies for improving the circularity, energy performance, and other environmental sustainability aspects of products. Based on the objectives of the new proposal, repurposing EVBs is desirable as the battery extends its life cycle.

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

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

4.2 Norway

The new Battery Regulation will be enforced in all 27 EU Member States. However, countries such as Norway, Iceland, Liechtenstein, and Switzerland are not members of the EU. Instead, they are the four members of the European Free Trade Association (EFTA), an intergovernmental organization established to promote free trade and economic integration between its Member States within Europe and globally. Furthermore, the European Economic Area (EEA) Agreement unites the EU Member States and three EFTA countries – Norway, Iceland, and Liechtenstein – in the Internal Market. The EEA Agreement requires incorporating EU legislation regarding the four freedoms, state aid, competitions, and horizontal policies (EFTA, n.d.). Thus, Norway must implement EU laws concerning competition, investments, labor, procurement and sale of services, banking and insurance, and trade in goods (The Explorer, 2020). 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 regulatory framework. Car wreck companies and private people sell EoL EVBs online, and the highest bidder gets the battery. As a result, many do-it-yourself (DIY) projects are taking place, such as reusing EVBs for EVs or repurposing them for residential energy storage applications (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 second-life applications (S. Roschier, 2020).

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

The strategy highlights the strengths of Norway in becoming a leading host country within the BVC. These include renewable electricity at competitive prices, expertise in the relevant industry, world leading in the transport sector's electrification, a skilled workforce, and stable political governance. Furthermore, ten actions to attract investments to the battery industry are 1. leadership in sustainability, 2. attractive hosting, 3. industrial partnership with other countries, 4. capital, loans, and guarantees, 5. competencies, 6. abundant renewable power supply, 7. industrial sites and infrastructure, 8. coordinated public processes, 9. pilot municipalities in growth, and 10. tomorrow's battery solutions in a strengthened ecosystem (Minstry of Trade, Industry and Fisheries, 2022).

The strategy also presents the entire BVC, as shown in Figure 11. Once the EoL battery is collected, there are two alternative options. The battery can either be repurposed for a second-life battery system or recycled into materials that can be reused for battery manufacturing or used for other purposes. However, the second-life battery systems will eventually face recycling. The strategy also discusses the different Norwegian repurposing actors. For second-life battery systems, it mentions ECO STOR, Evyon, Alternative Energi, and Marna Energi, which provide BESS for households, often in combination with solar and wind power production, and Hagal, which offers single-cell monitoring to maximize the utilization of used and new batteries. It also identifies that repurposing of batteries could be an attractive opportunity for value creation in Norway, as they are at the forefront of EV adoption (Minstry of Trade, Industry and Fisheries, 2022).

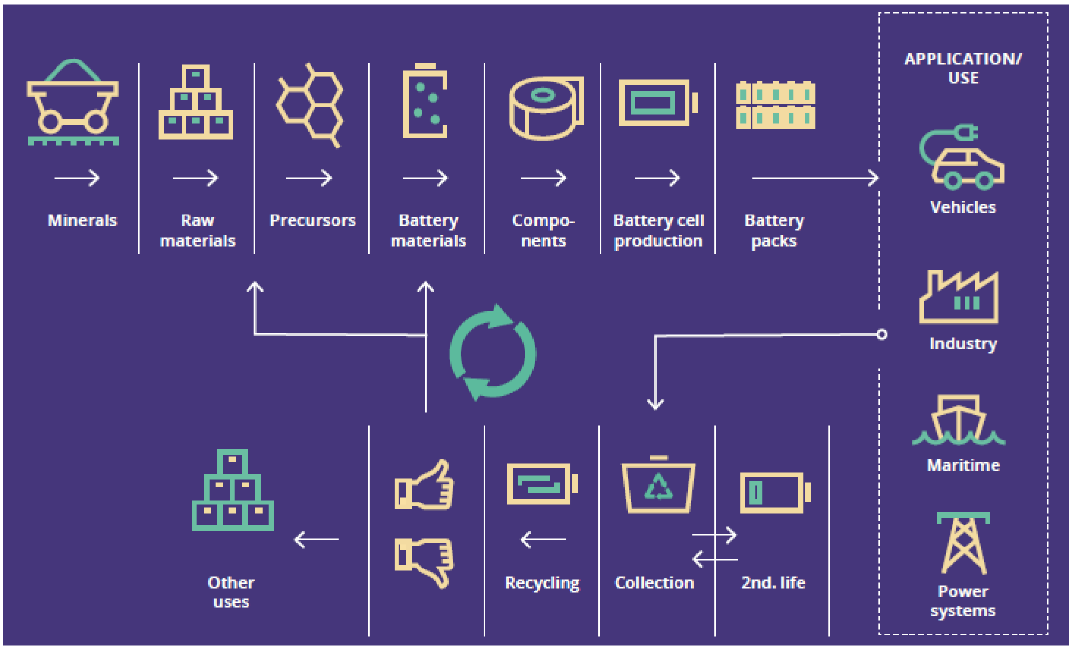


Figure 11: BVC in Norway's battery strategy. Reprinted by permission of (Minstry of Trade, Industry and Fisheries, 2022).

The main recycling actors Hydrovolt, Glencore Nikkelverk, and Resitec are also introduced. The strategy emphasizes that Norway has an excellent starting point for recycling due to its specialized competence and industrial facilities already in operation. The new recycling requirements of the Battery Regulation are also acknowledged. Many of the ten actions introduce supporting measures for large-scale establishments such as recycling facilities. For instance, action four discusses the financial challenges of establishing large facilities, which is why the Government is considering granting guarantees, loans, and equity to support major investment projects. In addition, action seven aims to provide access to industrial areas with adapted infrastructure, especially for new large-scale establishments. Also, action nine emphasizes supporting pilot municipalities hosting major industrial establishments (Minstry of Trade, Industry and Fisheries, 2022).

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

4.3 Finland

As Finland is part of the EU, it currently follows the Batteries Directive. The **Finnish Government Act on batteries**, **Valtioneuvoston asetus 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.

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

The strategy highlights that Finland possesses numerous advantages that position it for success in the battery industry. These include reserves of battery metals such as nickel, cobalt, and lithium, expertise in producing and recycling battery metals, cooperation between the public and private sectors, and socially and ecologically sustainable production. In addition, the strategy presents the main Finnish operators in the BVC, as illustrated in Figure 12. The repurpose operators include Merus Power, Wärtsilä, Fortum, and Helen (Työ- ja elinkeinoministeriö, 2021). However, unlike the Norwegian battery strategy, these are not start-ups solely focused on providing second-life battery solutions. Instead, Wärtsilä is collaborating with Hyundai Motor Group to repurpose their EVBs for second-life ESS (Wärtsilä Corporation, 2018). Fortum has worked with Volvo Cars and Comsys to pilot second-life solutions for batteries (Fortum Corporation, n.d.). No information about Merus Power, which offers various ESS, and the energy company Helen, could be found about their involvement in repurposing projects. In addition to those mentioned, there is Cactos, a company founded in 2021 that repurposes EVBs for ESS.

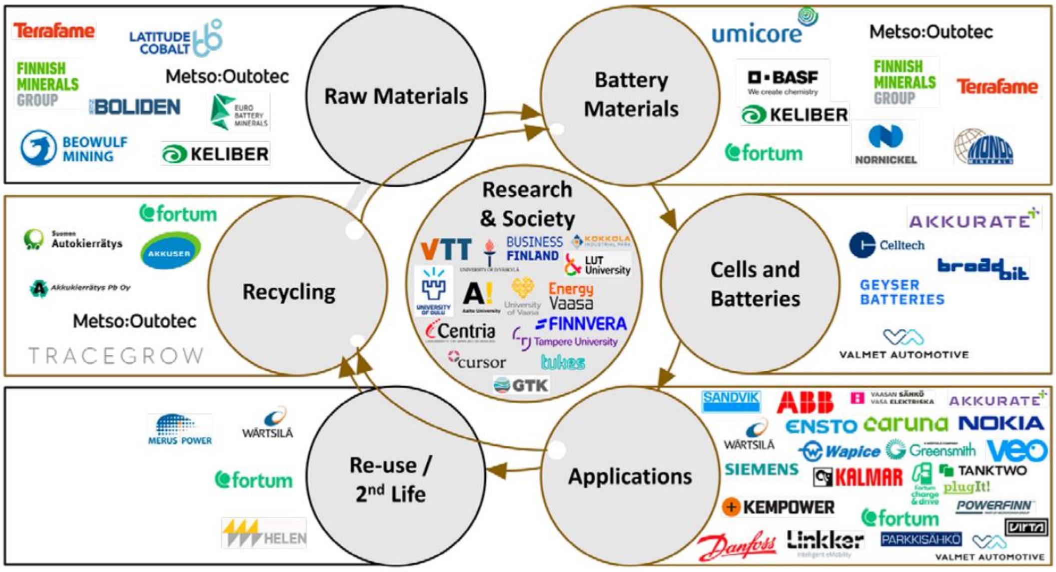


Figure 12: Main operators in the Finnish BVC (Ministry of Economic Affairs and Employment, 2021).

The battery strategy also emphasizes that Finland intends to promote circular economy (CE) of batteries. It states that CE is necessary for a sustainable success for the battery industry. Moreover, it is highlighted that Finland has the know-how, technologies, industrial activities, and research projects in several areas of CE. As an example, the Finland-based circular ecosystem of battery metals consortium (BATCircle) aims to increase the number of recycled LIBs. However, it also notes that CE is much more than just recycling, and that one key goal is to extend the battery life cycle through repair, reuse [repurpose], or remanufacturing. It is mentioned that the reuse [repurpose] of batteries provides new opportunities and that Finland has reliable legislation supporting both reuse [repurpose] and recycling (Työ- ja elinkeinoministeriö, 2021).

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

5. Ecodesign

Ecodesign is an approach to include 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 **Ecodesign Directive** has been implemented in the EU to improve 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 **Ecodesign for Sustainable Products Regulation**. This regulation will include electric vehicle batteries (EVBs), considering 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. The upcoming regulation was described in more detail in chapter 4.

EVBs can be eco designed by considering the materials selection, module, and pack design, and standardisation of battery pack design and BMS. Environmentally benign and non-hazardous materials should be selected to minimize the environmental impact. The biggest challenge with reuse and recycling of EVBs is the non-standardisation of EVB modules and pack designs. Standardisation of battery pack design and BMS will make it significantly easier and less costly to repair, remanufacture, refurbish, or repurpose EVBs from several different makes and models. The disassembly process for EVB packs and modules must be quick and low cost, and the components must be possible to replace or reuse.

5.1 Disassembly

Challenge 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.

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 reductionof 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.

Adhesion is 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 inhibits 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 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.

Below, as examples, two battery designs (Tesla and Nissan Leaf) are described in a bit more detail. Nissan Leaf is one of the first EVs to enter the market, and many EoL batteries from Nissan Leaf are now being reused in second life applications such as BESS. Tesla is chosen due to their special design of their battery packs, which makes reuse, remanufacturing, and recycling more challenging.

5.1.1 Nissan Leaf

The Nissan Leaf was first introduced in 2010 and is one of the world's best-selling EVs. Many of the Leafs have reached end of 1st life, and some are now in use as second life BESS. The EVB pack design and cell chemistry has gradually improved since the introduction in 2010. The Nissan Leaf employs pouch cells as its battery cell type, which need to be supported by a mechanical structure that holds the individual cells together in a module.

Figure 13: Cutaway of the 2019 Nissan leaf e+ (left) battery pack and (right) battery module (Nissan Motor Corporation, 2023).

The first-generation Leaf used a 24 kWh EVB with a LMO (lithium manganese oxide) cathode material, while the third generation Leaf uses as 62 kWh EVB with an NMC cathode material. The design of the battery module has changed from a 4-cell module to a module with a customizable amount of battery cells. The development of the Nissan leaf battery pack is shown in Figure 14. The first- and second-generation modules has the cells glued together and connected with a connector, while in the third generation the cells are laser welded together in a module. The laser welding of cells in a module complicates the disassembly process of the modules. The Nissan Leaf has used between 24 and 48 battery modules in their battery packs.

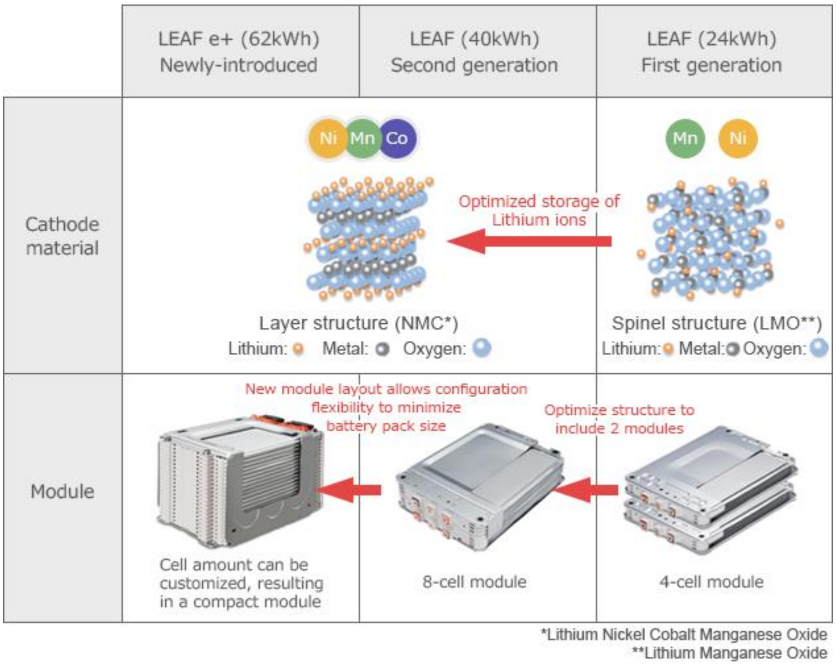


Figure 14: Development of Nissan Leaf cathode material and module design (Nissan Motor Corporation, 2023).

To remove and disassemble the Nissan Leaf battery pack, first the high-voltage connectors are disconnected. Then the battery pack of the Nissan Leaf can simply be unscrewed and removed from the vehicle. The pack is sealed, to be waterproof, but can be opened to access the battery modules. The modules can be unscrewed from the battery pack and opened to access the cells. However, the cells are glued and/or welded together, making it complicated to disassemble without destroying the components.

5.1.2 Tesla

The first Tesla model, the Roadster, was launched in 2008 and was the world's first EV with a range over 320 km per charge. It established Tesla as a leading EV manufacturer. Since then, Tesla has introduced the Model S in 2012, Model X in 2015, Model 3 in 2017, and Model Y in 2020. The models are continuously updated and revised over time. Tesla has used $LiCoO_2$ (lithium cobalt oxide), NCA, NMC, and LFP cathode materials. Tesla has exclusively used cylindrical battery cells, of various dimensions, with between 4 and 16 individual battery modules in their EVs. In the later years, Tesla has pioneered structural battery packs.

The ease of removal and disassembly of Tesla battery packs vary, as their design has been gradually changed over time. In general, the Tesla battery packs can be unscrewed and removed from under the EV frame. The battery modules are in general fastened using welding and adhesions, making it difficult to disassemble the battery pack.

As the number of EVs continues to grow, it will be important to develop new methods and technologies for repairing, maintaining, and repurposing battery packs, to ensure that these components can be reused and recycled efficiently and sustainably.

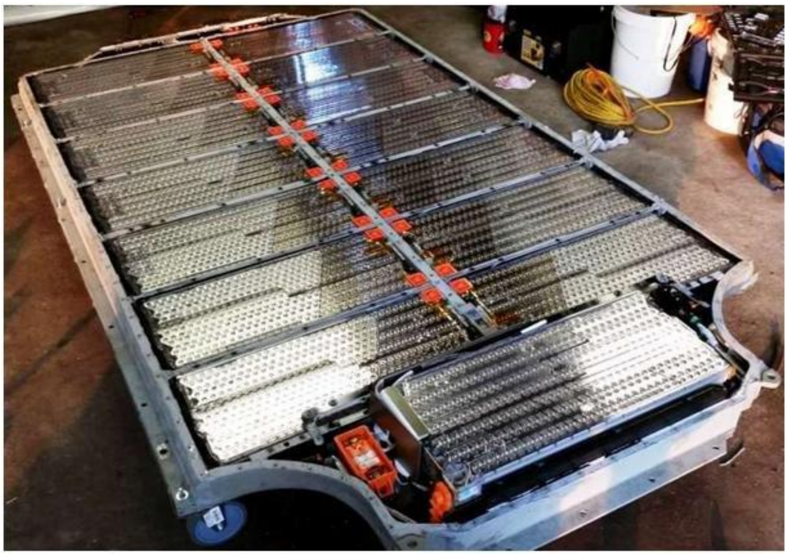


Figure 15: 2017 Tesla Model S battery pack. The battery pack as 16 modules, and 7104 cells. (Cuma, 2017)

5.2 Monitoring of the battery state

As described in chapter 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 proposed new EU Battery Directive will support the usage of BMS data for repurposing, as discussed in chapter 4. The proposal requires that EV battery BMS should store the data related to state of health and expected lifetime of batteries. Read-only access should be provided to end-user or any third party acting on its behalf for facilitating the preparing for reuse, repurposing, or remanufacturing (European Commission, 2020).

The precise estimation of battery state 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. (2022) research related to artificial intelligence (AI) and BMS is on-going in many places. Combining AI-tools with cloud computing and block chain technology could enable the development of digital twins that could offer more accurate estimation for the battery state (Liu, Placke, & Chau, 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).

A company called 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).

5.3 Optimized charging

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 (Ahmadi, Young, Fowler, Fraser, & Achachlouei, 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 (Thakur, Leite de Almeida, & Baskar, 2022).

5.4 Digital battery passport

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 proposal for the new Battery Regulation will require that EV batteries have a digital passport that includes information about the battery model, chemistry, where the materials are sourced, production site, user data, etc. All EV batteries placed on the market or put into service from 42 months after the regulation has entered into force need to have a battery passport (European Commission, 2020).

To be useful, a passport should include meaningful data to support decision making. Berger et. al. (2022) presents a concept for which type of data the passport should include. According to the study there are several stakeholders in the EV battery value chain that could utilize the information stored in the passport. Original Equipment Manufacturers 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 (Berger, Schöggl, & Baumgartner, 2022).

Research has identified several categories where information is needed. These include battery chemistry and system, sustainability and circularity, diagnostics, performance and maintenance, as well as value chain actors. Battery information includes product information such as application type, battery chemistry and battery structure related specifications. 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 actors category contains data on those who have been involved at any point in the EV battery's life cycle (Berger, Schöggl, & Baumgartner, 2022).

The proposal for the new EU Battery Regulation's requirements seems to support the research findings. According to the proposal, 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 Commission, 2020).

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[1]. However, aged lithium-ion batteries present a significant safety hazard.

6.1 Thermal runaway

Challenge 7

Negative public perception regarding EV battery repurposing for BESS, primarily driven by concerns surrounding perceived high fire hazards and associated risks, leading to heightened public apprehension.

Thermal runaway can lead to catastrophic battery failure such as fire, explosion, release of toxic and flammable gases, and jet flames. Thermal runaway, while unlikely, is the most common catastrophic failure mode of LIBs. According to Fent et al. (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 vehicles 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. Thermal runaways can occur in EV batteries when the temperature inside the battery reaches a critical temperature (Approximately 195 °C for LFP and 170 °C for NMC (Duh, et al., 2021)) that causes an exothermic chemical chain reaction to occur, leading to decomposition reactions of the battery component materials. LIBs can release large amounts of energy during thermal runaway, and in the subsequent fire. 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, Sugawa, Suwa, & Ogawa, 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 BESS has a PHRR of 25 kW (Sun, Bisschop, Niu, & Huang, 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.

Generally, 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 the battery pack accessibility for fire suppression. The battery pack is typically placed between the axles in the floor of the vehicle. This is done to reduce the risk of damage to the battery pack in the event of a car crash. EV batteries can self-ignite during normal charging, parking, and driving conditions, due to battery failure. In addition, EV batteries can reignite after being extinguished as the thermal runaway event can still be ongoing. 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

---

[1] 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.

Funded by the European Union

fires have attracted a considerable amount of negative media attention. This attention has a negative effect on the public opinion of the safety of EVs and can have a negative effect on the public acceptance of EV battery repurposing for BESS.

Battery failure is caused by mechanical, electrical, and/or thermal abuse of the battery. If the batteries are damaged mechanically, a short circuit may 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; however, mechanical abuse is unlikely for BESS. EV batteries repurposed for BESS may, however, have mechanical damage that has occurred during their 1st life and which has not been identified during battery evaluation for second life repurposing.

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 overdischarging, and thermal abuse, can lead to internal short circuiting, which is the most common reason for thermal runaway (Feng, et al., 2018). Internal short circuiting can for example occur if the separator material is heavily degraded or a 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.

6.2 Sudden loss of energy capacity

Challenge 8

Reliability of 2nd life BESS is a concern due to the potential for sudden loss of energy capacity in lithium-ion batteries.

LIBs, while generally reliable, can unexpectedly fail before their projected end-of-life. These batteries are designed to last between 6-8 years and can undergo 1000-3000 cycles before their SoH degrades to 80%. Nevertheless, they may encounter a phenomenon 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), Li-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

Funded by
the European Union

battery management systems, and advanced electrode materials promise a future where battery cycle life and safety are significantly enhanced.

6.3 Safety in the logistics phase

Challenge 9

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.

Batteries at the end of their lifecycle need to be systematically collected, transported, and stored before they can be repurposed in circular economy initiatives. 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 thorough evaluation. A significant challenge in this process lies in the scarcity of data regarding the battery's first life. Detailed historical operation information, including charge-discharge rates, operating temperatures, and cell voltages, is not consistently accessible. This kind of data could significantly enhance diagnostic algorithms for battery packs before they enter the logistical phase. The advent of a 'battery passport,' coupled with precise diagnostic and prognostic algorithms, could facilitate the early identification of damaged battery packs. As discussed in chapter 4, 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.

6.4 Safety of second life battery energy storage systems

Challenge 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.

The meticulous planning of battery rooms and the deliberate installation of second-life Battery Energy Storage Systems (BESS) are vital for their safe and effective operation. 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 second-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, which will significantly enhance the safety and resilience of second-life BESS. As discussed in chapter 4, the absence of explicit standards and certifications for second-life battery installations is 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 second-life battery industry.

The primary safety and 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 second life use of aged LIBs. This chapter has particularly focused on addressing safety concerns during the collection, transportation, and storage of EoL batteries, as well as ensuring safety in the installations of second life BESS. By comprehensively examining these challenges and implementing effective safety measures, we can foster trust and confidence in the cycle life, performance, and safe utilization of EVBs, driving the transition towards a sustainable and reliable electric future.

7. Summary and conclusion

In this report, we have thoroughly examined the challenges associated with extending the lifetime of electric vehicle batteries (EVBs), categorizing them into four main areas: technical, regulations & legislations, ecodesign, and safety & reliability. Through our analysis, we have identified ten key challenges that impact the longevity of EV batteries, and these challenges are summarised in Table 4. It is important to note that many of these challenges are interrelated within each category, emphasizing the complexity of addressing extended battery lifetime.

Table 4: Summary of upcoming and current challenges for extending EVB lifetime.

	#	Challenges	Potential consequences	Risk mitigation
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.	Unsafe practices, potential hazards, increased likelihood of accidents, mishandling, improper disposal, and consequential risks to workers, the environment, and public safety.	The implementation of an upcoming battery passport, which grants access to historical data of batteries, will significantly contribute to mitigating this risk.
	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.	Compatibility challenges due to the diverse range of battery characteristics, technical complexity requiring expertise and specialized equipment, limited warranties and support from manufacturers, uncertain performance and safety implications, as well as the need to assess the economic viability of these activities.	Standardized protocols, research, collaboration, and innovation to realize the benefits of extended EVB lifespans.
	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.	Increased complexity and costs associated with extending the life of EVBs.	Algorithms of battery evaluation with improved efficiency and accuracy. Simultaneously, investing in research and development to explore novel evaluation techniques can lead to more streamlined and effective processes for assessing the state of health, safety, and remaining useful lifetime of EVBs.
Regulations & legislations	4	The absence of a regulatory framework, adequate testing protocols, and established safety standards hinders the repurposing of electric vehicle batteries.	The absence of clear safety standards significantly heightens the risk of accidents, fires, and other safety hazards. Furthermore, it can lead to improper disposal and inadequate recycling practices.	Establishment of comprehensive regulations, safety standards, testing protocols, along with promoting research, enhancing public awareness, and fostering collaboration among stakeholders.
	5	The forthcoming EU battery directive prioritizes material recycling of	The increased demand for EoL batteries to meet the required quantity	Incorporating provisions specifically addressing EoL batteries

		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.	of recycled materials in new batteries may lead to rising costs, while simultaneously hampering the exploration and development of circular activities aimed at optimizing battery lifespan and minimizing waste.	and exempting them from the regulations, thus allowing for alternative approaches and strategies for their management.
Ecodesign	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.	Increased cost of disassembly, potentially to the degree where it is more profitable to recycle the battery pack rather than extending its lifetime.	Standardization of EVB architectures, and development of automation techniques for disassembly of EV battery packs.
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.	Low market demand for EoL batteries, hindering the development of a circular economy for battery resources.	The results from the safety tests ran on EoL battery packs insuring the inexistence of fire hazard should be shared with clients to provide reassurance on the use of EV battery in BESS.
	8	Reliability of second life BESS is a concern due to the potential for sudden loss of energy capacity in lithium-ion batteries.	Reduced profitability of second life BESS.	Advanced evaluation of second life BESS is necessary to ensure reliable energy storage performance.
	9	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.	Increased risk of fires due to a dense storage of EoL batteries. A fire starting from a battery pack could spread and increase drastically the consequences of the fire.	The upmost attention should be placed on the handling and storage of EoL batteries. Fire suppression systems for BESS need to be designed for the purpose, as battery fires are unique compared to other building fires.
	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.	High risk of property damage and endangers human life due to the potential for accidents, fires, and hazardous conditions.	Further research and development on battery room design is imperative, covering aspects such as the selection of appropriate construction materials, advanced fire-suppression systems, and efficient room ventilation.

To overcome these challenges, collaborative efforts between industry stakeholders, policymakers, and researchers are needed. Technological advancements in battery materials, manufacturing processes, design of battery architectures, and battery management systems can help address these challenges and enhance EVB lifetimes. The development and implementation of clear regulations and legislations are imperative to establish standards and frameworks that promote sustainable battery lifecycle practices.

Furthermore, eco-design principles should be integrated into battery manufacturing processes to minimize environmental impacts and facilitate efficient repair, refurbishment, remanufacturing, repurposing, and recycling. Emphasizing safety and reliability through robust design is essential to install consumer confidence and ensure the safe operation of EV batteries throughout their extended lifetime.

In conclusion, extending the lifetime of EVBs requires a multi-faceted approach that encompasses technical innovation, supportive regulations, eco-design principles, and a strong focus on safety and reliability. By addressing these challenges collectively, we can unlock the full potential of EVBs, promote sustainability, and contribute to the wider adoption of EVs, thereby advancing the transition to a greener and more sustainable future.

8. References

A. Kampker, H. H. (2016). Evaluation of a remanufacturing of lithium ion batteries from electric cars. *International Journal of Mechanical and Mechatronics Engineering, 10*(12), 1929-1935.

Ahmadi, L., Young, S., Fowler, M., Fraser, R. A., & Achachlouei, M. A. (2015). A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems.

Battery University. (n.d.). *BU-205: Types of Lithium-ion*. Retrieved May 12, 2023, from https://batteryuniversity.com/article/bu-205-types-of-lithium-ion

Baum, Z. J., Bird, R. E., Yu, X., & Ma, J. (2022). Lithium-ion battery recycling─ overview of techniques and trends.

Berger, K., Schöggl, J. P., & Baumgartner, R. J. (2022). Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases. *Journal of Cleaner Production*.

BloombergNEF. (2021, November). Retrieved from https://about.bnef.com/blog/global-energy-storage-market-set-to-hit-one-terawatt-hour-by-2030/

Brick Court Chambers. (2016, July 6). *EFTA and the EEA: What are they?* Retrieved from Brexit Law: https://brexit.law/2016/07/06/efta-and-the-eea-what-are-they/

Casals, L. C., García, B. A., & Cremades, L. V. (2017). *Electric Vehicle Battery Reuse: Preparing for a Second Life.* Journal of Industrial Engineering and Management.

CENELEC. (n.d.). CLC/TC 21X - Secondary cells and batteries. Retrieved 04 19, 2023, from https://standards.cencenelec.eu/dyn/www/f?p=305:22:1471860582466201::::FSP_ORG_ID,FSP_LANG_ID:1257217,25&cs=1713A95D8AC1F4E337203EA2AAEC315B0

CENELEC. (n.d.). *European Standards.* Retrieved April 20, 2023, from Cenelec.eu: https://www.cencenelec.eu/european-standardization/european-standards/

Council of the European Union. (2023). *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020. 5469/23.*

Cuma, M. U. (2017). Design considerations of high voltage battery packs for electric buses. *Int. J. Adv. Automot. Technol*.

D. Werner, A. L. (2017). Thermal conductivity of Li-ion batteries and their electrode configurations - A novel combination of modelling and experimental approach. *Journal of Power Sources, 364*, 72-83.

Duh, Y.-S., Sun, Y., Lin, X., Zheng, J., Wang, M., Wang, Y., . . . Yu, G. (2021). Characterization on thermal runaway of commercial 18650 lithium-ion batteries used in electric vehicles: A review.

Eatron Technologies. (2023, 3 22). *Eatron Technologies*. Retrieved from BMSTAR - Battery mangement system: https://eatron.com/portfolio/bmstar-battery-management-system/

EFTA. (n.d.). *How EU Law becomes EEA Law*. Retrieved 04 19, 2023, from EFTA.int: https://eealaw.efta.int/

Europan Parliamentary Research Service. (2022). *New EU regulatory framework for batteries.* Retrieved from https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689337/EPRS_BRI(2021)689337_EN.pdf

Funded by the European Union

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

European Commission. (2020). *Questions and Answers on Sustainable Batteries Regulation.* Retrieved from https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_2311

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

European Commission. (n.d.). *Batteries and accumulators.* Retrieved from [https://environment.ec.europa.eu/topics/waste-and-recycling/batteries-and-accumulators_en

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

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

Feng, X., Ouyang, M., Liu, X., Lu, L., Xia, Y., & He, X. (2018). Thermal runaway mechanism of lithium ion battery for electric vehicles: A review. *Energy Storage Materials*.

Finnish Government. (n.d.). Jätelaki 646/2011. Retrieved from https://www.finlex.fi/fi/laki/ajantasa/2011/20110646

Finnish Government. (n.d.). Valtioneuvoston asetus paristoista ja akuista 520/2014. Retrieved from https://www.finlex.fi/fi/laki/alkup/2014/20140520

Fortum Corporation. (n.d.). *Second life batteries, expertise and a can-do attitude – innovation boosts hydropower plant*. Retrieved from https://www.fortum.com/about-us/our-company/strategy/decarbonisation-joint-effort/second-life-batteries-hydropower-plant

Grudzień, P. (2022). *Is there life after death for europes lithium ion batteries*. Retrieved April 19, 2023, from Energy-Storage.news: https://www.energy-storage.news/is-there-life-after-death-for-europes-lithium-ion-batteries/

Haram MHSM, L. J. (2021). Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges. *Alexandria Engineering Journal, 60*(5), 4517-4536.

Harper G, S. R. (2019). Recycling lithium-ion batteries from electric vehicles. *Nature, 575*(7781), 75-86.

Hoarau Q, L. E. (2022). An assessment of the European regulation on battery recycling for electric vehicles. *Energy Policy, 162*, 112770.

Hossain E, M. D. (2019). A Comprehensive Review on Second-Life Batteries: Current State, Manufacturing Considerations, Applications, Impacts, Barriers & Potential Solutions, Business Strategies, and Policies. *IEEE Access, 7*, 73215-73252.

Hua Y, L. X. (2021). Toward Sustainable Reuse of Retired Lithium-ion Batteries from Electric Vehicles. *Resources, Conservation and Recycling, 168*, 105249.

IEA. (2022). *Global EV Outlook 2022.* IEA.

Funded by
the European Union

IEA. (2022). *World Energy Outlook 2022.* Paris: IEA. Retrieved from https://www.iea.org/reports/world-energy-outlook-2022

Inside EVs. (2015). Retrieved from https://insideevs.com/news/328909/tesla-or-gm-who-has-the-best-battery-thermal-management/

J. Jaguemont, N. O. (2018). Phase-change materials (PCM) for automotive applications: A review. *Applied Thermal Engineering, 132*, 308-320.

J. Jyoti, B. P. (2021). Recent advancements in development of different cathode materials for rechargeable lithium ion batteries. *Journal of Energy Storage, 43*, 103112.

Jiang, Y., Jiang, J., Zhang, C., Zhang, W., Gao, Y., & Guo, Q. (2017). Recognition of battery aging variations for LiFePO4 batteries in 2nd use applications combining incremental capacity analysis and statistical approaches. *Journal of Power Sources*, 180-188.

José Potting, M. H. (2017). *CIRCULAR ECONOMY: MEASURING INNOVATION IN THE PRODUCT CHAIN.* The Hague: PBM Netherlands Environmental Assessment Agency.

Lima, P. (2018). *PushEVS*. Retrieved from 2018 Nissan Leaf battery real specs: https://pushevs.com/2018/01/29/2018-nissan-leaf-battery-real-specs/

Liu, W., Placke, T., & Chau, K. T. (2022). *Overview of batteries and battery mangement for electric vehicles.* Energy reports.

Lluc Canals Casals, B. A. (2017). Electric Vehicle Battery Reuse: Preparing for a Second Life. *Journal of Industrial Engineering and Management* , 278.

Lovdata. (2004, Juni 1). Avfallsforskriften. Forskrift on gjenvinning og behandling av avfall (FOR-2004-06-01-930). Retrieved from https://lovdata.no/dokument/SF/forskrift/2004-06-01-930

MARBEL. (2021). *D2.5 Recycling and ecodeign guidelines.* EU Horizon project MARBEL.

MARBEL. (2021). *D2.5 Recycling and ecodesign guidelines.* EU Horinzont project MARBEL. Retrieved from file:///C:/Users/lindarek/Downloads/MARBEL_D2.5_Recycling%20and%20ecodesign%20guidelines_vdef%20(1).pdf

McDougall, N. (2023). *The operation environment for repurposing electric vehicle lithium-ion batteries for energy storage applications in the EU.* Aalto University. doi:https://aaltodoc.aalto.fi/handle/123456789/120215

Ministry of Economic Affairs and Employment. (2021). *National Battery Strategy 2025.* doi: ISBN 978-952-327-725-0

Minstry of Trade, Industry and Fisheries. (2022). *Norway's battery strategy.* Retrieved from https://www.regjeringen.no/contentassets/a894b5594dbf4eccbec0d65f491e4809/norways-battery-strategy_singlepages_web.pdf.

Minstry of Trade, Industry and Fisheries, Office of the Prime Minister. (2022). Roadmap - The green industrial initiative. Retrieved from https://www.regjeringen.no/contentassets/1c3d3319e6a946f2b57633c0c5fcc25b/roadmap_the-green-industrial-initiative_singlepages_web.pdf

Morrow Batteries. (n.d.). Retrieved from https://www.morrowbatteries.com/copy-products

Nichols, D. (2023, January). *Green Cars*. Retrieved from www.greencars.com: https://www.greencars.com/greencars-101/ev-battery-warranties-and-exclusions

Nissan Motor Corporation. (2023, 05 11). Retrieved from Nissan Global Newsroom: https://global.nissannews.com/en

Nissan Motor Corporation. (2023, 05 11). *Nissan Global*. Retrieved from https://www.nissan-global.com

NXP Semiconductors. (2022, 10 10). *NXP Semiconductors*. Retrieved from AI-Powered Cloud-Connected Battery Mangement Systems for Electric Vehicles: https://www.nxp.com/company/about-nxp/ai-powered-cloud-connected-battery-management-system-for-electric-vehicles:NW-NXP-AI-POWERED-CLOUD-CONNECTED-BATTERY

Parliament, E. (n.d.). DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives. *Official Journal of the European Union, L312*. Retrieved from https://www.reach-compliance.eu/english/legislation/docs/launchers/waste/launch-2008-98-EC.html

Rallo H, B. G. (2020). Economic analysis of the disassembling activities to the reuse of electric vehicles Li-ion batteries. *Resources, Conservation and Recycling, 159*, 104785.

Redwood Logistics. (2023). Retrieved from https://www.redwoodlogistics.com/what-is-a-circular-supply-chain/

S. Roschier, A. P. (2020). *Assessment of Li-ion battery reuse solutions - final report.* Gaia Consulting Oy, Business Finland. Retrieved from https://www.businessfinland.fi/4974e0/globalassets/finnish-customers/02-build-your-network/bioeconomy--cleantech/batteries-from-finland/assessment-of-li-ion-battery-reuse-solutions.pdf

Shahjalal M, R. P. (2022). A review on second-life of Li-ion batteries: prospects, challenges, and issues. *Energy, 241*, 122881.

Sun, P., Bisschop, R., Niu, H., & Huang, X. (2020). A review of battery fires in electric vehicles. *Fire technology*.

Take-e-way. (2022). *EU Battery Regulation coming in 2023?* Retrieved 04 19, 2023, from Take-e-way: https://www.take-e-way.com/news/eu-battery-regulation-coming-in-2023/

Thakur, J., Leite de Almeida, C. M., & Baskar, A. G. (2022). Electric vehicle batteries for a circular economy: Second life batteries as residential stationary storage. *Journal of Cleaner Production*.

The Explorer. (2020). *Doing business: How Norway is integrated into the European single market*. Retrieved April 20, 2023, from https://www.theexplorer.no/stories/other/doing-business-how-norway-is-integrated-into-the-european-single-market/

Toyota. (2021). *Toward Carbon Neutrality: Toyota's Battery Development and Supply.*

Työ- ja elinkeinoministeriö. (2021). *Kansallinen akkustrategia 2025.* doi: ISBN 978-952-327-635-2

Watanabe, N., Sugawa, O., Suwa, T., & Ogawa, Y. (2012). Comparison of fire behaviors of an electric-battery-powered vehicle and gasoline-powered vehicle in a real-scale fire test. *Second International Conference on Fires in Vehicles*.

Wikipedia. (n.d.). Retrieved from Tesla Model S: https://no.frwiki.wiki/wiki/Tesla_Model_S

Wood Mackenzie. (2020, 08 17). Retrieved from Wood Mackenzie: www.woodmac.com/

Wärtsilä Corporation. (2018). *Wärtsilä and Hyundai Motor Group announce energy storage partnership maximizing second-life electric vehicle batteries*. Retrieved from Wartsila.com: https://www.wartsila.com/media/news/26-06-2018-wartsila-and-hyundai-motor-group-announce-energy-storage-partnership-maximizing-second-life-electric-vehicle-batteries-2216004

Xjong, R. (2020). Battery SoC and SOH estimation. In *Battery mangement algorithm for electric vehicles.* Singapore: Springer.

Yang, H., Zhou, S., Huang, Y., Liu, X., Ling, H., & Zhou, X. (2020). Sustainable value chain of retired lithium-ion batteries for electric vehicles. *Journal of Power Sources*.

Zhu J, M. I. (2021). End-of-life or second-life options for retired electric vehicle batteries. *Cell Reports Physical Science, 2*(8), 100537.