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BATMAN report

Modeling Business Ecosystems for spent Lithium-ion batteries

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BATMAN

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Abbreviations

BMS	Battery Management System
EOL	End-of-Life
EPM	Ecosystem Pie Modeling
EV	Electric Vehicle
EVL	End-of-Life Vehicle
ESS	Energy Storage System
EPR	Extended Producer Responsibility
EU	European Union
ICE	Internal Combustion Engine
LIB	Lithium-ion Battery
OEM	Original Equipment Manufacturer
R&D	Research and Development
SOH	State of Health
ToU	Time of Use

Executive Summary

Given the transition towards electric mobility, we can expect a rapidly increasing number of spent batteries to reach their end-of-life in the future. For one thing, there needs to be a system in place that has both the ability and the capacity to handle it. For another, the batteries contain a large share of valuable materials that can and ought to be recycled and returned into the system and, at the same time, ease the pressure exerted by raw material dependencies. Moreover, after the first life, the spent batteries have a remaining lifetime that can be used in other applications (other than mobile) to harvest the residual value they may contain. To set up such a system and exploit the involved business opportunities, we need to adopt a perspective that looks beyond conventional linear value chains that transcend the borders of established industrial sectors.

To shed some light on these challenges, qualitative modeling of the business ecosystem(s) related to spent batteries was performed from a European perspective and with particular attention to the Norwegian context. Such modeling addresses questions like how the system functions from a business point-of-view; who gains what, and who takes what? The modeling also uncovers critical dependencies, gaps, and potential risks in the ecosystems. Two adjacent ecosystems were considered: the ecosystem that undertakes to pursue a circular model by sustainably recycling materials from spent batteries, and the ecosystem that pursues a circular model by sustainably exploiting opportunities related to second use of the batteries. The modeling only considered commercial actors.

The modeling points to several important issues. Five of them are pinpointed here.

First, the variety of different positions actors can occupy in the ecosystem through their business models becomes apparent. Most notably, there are clear tendencies towards various vertical integration in different sections of the ecosystem. This seems to be driven by a wish to secure the supply of raw materials among battery component and pack producers, on the one hand, and by automotive original equipment manufacturers wish to ensure efficient supply of custom-designed batteries, on the other. Downstream vertical integration and physical proximity among the actors in battery production also make sense due to a large amount of scrap that ramping up the production is likely to cause.

Second, the role of and need for regulations has become more apparent and drives both research and development activities as well as business model choices. The new European Union battery regulation (December 2020) sets stricter requirements for battery recycling. However, there seems to be a consensus among stakeholders and the European Commission that market forces shall drive the possible second use of batteries.

Third, the battery ownership model is an essential feature of the original equipment manufacturers' business models and is an important decision that will influence the electric vehicle and battery value chains. The sources interviewed believe that most ownership models will keep the electric vehicle owner or a third party as owners. It is also expected that the interest in and control of their LIBs will continue to increase. In Norway, the prevailing regulations have facilitated a well-functioning system where the car dismantlers are in control of the EVL (including its battery).

Fourth, the modeling identifies the role of gatekeepers in the second use ecosystem. One such role is the one taken by automotive original equipment manufacturers through their ability to restrict access to the battery management system. Another is the one possessed by car dismantlers who can decide where the retired cars and batteries returned to/via them will be channeled. A third one is the one held by the extended producer responsibility contractor or dismantler.

Fifth, there are financial barriers to overcome for second use, which highly depend on the prices of new versus spent battery packs. One way to partly overcome these obstacles is to repurpose the battery management system without any remanufacturing of the battery pack or module itself to save costs. Furthermore, there are unsolved challenges regarding responsibility during and after second use related to who will be responsible for the quality and security of second use batteries, and who will pay the recycling cost afterward. If spent batteries are not considered as waste in the future, the repurposer will be responsible.

1 Introduction

Electrification of transportation is an attractive strategy to reduce climate- and environmental impact from the sector. This transition requires large volumes of high-capacity batteries, especially lithium-ion based [1], [2]. Lithium-ion batteries (LIB) contain several economically valuable materials that can also be environmentally hazardous if not managed sustainably throughout the lifetime of the batteries. Improved LIB recycling rates are essential to increase the sustainability[1] of batteries; however, it is currently facing dilemmas [3]. Product life extension by enabling second use of batteries is another sustainability strategy that has gained interest among battery stakeholders [4]–[6]. Similarly, several barriers for second use need to be tackled.

This report strives to shed light on the challenges mentioned above and barriers by discussing the business ecosystems and the business models for enabling the current and a potential circular economy around LIBs in Norway and Europe. The report looks more closely at how the industry works in each of the stages in Figure 1 [7], which presents a generic circular value chain for electric vehicle batteries. In short, the report addresses the questions of "who does what and who takes what" in the LIB ecosystem(s). The ecosystems in this report focus on electric cars. However, several actors operate in other value chains as well, including electronics and other means of transport such as trucks, buses, and ships (for a complete list of applications and their requirements, see Skare et al. [8]. While a circular approach to LIBs includes recycling, reuse, and second use, this report mainly considers recycling and second use (reuse as a circular strategy means new use in the same type of application originally manufactured for, e.g., in an electric vehicle (EV)).

A particular interest of the report is the impact of business models on the ownership of the LIBs at the end-of-life (EOL) stage. This is an essential factor in understanding (and potentially regulating) for introducing more efficient recycling and secondary use and the current market, driven by the supply of spent batteries (everything indicates that there shall be a demand).

There are many earlier reports on the LIB value chain that provide various numerical scenarios for the industry's growth and efficiency [9]–[11]. However, very few (if any) provides an overview of different business model-logics that interact in the various business ecosystems emerging in the industry. Therefore, this report is to be seen as an explorative study of the systemic dependencies in an industry in the making.

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[1] In this report we use the word "sustainable" meaning a property that avoids negative economic, social, and environmental impact of the battery production, use and disposal.

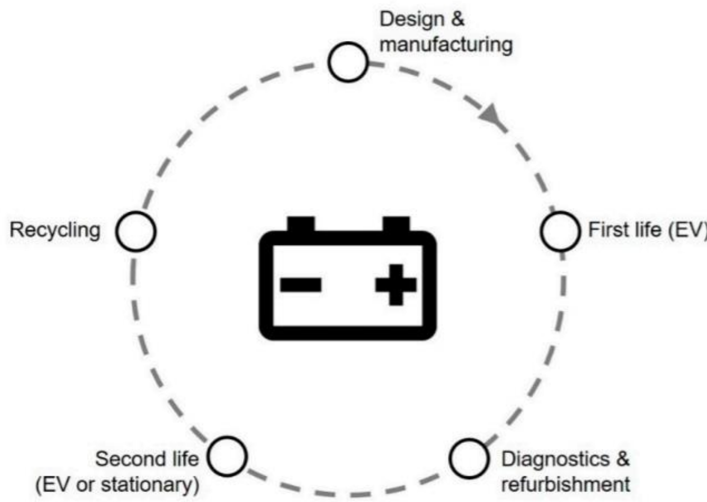


Figure 1: Electric vehicle battery circular value chain (adapted from [7]).

This report complements earlier reports on LIB technologies [8], the movement of LIBs in the Norwegian transport sector [12], and LIB policy trends in the European Union (EU) [13]. The development of the LIB technologies (notably chemistries) and the EU's new regulatory framework for batteries [14] and other regulations will significantly impact the business models and ecosystems in the industry.

2 Concepts and methodology

2.1 Defining the concepts of a business ecosystem

The business (innovation) ecosystem concept has become popular over the last years both in business and policy. It is commonly used to refer to new types of industries and business networks emerging due to changes to existing more linear value chains. Also, on occasions when a new business transcends the borders of existing value chains or industries. For this report, we refer to two related definitions. First, we quote the one by Thomas and Autio [15], saying that a business (innovation) ecosystem is:

> *…a community of hierarchically independent yet interdependent heterogeneous participants who collectively generate an ecosystem output (and related value offering targeted at a defined audience).*

The "ecosystem output" in the above definition is here used to refer to a focal value proposition that is common for the whole ecosystem (hence also denoted "ecosystem value proposition") as indicated in the ecosystem definition by Adner [16]:

> *…the alignment structure of the multilateral set of partners that need to interact in order for a focal value proposition to materialize.*

The main difference to the conventional concept of a value chain lies in its focus on potential (new) partners that lie off the chain, on multilateral dynamics, and on alignment strategies for keeping the ecosystem together.

2.2 Ecosystem modeling

This report's specific tool is the ecosystem pie model (EPM), which can be described as a tool for qualitative modeling of innovation ecosystems [17]. The tool departs from the Ecosystem Value Proposition (EVP), that is, the collectively produced output. It then considers each actor (in this case, firm-actors) in the ecosystems that are engaged with value creation and captures on the supply side of the ecosystem, that is, those actors that are necessary to produce the EVP. It does so in terms of five elements (and their interrelations), as explained in Table 1.

Table 1: Description of the key elements in ecosystem modeling using the EPM tool [18].

Element	**Description**
Resources	Resources at the disposal of the actor to be utilized for performing the activities that create value within the ecosystem.
Activities	Activities performed in converting resources into value additions toward the ecosystem.
Value addition	The unique productive contribution of the actor to the ecosystem.
Value capture	The type, mechanism, and quantity of value captured by the actor from the ecosystem.
Dependence	The extent to which the actor is dependent on the success of the ecosystem. Represented with letters on the following scale: low = L, medium = M, high = H (in circles in the EPM).
Risk	The potential inability and unwillingness of the actor to supply their productive contribution to the ecosystem. Represented by a three-color scheme: high = red, medium = yellow, and low = green.

2.3 Business model

Following the above-quoted definitions and the elements in Table 1, a business ecosystem can be seen as a group of companies with interlinked business models. A business model emphasizes value creation, delivery, and value capture of a business, as illustrated in Figure 2. It should consist of elements such as customers and infrastructure to plan how (and why) the business should operate. Business models for a circular economy, or circular business models, is a more recent term with growing interest. The aim is to narrow, slow down, and close material loops, in this context, from retired LIBs [19].

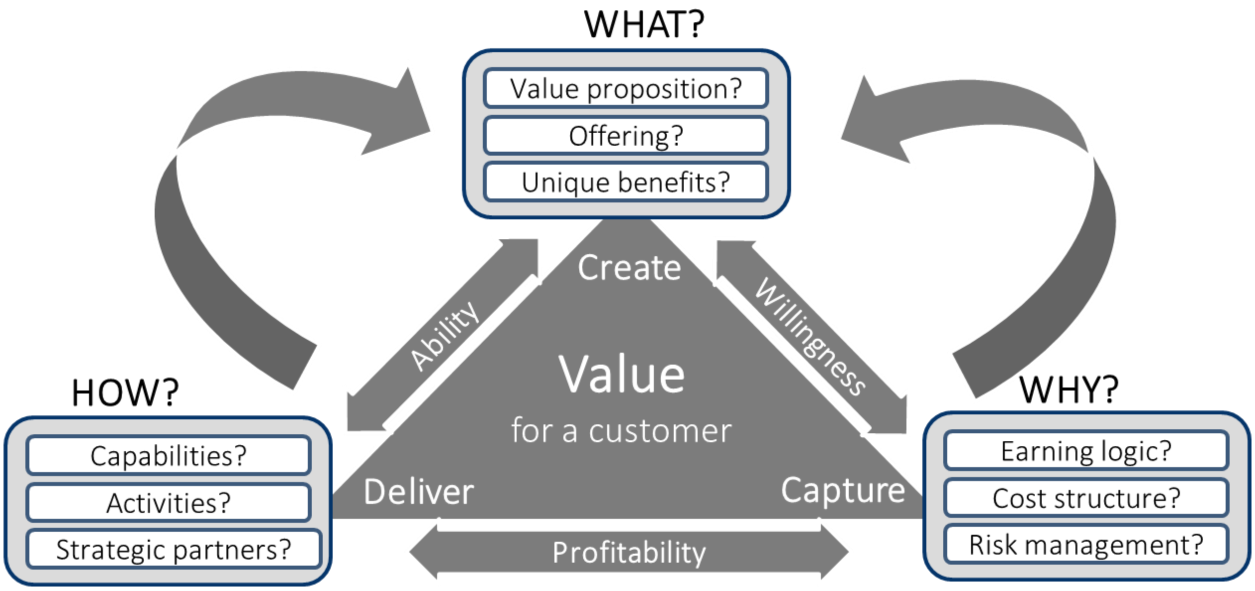


Figure 2: A conceptual perception of a business model.

2.4 Data sources

The content is based on several interviews with battery industry stakeholders and experts in various battery related activities (a list of informants and sources is provided in Chapter 9), research literature, industry reports, webinars, and a study by the University of Agder and Pontifical Xavierian University and University of La Sabana [20].

In the latter novel study, the Delphi method was applied where a battery expert panel provided insights. The panel had different professions and 5+ years of experience in the field, located in various countries in Europe, North- and South America.

3 An overview of the LIB ecosystem and its actors

3.1 Actors

The overall LIB ecosystem connects in a circular manner the automotive, metals, and energy industry and its respective value chain members and a set of actors less commonly considered in conventional value chain analysis, such as regulators and dismantlers and the car owners themselves.

Figure 3 lists the main players (European players marked with a yellow asterisk. What is interesting in the figure is the variety of vertical positions those different actors can take. For example, Umicore spans the chain from recycling via raw materials production to electrode materials, or BYD that covers both battery cell, battery pack, and vehicle production as well as recycling.

For this report, we focus on firm actors. This will leave out otherwise important actors, such as governments (or regulators), research institutions, and industry associations, whose role may be pinpointed in parts of the reports as deemed relevant.

We have chosen to split the analysis into two ecosystems, the LIB recycling, and the LIB second use ecosystem, although they could be considered one. The reason is that they show different dynamics and dependencies, and hence the results of ecosystem models will look different. Thus, we consider the following actors in the LIB recycling ecosystem:

- Battery component and pack producers (including producers of precursors, components, cells, and complete battery modules or packs)
- Automotive Original Equipment Manufacturers (OEMs)
- Car distributors
- (Car owners - mentioned but omitted from the model)
- Car dismantlers
- Battery dismantlers
- Metal/mineral processors (both extractors and refiners)
- (Metal/mineral traders and merchants – mentioned but omitted from the model)

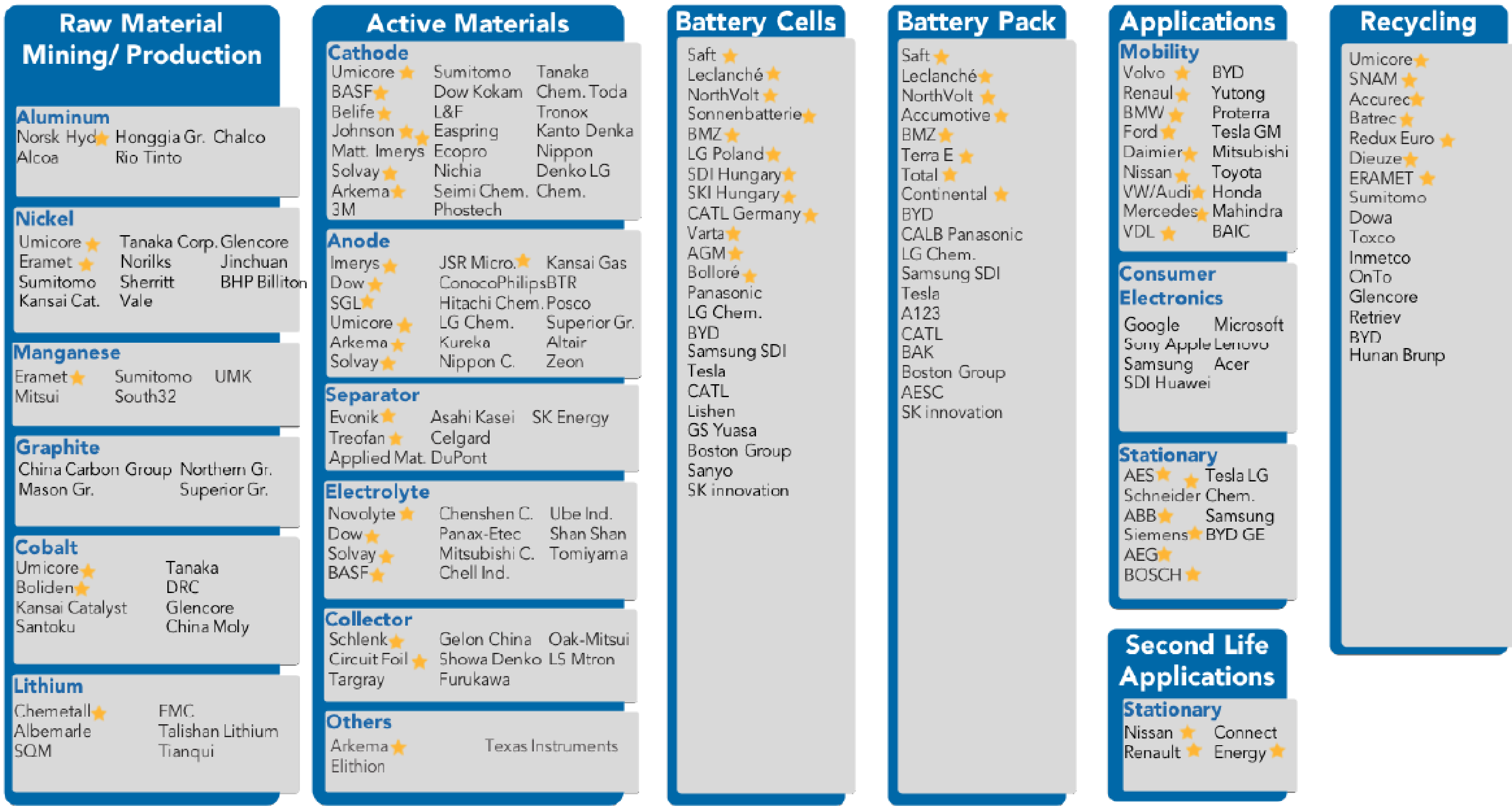


Figure 3: Battery value chain and main players [21].

As for the LIB second use ecosystem, we consider the following actors:

- Battery component and pack producers
- Automotive Original Equipment Manufacturers (OEMs)
- (Car distributors - omitted for the sake of simplicity, unchanged role)
- (Car owners - mentioned but omitted from the model)
- (Charging infrastructure - mentioned but omitted from the model)
- Car dismantlers
- (Battery dismantlers - omitted for the sake of simplicity, unchanged role)
- Battery repurposers
- System integrators / Energy Storage System (ESS) providers
- Grid owners and operators

3.2 EPR effects on ecosystem

On a general level, it is to be pointed out that the LIB (together with the EV itself) is subject to extended producer responsibility (EPR) regulations (also see the discussion in section 3.1). Hence, the OEMs are required to arrange for safe and appropriate handling of spent batteries (and cars). Typically, they do it through an EPR contractor (a special purpose vehicle) that collectively handles the EPR for the OEMs (e.g., via the car importers). The EPR contractor coordinates the collection of retired vehicles (typically from car dismantler firms) and may then assign a recycling company (earlier in the report denoted “battery dismantler”) to handle the battery safely, or it may opt to itself set up and operate dismantling facilities. To finance the operations, the EPR contractor charges a waste handling fee. Hence, at the EOL, the battery may pass through three different actors that may or may not be interested in exploiting the residual value of the battery itself: the car owner, the car dismantler, and the battery dismantler. The action path they choose is impacted by the business models of themselves and the OEMs.

3.3 The Norwegian context

Although this report looks at LIB ecosystems from a European perspective, it has a particular interest in the Norwegian context. Norway is a front-runner in EV market share compared to the rest of Europe (and most parts of the world). The main reason is the Norwegian government's strategy to boost EV sales. Political incentives (e.g., the exemption for EVs for value added tax) were activated a few years**.** As a result, the EV stock in Norway has grown from about 20 000 in 2013 to 300 000 in 2020 [22].

As an electric car has an expected lifetime of 5-15 years (opinions vary among sources), they have not reached end-of-(first)life (EOL) yet, except for a smaller amount that is damaged**.** Thus, the volumes resulting from the increased market share will start in 5-8 years, and the retired LIB market and value chain is not possible to fully predict. The current car value stream and deposit system in Norway is illustrated in Figure 4.

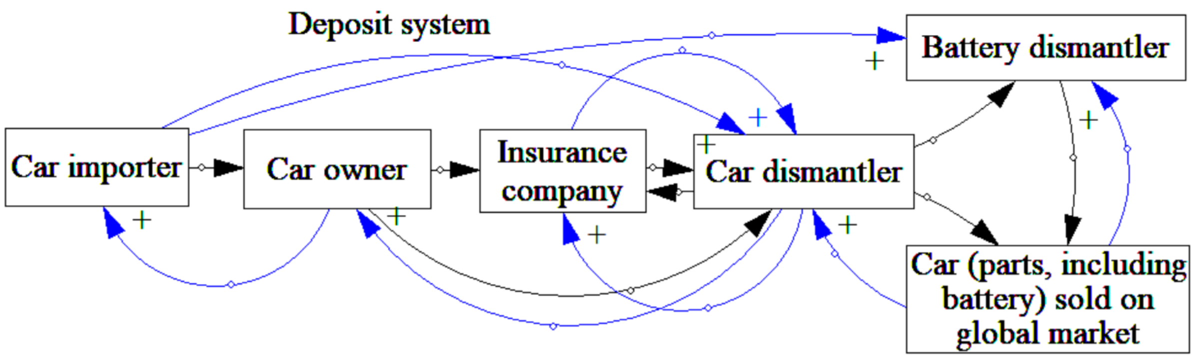


Figure 4: Illustration of the Norwegian spent car value stream. Black arrows represent physical flows and blue monetary flows.

All importers of cars in Norway must be a part of the approved deposit system (Autoretur). Thus, the importers cover the costs of several local car dismantlers, who pay individual consumers 3000 NOK per car if they deliver it to one of the dismantlers. When purchasing a new or spent car, consumers can receive a form of warranty from the vehicle producer, importer, or distributor [23]. When the warranty is expired or applies to damages outside the scope of the warranty, an insurance company cover the cost that were a part of the previously signed insurance agreement. Car dismantlers and insurance companies in Norway have local agreements where the latter sells cars to the car dismantlers. The dismantlers also sell spent car parts to the insurance company, as illustrated in Figure 4. However, this supply only covers a small percentage of the total demand for spare parts.

The Norwegian deposit system leads to an effective collection of spent cars and batteries and is a manner to manage the EPR. Left car wrecks are a more significant issue in other European countries that are EU members, where a similar functional deposit system is not widely in place. The sources indicate that the existing Norwegian retired car value stream will operate similarly, also with future retired LIB volumes. This system is well established and unique in Europe because of the deposit system. This system is highly valued by several actors, including the Norwegian government. Vehicle manufacturers entering the Norwegian market are not necessarily expecting this strict, nation-wide system to collect spent cars; however, the current system forces a need to change and adopt to this model when entering the Norwegian market. For example, it is more challenging for an OEM in Norway to control and manage the vehicle and battery after consumption compared to other European countries.

What is expected to change in the future is that value chain activities will be located in or closer to Norway, compared to the current situation. This includes battery cell manufacturing and recycling.

4 Modeling of the LIB recycling ecosystem

4.1 Overview and the ecosystem value proposition

The LIB ecosystem moves in parallel with the broader automotive ecosystem and its established value chains and actors. Nevertheless, the shift in power train technology is causing a disruption of the automotive value chain with LIB rendering an enormous competence pool and industrial process built around the internal combustion engine obsolete (or reducing its importance) in the next few decades [24], [25]. Similarly, the introduction of carbon-free but intermittent energy sources in the energy system is (together with digital technologies) shaking up the energy industry and increasing the call for (inexpensive) energy storage system solutions.

To start with, The EVP for the LIB recycling ecosystem is defined as follows:

> ***Sustainable LIB recycling means profitable recycling that is continually not harmful to the environment and society.***

The way the EVP is formulated is crucial for the modeling as the elements listed in Table 1 all shall be understood from the EVP perspective. The above formulation expresses an ambition for circularity (in the form of recycling) and sustainability (in the form of a profitable activity that is not harmful to people or the plant).

4.2 Actor by actor analysis

4.2.1 Battery pack and component producers

The battery pack is in itself brought about through a long supply chain with all its components and assembly stages: precursors, the electrodes, the electrolyte, the cells, and the battery module and pack. The value created by this value chain is the production done in efficient, high-capacity factories (i.e., “Gigafactories”) that can exploit increasing economies of scale and the use of “Factory-of-the future concepts” [26]. Another aspect of battery production concerning the EVP mentioned above is the CO_2 footprint of the battery manufacturing process. For example, a Nissan Leaf 30kWh battery may double the emissions from manufacturing the vehicle (in comparison to an ICE powered vehicle), which increases with the battery's size [27]. This provides an opportunity for automotive OEMs that can source their batteries from a low emission value chain. However, high emissions may be offset compared to an ICE powered vehicle in a short time during use [28].

Manufacturers of LIBs and their components can be considered the focal actor around which innovation the ecosystem will be built and are thus highly dependent on the ecosystem's success. There seems to be no significant risk for their capability (and willingness) to perform their role in the ecosystem. However, it is clear that European actors are starting their journey far behind their Asian peers [11] and are unlikely to achieve as high efficiencies in their factories as currently seen in China (e.g., due to the lack of economies of scale).

Due to such inefficiencies in the ramp-up phase, it is likely that a considerable amount of scrap will be produced in the battery manufacturing process, as illustrated in Figure 5. The amount of available production scrap in Europe is currently low but is likely to grow and be the main feed for European recycling plants in a few years [29].

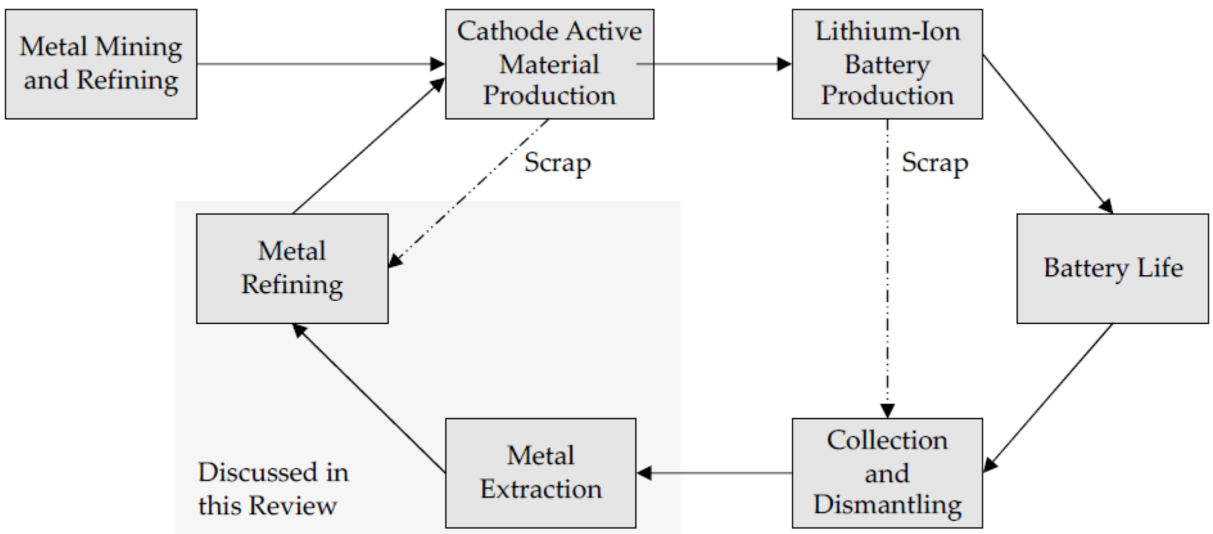


Figure 5: A closed loop production system for batteries [29].

Therefore, likely business ecosystem features will be close partnerships between battery producers and metal recyclers and factories' co-location to reduce transportation costs. An extreme version of this business model for battery producers is a vertical integration upstream (cf. Northvolt intends to cover the whole chain from recycling to battery pack assembly).

4.2.2 Automotive OEM

The value created by the automotive OEMs concerning the EVP is indeed massive, but at the same time, one of their key resources, the ICE competence, is becoming more and more obsolete. Tesla (together with several Chinese peers such as BYD), coming from outside the ICE ecosystem, has effectively shown that the ICE competence is by no means a prerequisite for entering the EV market. Hence, the future added value stems from other production and supply chain capabilities, enabling cost-efficient manufacturing of EVs. The big question is whether the large OEMs can master the shift from ICE to LIB in their factories (cf. VW conversion of their Zwickau plant to an EV factory). It is clear, though, that they neither can nor want to miss the EV boom, which makes them highly dependent on the success of the LIB ecosystem. It is also likely that the European OEMs will adopt increasingly circular business models as EU regulations for battery materials recycling sets stricter requirements. The risk that these OEMs would not be able to fulfill their role (or be unwilling to) is low, although the shift would not be as smooth as expected.

The value capture mechanisms for OEMs are likely to remain the same, that is, new car sales or car leasing schemes. However, it will slightly change the business model of the OEM and car distributors because EVs have fewer parts (i.e., expect a reduction of spare parts sales on the EV market). A new business model is based on battery leasing. Currently, it seems that the main driver for battery leasing is increased new EV sales (reducing consumer perceived uncertainty in front of new technology) rather than only a desire to control the ownership at EOL of the battery. However, there are other mechanisms for the OEMs to incentivize the return of spent batteries, such as replacement offerings (cf. BMW i3). In these cases, the OEM provides the opportunity to purchase a replacement of the spent EV battery with a new one.

Another potentially impactful business model in this regard is one based on the car or ride-sharing, which seems to be more likely for large urban regions with high people density [12], [30]. However, it appears that some OEMs (notably Daimler and BMW) that have been testing such business models for the near future are turning their focus back to business models based on individual ownership [31].

As for the recycling of end-of-life-vehicles (ELVs), the EPR drives the recycling market. In Norway, most of the car importers have joined forces through Bilimportørenes Landsforening (the car importers' national association), which, in turn, established and assigned one company for handling ELVs, Autoretur. The association formed close cooperation with Batteriretur for handling LIBs (see section 4.2.6).

4.2.3 Car distributors

The standard model for car distribution is to award the right for car distribution to a local car importer in each country. That importer then distributes the cars to local car dealers taking care of the sales (and in many cases also maintenance) of vehicles according to a contract with the OEMs. Some brands, notably Tesla, have chosen a direct distribution model where they themselves cover the whole value chain.

4.2.4 Car owners

The car owners have been included in the ecosystem modeling because they effectively own the LIB at EOL and hence at least theoretically can decide what to do with it. This has some implications for the ability of the ecosystem to collect the LIBs for recirculation. However, car owners are omitted from the resulting ecosystem model shown in Figure 9 due to their otherwise relatively limited and prominent role.

4.2.5 Car dismantlers

Car collectors and dismantlers have existed for decades and play an essential role in the recycling ecosystem [32]. Most LIBs are and likely will be collected by them, and this collection has earlier been pointed out as a less researched theme [33], which underlines the importance of this actor. The majority of spent batteries end up at an approved car dismantler that then typically contracts the EPR contractor assigned by the car importers. The added value provided by the car dismantlers is the network of stations they provide for an easy return of an ELV as well as in their ability to dismantle the battery from the rest of the car in a safe and efficient manner. The car dismantlers are per se not dependent on the success of the recycling ecosystem because a considerable part of their income comes from independent sales of spent spare parts [32][34] and batteries to various interested buyers. The established network of car dismantlers also ensures that there is a base infrastructure of retired LIBs. However, the lack of regulations and restrictions on safely handling spent batteries still constitutes a risk.

In Norway, the association for car dismantlers expect high ethical and competence standards from their members to mitigate the risk with handling high-energy batteries. Yet, a small share of the car dismantlers operates independently and interpret the regulations differently and does not comply with the standards of the associations. This means an unpredictable flow of car parts, including batteries, from these organizations. Therefore, there is an interest to clarify the regulations in terms of who are “able to” handle the spent cars and batteries, to avoid misinterpretations and potentially dangerous situations of reuse or repurpose. To counteract unfortunate episodes, there are several initiatives to educate staff in Norway with courses inn safe handling and diagnosis of batteries.

4.2.6 Battery dismantlers

Battery dismantling is, as previously mentioned, a business driven by the EPR regulations. Hence, the added value lies in helping car importers (and automotive OEMs) fulfill the regulatory duty. In this regard, the key activities revolve around handling the logistics of spent batteries and deactivating and dismantling the mechanical components for further recycling. Today, logistics is a significant cost item, especially as they, as a rule, require special transportation for dangerous goods (ADR). Some changes to this may be upcoming, for example, in the case of undamaged and sealed batteries that only have been removed from their original vehicle body. Nevertheless, efficient coordination of increasing flows of EOL LIBs is a key competence and activity of the battery dismantlers.

Handling of the LIBs themselves requires good knowledge of different high-energy battery types to be able to set up safe and efficient systems for deactivation and dismantling. Battery dismantling is still a reasonably labor-intensive activity and is expected to remain so for the near future despite research efforts on the automation and robotization of the disassembly process. Currently, the variety of different battery types (both in terms of chemistry and cell design) is so big that it is challenging to fully automate the dismantling process. Standardization of battery types is neither likely to happen as long as the LIB technology is undergoing rapid development.

In Europe, the earning logic for a battery dismantler is the gate fees obtained from the car importers. The situation may, however, change quickly when the amount of EOL batteries increases. The revenue from selling the dismantled materials may constitute a larger share of the total revenues of a dismantler. A battery dismantler is highly dependent on the success of the ecosystem. However, the EPRs may have no own growth ambitions as such (besides fulfilling the regulatory duties of their clients). The dismantlers appear to be able and willing to play a role in the ecosystem. In the future, this may, however, be subject to both workshop capacity and availability of trained human resources for handling high-energy batteries.

Overall, the recycling value chains are rather heterogeneous, and various actors enter the market from different value chain positions, as shown in Figure 6.

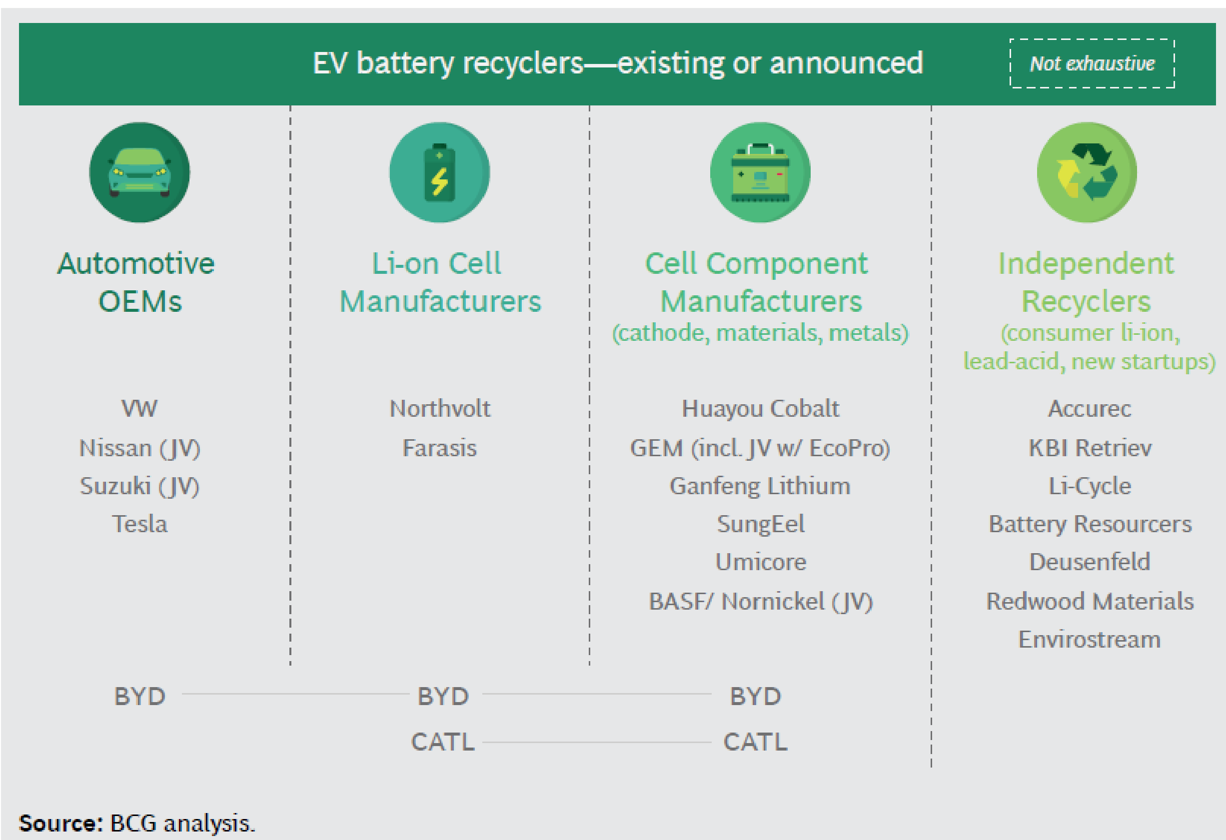


Figure 6: Actors engaged in EV battery recycling across the value chain [10].

4.2.7 Metal/mineral processors (extraction and refining)

After the mechanical treatment and physical separation of the spent LIB, different material fractions may be sold to processors of different minerals processors for their further extraction and refinement [35][2]. Various actors perform different parts of this process chain. Metals companies are typically specialized in one kind of metal, such that you will typically find aluminum producers, nickel and cobalt producers, and, for example, iron producers. Through their primary activity of extraction and refining, these companies create value in the form of a high-quality (battery-grade) metal product and an efficient refining process (i.e., high yield and as low carbon footprint as possible). Their key resources are the refineries and an R&D department that can continuously improve the process. In essence, there are two main process routes for extracting and refining raw materials from retired batteries: pyro- and hydrometallurgical, and various combinations of the two [35]. An overview of different process routes is provided in Figure 7[3]. The choice of the process can, to some extent, be seen as an element of the business model as the two routes have rather different properties. The selection may also be driven by regulation, especially as there will be demands on the recycling of lithium [14], which would favor the hydrometallurgical route. Depending on the source of electricity, the pyrometallurgical route also has a higher footprint, although, in Norway, the high supply of hydropower offsets that disadvantage.

On a general level, the minerals processors are, per se, not directly dependent on the success of the ecosystem, as their processes can handle both virgin and recycled raw materials. Still, as soon as the automotive industry by regulation is directed on a more circular route, they are bound to follow one of their most important customer segments, the automotive industry. There is no foreseeable risk that they could or would not fulfil their role in the ecosystems as there are existing refineries. However, tightening emission and recycling requirements exert some pressure on intensified R&D activity.

[2] "Black mass" containing several valuable metals is produced as an intermediate refining step before further extraction and refinement.
[3] Miners are excluded from this chart as the modeling considers the recycling ecosystem.

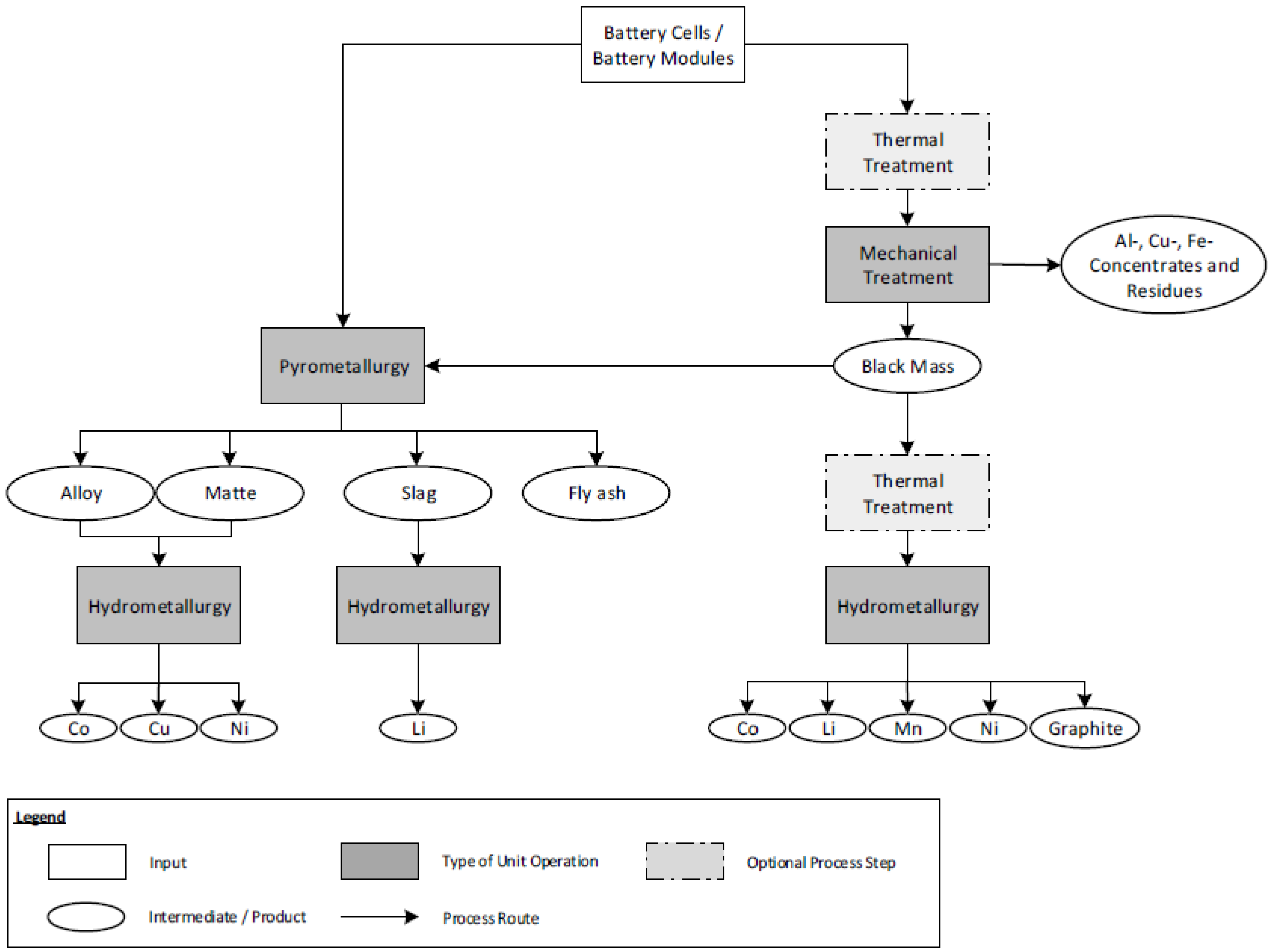


Figure 7: A flowchart over potential routes for the circular economy of LIBs [29].

4.2.8 Metal/mineral traders and merchants

A generic value chain for the metals industry is shown in Figure 8. In this report, we will not consider the upstream mining industry and its technology supply chain. What is characteristic of the metals industry is the existence of merchants and exchanges, such as the London Metals Exchange, on which platforms most of all non-ferrous metal futures business is transacted.

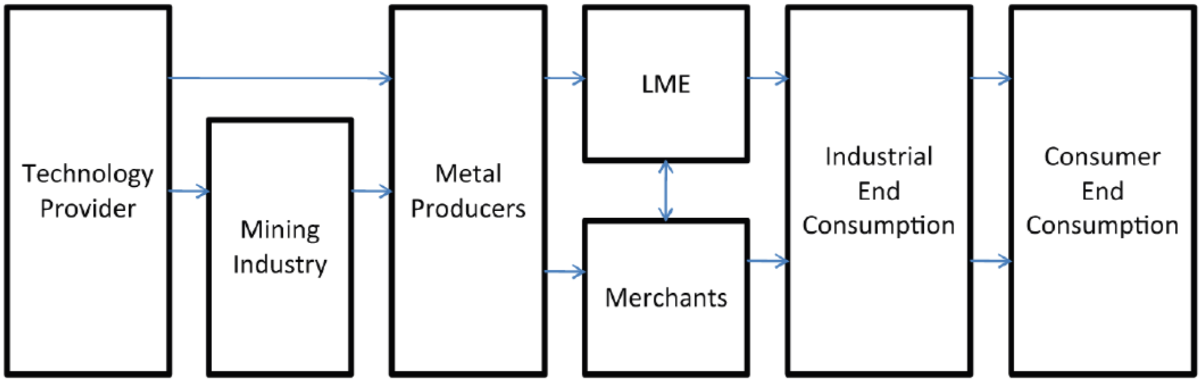


Figure 8: The generic value chain in the metals industry [36].

4.3 Resulting ecosystem model of LIB recycling ecosystem

The resulting EPM for the LIB recycling ecosystem is shown in Figure 9. The colors of the actors and the respective tables indicate different sectors (or value chains). Table 2 summarizes the observed dependencies and the assessed risk levels. It is to be pinpointed that the assessment does not make claims regarding specific companies, but it attempts to highlight some potentially essential issues of an evolving ecosystem and the involved actor groups on a general level.

The resulting EPM for the LIB recycling ecosystem is shown in Figure 9. The colors of the actors and the respective tables indicate different sectors (or value chains).

Table 2: A summary assessment of dependencies and risks in the sustainable LIB recycling ecosystem in Europe.

Actor	Dependence on the ecosystem	Risk for the ecosystem
Battery component and pack producers	***High*** – Highly dependent on the sustainable supply of battery raw materials.	***Medium*** – As of today, we do not have a proven ability to master the whole supply chain and production process for batteries on a large scale in Europe.
Automotive OEMs	***High*** – There have recently been European regulatory measures to increase the recycling rates for OEMs in terms of their EPR.	***Medium*** – For recycling to be efficient, batteries will have to be designed for disassembly and recycling. Although some of the newest car models cater to this, it is still not an industry-wide mature practice.
Car distributors	***Medium*** – Same as for the OEMs, but depending on the demand for EVs on a specific country market, they may as well continue with ICE powered vehicles.	***Low*** – For some car distributors, the EV market cannibalizes the existing business, which may impact their willingness to contribute to some countries. However, although they provide easier access to cars, they cannot stop consumer access to EVs. Overall, their role in recycling is minor.
Car dismantlers	***Medium*** – Needs to fulfill their regulatory duty in terms of waste handling, which currently does not constitute a problem. Car dismantlers have a potential power position that could enable a low-risk business of channeling batteries to different parties depending on their health, which makes them somewhat dependent on the success of the ecosystem (i.e., risk-free waste handling). Furthermore, car dismantlers receive a large part of their income from spent spare part sales, making them less dependent on recycling per se.	***Low*** – In principle, Norway has one of the best car collecting systems globally, and most dismantlers have agreements contributing to a predictable flow of spent batteries to the ecosystem. However, each dismantler controls the batteries after consumption and may themselves decide what to do with them. ***High*** – Car dismantlers possess the LIBs when the EV consumers have sold/ delivered it to them. As per current regulations, dismantlers are free to forward the battery to the buyer of their choice. A few dismantlers sell the batteries to unknown consumers, and if this continues with larger volumes, it will be a risk for the ecosystem's predictability. They are marked with a grey sub-sector in Figure 9.
Battery dismantlers	***High*** – Fulfil an essential role in the EPR system and are dependent on a functioning recycling market (off take) with high capacity.	***Medium*** – The availability of a skilled workforce may be a bottleneck in the future.
Mineral processors	***Medium*** – As such, the metal producers are not dependent on recycled raw materials, but to be sustainable and to be able to supply the European automotive industry with recycled materials, they are dependent on the supply of spent battery parts.	***Medium* -** The availability of sustainably recycled battery raw materials will, in the beginning, be uncertain but is likely to be the opposite in the longer run.

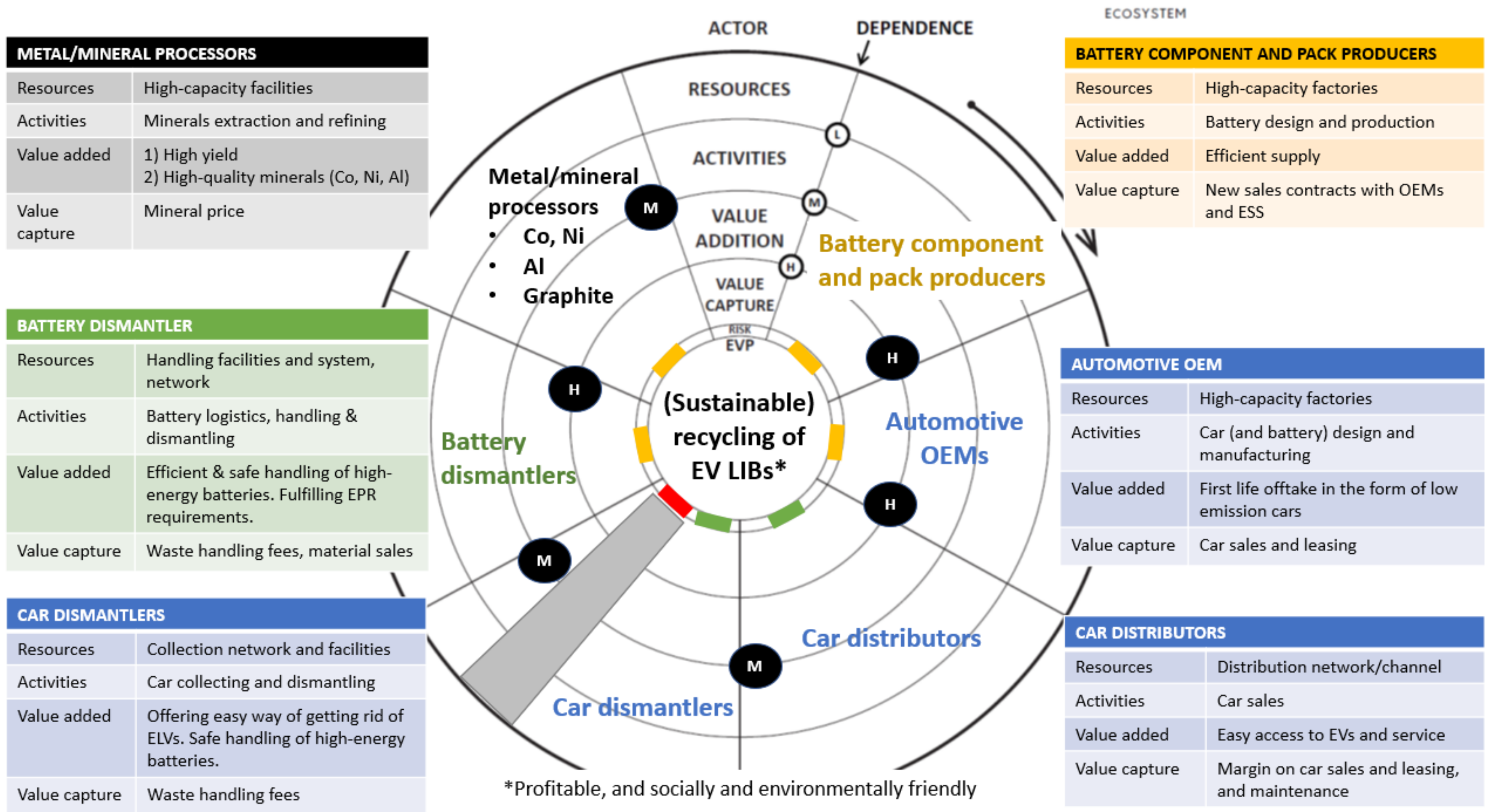


Figure 9: Ecosystem Pie Model of electric vehicle lithium-ion battery recycling community

5 Modeling of the LIB second use ecosystem

5.1 Overview and the ecosystem value proposition

Recycling eventually is the activity pursued increased circularity in the LIB industry and the focal activity for the automotive industry to secure its supply of raw materials. Before finally recycling the battery, it may make sense to prolong its lifetime by reusing it (in another car) or repurposing it for a second use as part of an ESS. This chapter deals with the ecosystem required for second use. Potential second use applications are shown in Figure 11**.**

The EVP for LIB second use ecosystem is defined as follows:

> ***Sustainable second use of LIBs means profitable repurposing that is continually not harmful to the environment and society.***

The way the EVP is formulated is crucial for the modeling as the elements listed in Table 1 all shall be understood from the EVP perspective. The above formulation expresses an ambition for circularity (in the form of a prolonged lifetime) and sustainability (in the form of a profitable activity that is not harmful to people or the plant).

5.2 Actor by actor analysis

5.2.1 Battery pack and component producers

In the second use ecosystem, the LIB manufacturer's role is the same as in the recycling ecosystem, but the incentives to participate in the ecosystem vary a lot. For a battery cell and pack producer, there is likely to be immense interest in new sales of storage solutions rather than participating in the second use ecosystem [10]. Hence, the dependence on the success of the ecosystem is low. As stated in section 4.2.1, however, there is no considerable risk concerning the battery producers' ability to supply the market with new batteries.

5.2.2 Automotive OEM

It can be expected that the OEMs, for the time being, are fully occupied with launching new EV models and converting their factories to EV production [10]. In this regard, the automotive industry is not dependent on the success of the second use ecosystem per se, as the new (December 2020) EU regulations do not require a certain degree of second use, although measures are given to allow it [14]. In such a case (and otherwise), they are likely to team up with stationary energy storage systems providers for the second applications [10]. They are not expected to constitute a risk for the second use ecosystem.

Nevertheless, the battery management system (BMS) gives the OEMs a particular gatekeeper role in the second use ecosystem. It is crucial for all batteries, especially for lithium-ion based, to ensure safe and reliable operation and gets increasingly advanced in track with technological innovations. The BMS is a computer-based control system that adjusts the battery operation to specific applications, conditions, and consumption. It controls the charge and discharge rates (C-rate), monitors battery parameters such as current and voltage, and performs various safety and quality measures, e.g., thermal control. The programmed system and data are private property for the automotive OEM, and access to third parties is limited. The BMS with its algorithms and data is considered as a company secret, also due to safety reasons, to avoid third party access and misuse of the battery. The BMS is one of the significant challenges in second use of LIBs.

5.2.3 Car owners

Car owners are mentioned here in the capacity of their role as a potentially new actor in future energy ecosystems through vehicle-to-grid (V2G) systems that may become an element in new business models among energy companies [37]. However, V2G can face challenges due to battery degradation, which will occur more rapidly. When the car owners own the LIB, they will not control the battery after it is sold and delivered to the car dismantler. Hence, they will not play a direct role in the second use ecosystem apart from individual car/battery owners who decide to reuse the battery for their private purposes and apart from the potential role as a competitor to the second use applications in terms of their ability to contribute to V2G systems. As these roles are expected to be minor (at least in the near future), car owners are omitted from the ecosystem model.

5.2.4 Car dismantlers

Car dismantlers essentially play the same role in the second use ecosystem as in the recycling ecosystem. For the same reasons as in the recycling ecosystem, their dependence on the ecosystem is low. However, given their gatekeeper position and low risk of participation, the second use market could be a major business opportunity when the spent LIB volumes arrive if the value streams remain unchanged.

5.2.5 Battery repurposers

In the second use ecosystem, the spent battery moves from the dismantler (or from the one who possesses the battery at EOL) to a battery repurposer that performs an additional activity of repurposing the battery, either by both remanufacturing the battery pack (or module) and reprogramming the BMS or by only doing the latter. Repurposing requires some expertise in the functioning of the battery. The added value therein lies in the remaining lifetime and residual value that the battery may possess. The value space where the repurposer operates is, however, narrow, as shown in Figure 10. For one thing, the cost of new batteries is continuously decreasing. For another, the value of the battery materials makes it increasingly interesting for mineral processors, depending on the volume of supply of retired batteries and the price of virgin raw materials. Therefore, the dismantler is not solely dependent on the success of the second use ecosystem, but the repurposers indeed are. There are competent repurposers around, and it is as such no major risk as to their ability or willingness to repurpose spent batteries, but the cost efficiency of the process is a question mark together with the supply of spent batteries for repurposing. The actors who possess the battery ownership at EOL are gatekeepers in this regard (for a further discussion on this topic, see Chapter 6). Therefore, an alternative business model is to use undamaged battery packs without any dis- and reassembly involved. As seen in Figure 10, such a model may radically improve the economics of repurposing.

However, a major hurdle for any repurposing is access to the battery management system (BMS). An alternative route is reprogramming the BMS, which is costly. Another issue is the uncertainty around where the EPR lies for repurposed batteries (by the OEM, the repurposer, or even the end-user). For these reasons, the most economical business model under prevailing regulatory conditions seems to be one that builds on a partnership between a storage solution provider and an OEM [10].

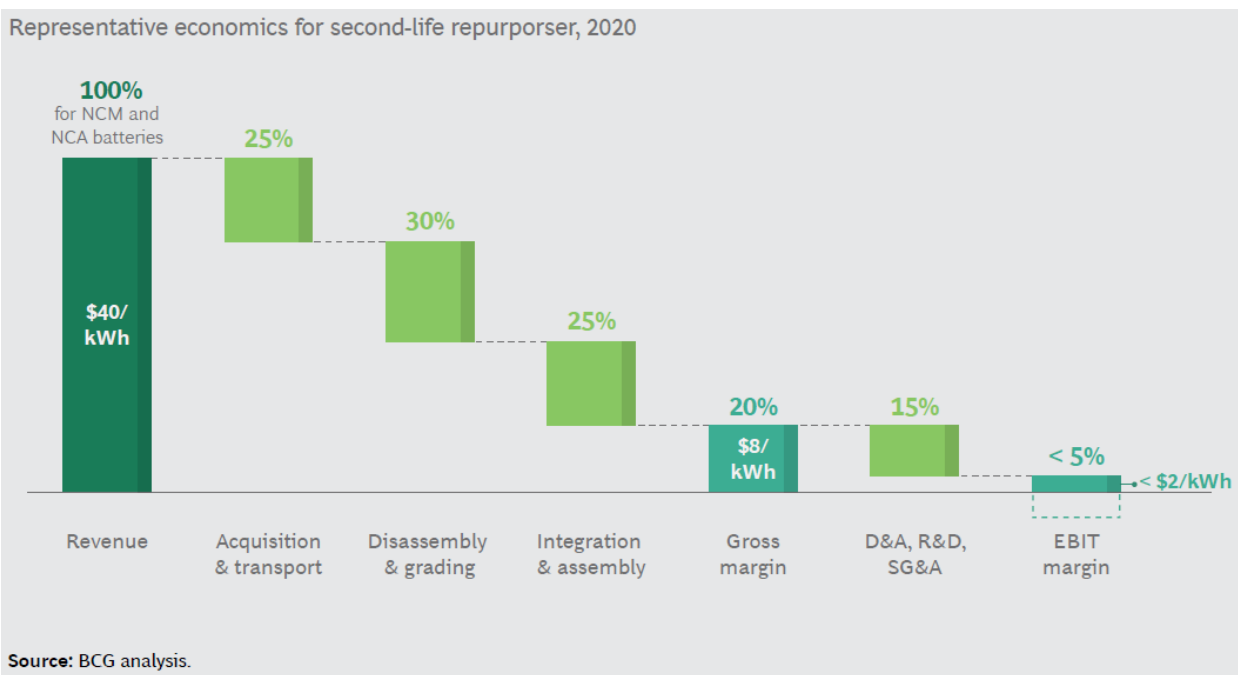


Figure 10: Representative economics for second use repurposer in 2020 [10].

5.2.6 Systems integrators / ESS providers

A battery alone does not make a complete storage solution but must be complemented by different components. Such ESS providers perform a systems integration activity by sizing, customizing, and optimizing the storage solution for a specific grid. The added value can briefly be divided into two major categories. One that improves the power quality and the reliability of the grid, and another that reduces energy costs by lowering the demand charge and/or introducing flexibility in terms of the time of use (i.e., by enabling price arbitrage) [38]. Figure 11 lists 14 such applications for four different customer segments. The value capture mechanism for system integrators seems to be direct sales. There might also merit trying out value-based pricing and service-oriented offerings (such as batter-as-a-service) [10]. The system integrator can also be a repurposer (or vice versa) as repurposing itself may not add enough value alone (see the previous Section).

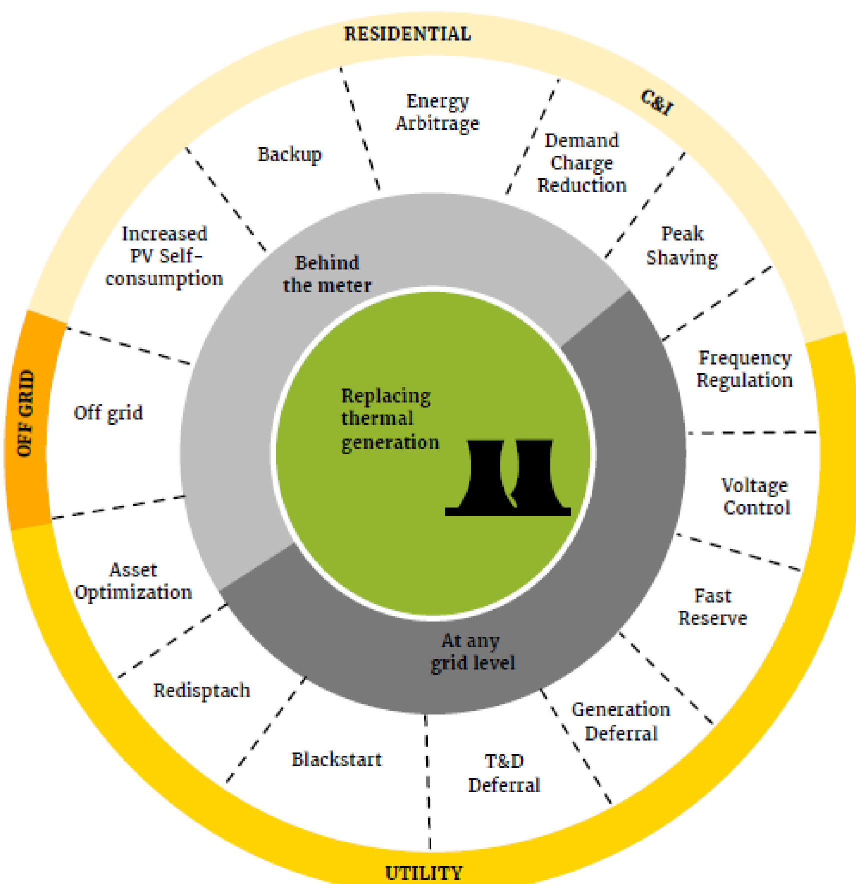


Figure 11: Different energy storage system applications for different customer segments [39].

The system integrators are dependent on the success of the second use ecosystems, at least as long as there is a clear price difference between new and second use batteries. The storage providers have proved to be both competent and willing to contribute to the success of the ecosystem. The supply of batteries is, however, in the short term, a challenge for them.

It is noteworthy that the complementary components (e.g., power electronics) may constitute an attractive niche market for some players. These suppliers also create opportunities for ESS providers to enlarge their supply scope towards more complete solutions [10].

5.2.7 Grid owners and operators

Figure 11 lists some common actors and customer types for ESS solutions. From the EVP point of view, their primary function is to provide the offtake of storage solution. However, currently, there does not seem to be a high demand for other values than the price difference among the grid owners or operators. With the increasing amount of intermittent energy sources introduces in our grids, there is also likely to be a continued demand for stationary storage solutions as along as viable business cases can be identified.

Companies building the charging infrastructure (and related technology) are a new actor that may be worth considering in the second use ecosystem. This is because the charging infrastructure may become a potential offtake for second use batteries and may, in that respect, contribute to growing the market size for second use batteries at the same time as it serves as an enabler for further EV penetration on the market.

5.3 Resulting ecosystem model of LIB second use ecosystem

Table 3 summarizes the observed dependencies and the assessed risk levels for the respective actor groups in the second use ecosystem. It is to be pinpointed that the assessment does not make claims regarding specific companies, but that it attempts to highlight some potentially important issues of an evolving ecosystem and for the involved actor groups on a general level.

The EPM for the LIB second use ecosystem is shown in Figure 12. The colors of the actors and the respective tables indicate different sectors (or value chains).

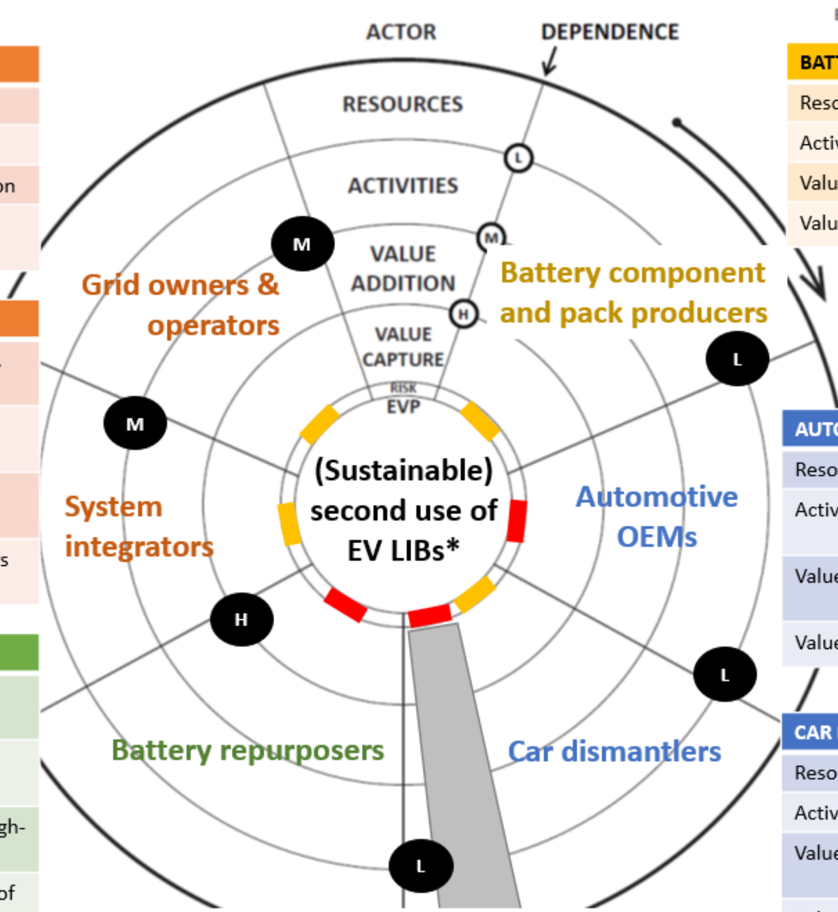
Table 3: A summary assessment of dependencies and risks in the sustainable LIB second use ecosystem in Europe.

Actor	Dependence on the ecosystem	Risk for the ecosystem
Battery component and pack producers	***Low*** – Is not dependent on an existing second use market for spent batteries.	***Medium*** – Has the capacity to supply the first life market with new batteries but may not have the willingness to promote a second use ecosystem as it cannibalizes on new sales to the ESS market. It may also render the price difference between first and second use batteries obsolete.
Automotive OEMs	***Low*** – Only required to recycle and not dependent on a second use ecosystem.	***High*** – Battery management system access (and battery design and standardization) may hamper the functioning of a second use ecosystem.
Car dismantlers	***Low*** – No explicit requirements for second use, but it is an opportunity for dismantlers to participate in the second use ecosystem given their position and low risk.	***Medium*** – Have control over the batteries after consumption and decide where to channel them in the chain (e.g. directly to recycling) and have a low-risk incentive to direct them to a second use ecosystem whenever there is a value arbitrage. ***High*** – A small share of the car dismantlers who possess the LIBs when the EV consumers sold/ delivered it to them sell it to individuals/ organizations without experience and skills to handle the LIBs. This can be a safety risk and resulting reputation damage for the whole ecosystem. They are marked with a grey sub-sector in Figure 12.
Battery repurposer	***High*** **-** Second use is a necessity for the repurposer.	***High*** – The success of the ecosystem is dependent on the possibility of efficient repurposing.
System integrators	***Medium*** **-** As long as there is a price difference between new and spent batteries (i.e., the latter is cheaper), there is a dependence.	***Medium*** – The willingness to contribute to the ecosystems exists as long as there is a demand for ESS and the price difference prevails. Given that there are quality assurance systems for second use LIBs.
Grid owners and operators	***Medium*** – As long as there is a price difference between new and spent batteries (i.e., the latter is cheaper), there is a dependence.	***Medium*** – The demand (business case) for stationary ESS exists, but the market is yet to take off.

GRID OWNERS & OPERATORS	
Resources	Grid
Activities	Grid operation
Value added	Load levelling, frequency regulation
Value capture	Effect balancing

SYSTEM INTEGRATORS	
Resources	Used battery source, engineering, system optimizing
Activities	Project development, sourcing, system design
Value added	1) Power quality & reliability 2) Demand charge & ToU
Value capture	ESS sales to grid owners/operators

BATTERY REPURPOSERS	
Resources	Handling facilities and system, network
Activities	Battery logistics, handling & repurposing
Value added	Efficient & safe repurposing of high-energy batteries
Value capture	Margin on the resales or leasing of used batteries



*Profitable, and socially and environmentally friendly

BATTERY COMPONENT AND PACK PRODUCERS	
Resources	High-capacity factories
Activities	Battery design and production
Value added	Supply of new batteries
Value capture	n/a (prefer new sales)

AUTOMOTIVE OEMs	
Resources	High-capacity factories
Activities	Car (and battery) design and manufacturing
Value added	Increasing the supply of new batteries; collecting batteries.
Value capture	n/a

CAR DISMANTLERS	
Resources	Collection network and facilities
Activities	Car collecting and dismantling
Value added	Source of used batteries. Safe handling of high-energy batteries.
Value capture	Value arbitrage on the second life market

Figure 12: Ecosystem Pie Model of electric vehicle lithium-ion battery second use community.

6 Battery ownership and circular business model discussions

At least, in the beginning, it is expected that the supply of retired batteries will be the limiting factor for both the recycling and second use of them rather than the applications in which they or their constituent materials can go. Therefore, one pressing question revolves around the ownership of the LIB at EOL. Among others, the choice of business model is expected to have implications for the ownership and hence the controllability of EOL LIBs. In this Section, some aspects of this phenomenon are discussed, including battery ownership models, stakeholders, and business models for sustainable EOL management, drivers and barriers for circularity of LIBs, and perspectives on second use practice.

6.1 Battery ownership models

Figure 13 illustrates the three recognized battery ownership models for EV batteries. Who owns the LIB will affect the business ecosystem and business models, including partners and infrastructure. Time of LIB retirement is another dimension influenced. This can be determined by time in years (calendar life), battery State of Health (SOH), or consumer behavior related to the battery application (e.g., an EV). Which factor determines the lifetime in the (first) application is likely affected by the battery ownership model [38], illustrated in Figure 13.

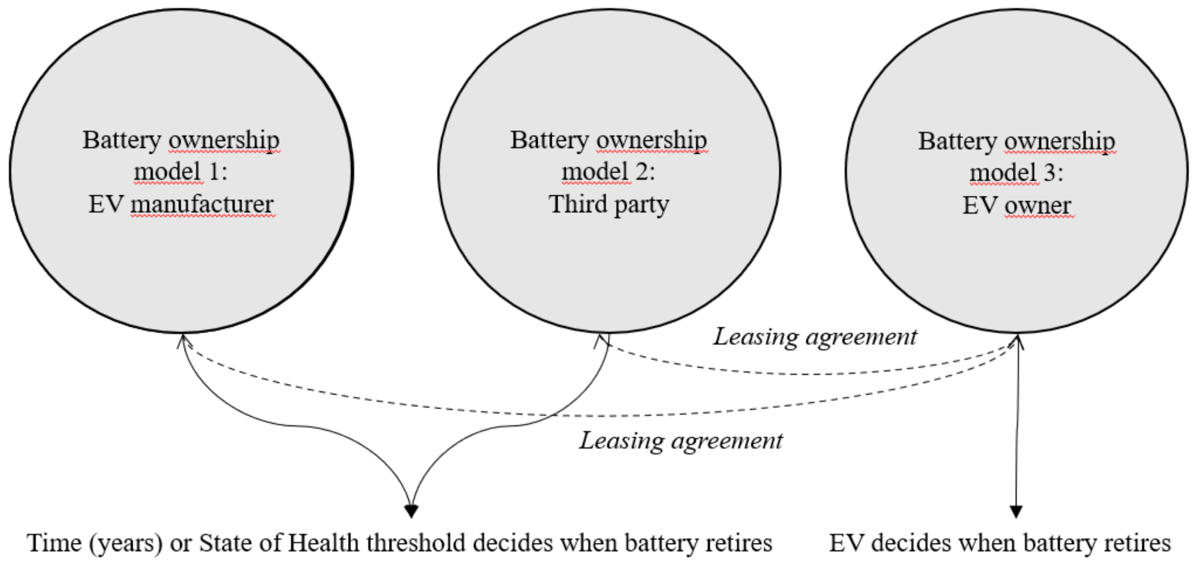


Figure 13: Alternative battery ownership models for electric vehicle batteries based on [38]. *Alternative owners marked grey.*

If an EV manufacturer (model 1) or a third party (model 2) own the battery, a leasing agreement is organized with the EV consumer, who rent the EV and battery. In these cases, the battery SOH or calendar lifetime can determine when it retires from the first application. Applying models 1 and 2 may increase the predictability of timing for actors in the business ecosystem.

6.1.1 Hybrid ownership model

A hybrid ownership model, illustrated in Figure 14, could be an alternative where the EV manufacturer offers battery maintenance service and an EOL contract agreement with the EV owner. This purposely will increase control of the battery and collection rate without owning it. A Chinese case company is presented with this model in a study by Jiao and Evans (2016). A hybrid model can open the opportunity to track and record data for each battery if the battery is provided with an identifier.

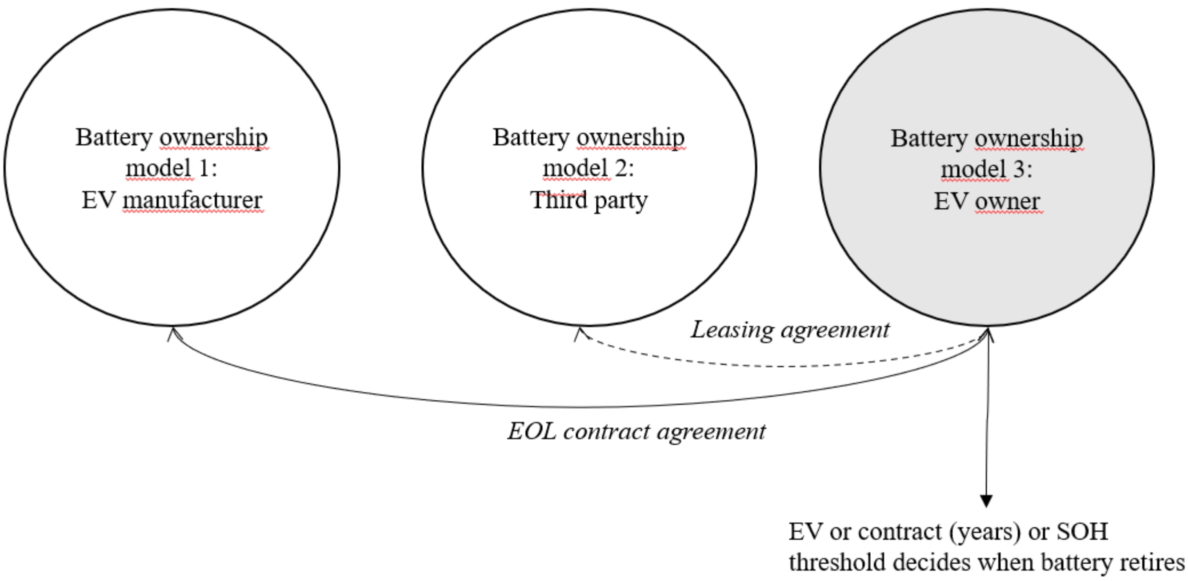


Figure 14: A hybrid battery ownership model for electric vehicle batteries based on [40] *and* [38]. *Owner marked grey.*

The nationwide Norwegian deposit system for non-refillable beverage cans is an example from another industry on how to increase control of collection rates of a product without owning it. In this recycling system, the consumer purchases the beverage and pays the extra deposit price they will receive in return when delivering the bottles and cans [41].

6.1.2 Future ownership

None of the sources interviewed (Section 9.1) believe that the battery ownership model will change from the EV owner or third party to the manufacturer. For Norway, such a shift in ownership model would lead to a less complete and effective deposit system, as this is based on EV owner ownership. If EV producers own the battery, about half of the economic value could be lost for car dismantlers, and the entire system (illustrated in Figure 4) would be challenged.

What is expected to change in the near future, is the EV producers' increased interest in and control of the spent EV batteries. Currently, their primary focus is on the organizational and technological shift (e.g., human skills and knowledge) from ICE powered to electric vehicles. The battery ownership model is a feature of the OEM's business model and will influence the EV and battery value chains, which is a significant decision.

6.2 Stakeholders for end-of-life management

Figure 15 presents the perceived importance of various stakeholders for EOL management of LIBs. The list of stakeholders was modified by the expert panel in the Delphi study before they ranked them on a Likert scale from 1 to 6 (1 means "not important at all" and 6 means "very important").

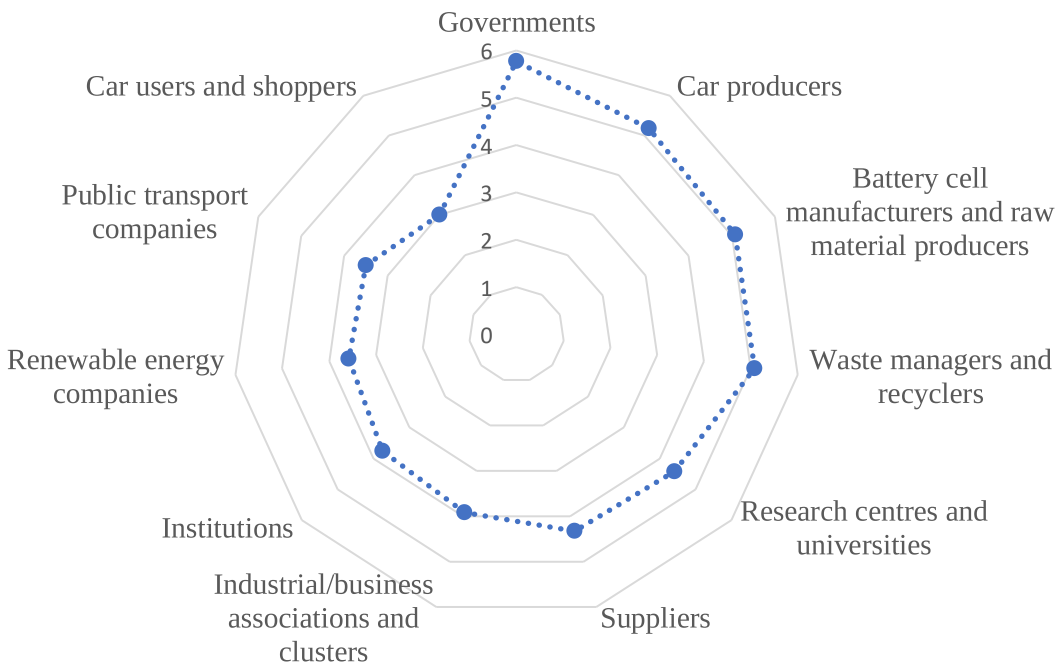


Figure 15: Stakeholders perceived importance for lithium-ion batteries end-of-life management.

6.3 Circular business models for lithium-ion batteries

As a part of the Delphi study described in Section 2.4 [20], various battery experts were requested to rank circular business models based on their potential to recapture value from spent LIBs. The panel modified the list before they ranked them; thus, some were proposed by the experts. The two business models for spent LIBs that were ranked the highest include activities related to second use. The third only includes battery recycling.

Suitable business models are needed to capture, create, and deliver value from technology such as LIBs. Thus, the type of model can largely influence economic viability. For example, if a third party owns the battery and rent it out to different customers, namely a product-as-a-service business model, this model can affect profits by creating more economic value per battery (Bocken et al., 2014). However, depending on consumer behavior, this model can lead to more cycles per calendar year, leading to a shorter battery lifetime (Martinez-Laserna et al., 2018).

6.4 Drivers and barriers for circular business models

Figure 16 presents drivers for upscaling circular business models for spent LIBs (i.e., to enable improved recycling and/or second use). The list of drivers was modified by the expert panel in the Delphi study before they ranked them on a Likert scale from 1 to 6 (1 means “not important at all” and 6 means “very important”). The results indicate that regulations that benefit the economic viability of second use batteries and improved recycling rates are currently the most important to upscale circular practice.

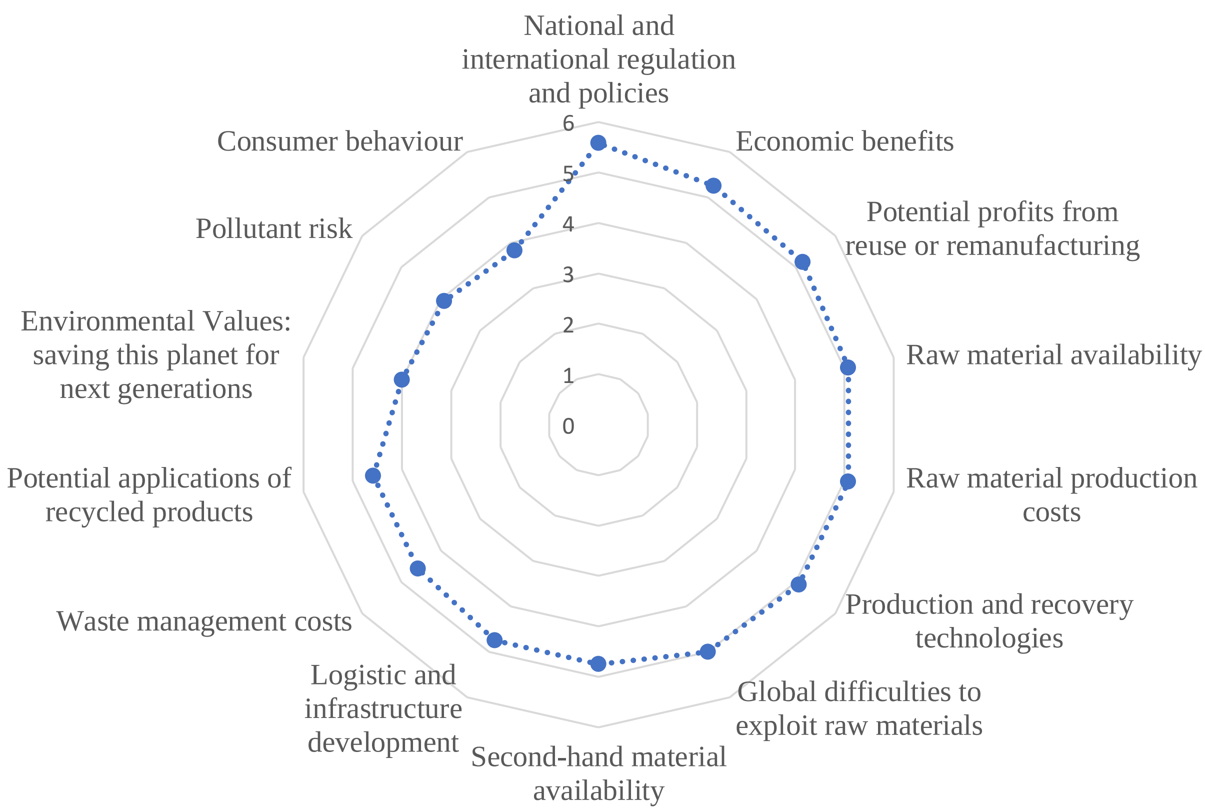


Figure 16: Drivers for circular business models of lithium-ion batteries.

Figure 17 presents barriers for upscaling circular business models for spent LIBs. The list of barriers was modified by the expert panel in the Delphi study before they ranked them on a Likert scale from 1 to 6 (1 means “not important at all” and 6 means “very important”).

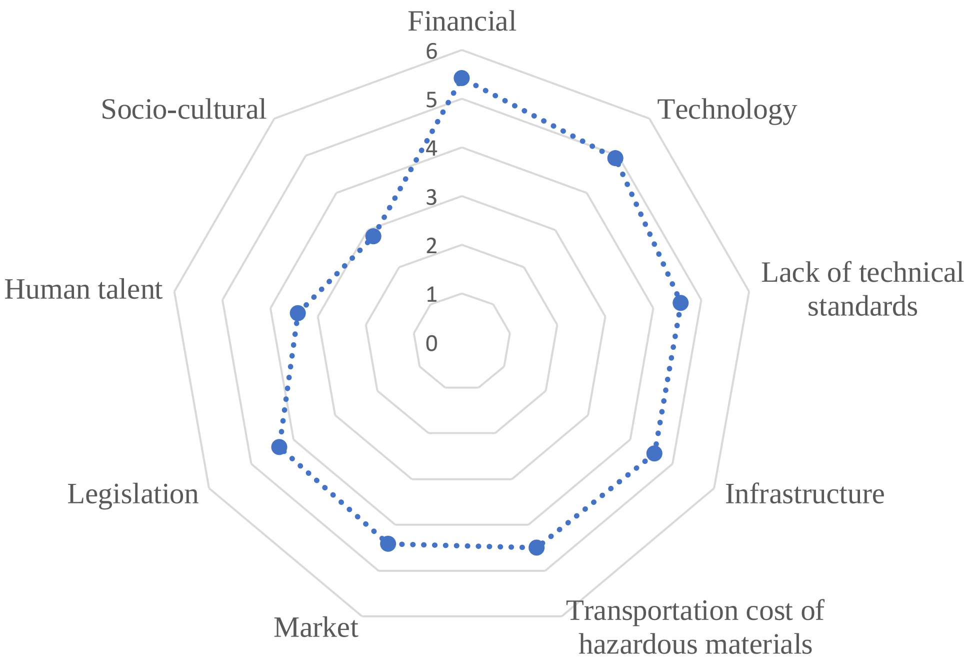


Figure 17: Barriers importance for circular business models of lithium-ion batteries.

Table 4 presents highlighted sustainability dilemmas for LIBs and innovations needed to increase sustainability (i.e., profitable while environmentally and socially friendly). The lists show merged results of various suggestions from the expert panel in the Delphi study.

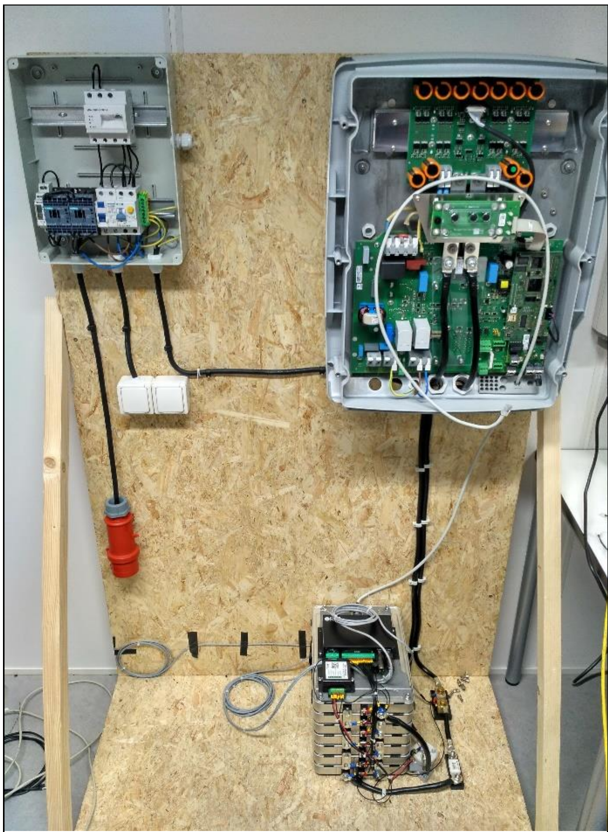
Table 4: Sustainability dilemmas and innovations for lithium-ion batteries mentioned by the panel.

Sustainability dilemmas for LIBs	**Innovations needed to increase sustainability**
• Highly energy consuming manufacturing processes • Availability of sustainably produced raw materials • Lack of sustainable recycling technologies and infrastructures • Transportation challenges due to geographical dominances • Safety concerns	• Increase battery capacity and lifetime • Design for remanufacturing, second use, and recycling • Shared ownership models (LIB as a service) • Reduce size and price

6.5 Perspectives on second use

All information sources are uncertain regarding the share of LIBs repurposed for second use before recycling or if most will be directed directly to recycling. As previously indicated, there are potential opportunities and challenges (or even barriers) with second use of LIBs. This section discusses a few relevant topics.

Table 5: To the left, an ESS of spent EV LIBs with the battery pack in the bottom. To the right, a closer look at the battery pack [photos: Bernhard Fässler at the University of Agder].

	
In the bottom, a battery energy storage system with BMS, connected to the AC/DC converter. The grey box on the left side is the switch cabinet with fuses and the connector (red plug) to the grid.	A closer look at the battery in the bottom, these are seven Nissan Leaf modules combined to a new battery energy storage system. The black box on top is the BMS.

6.5.1 Volumes and access

There are, as of now, no regulations that force or directly encourage second use of LIBs. However, OEMs in Europe must today ensure that 50% of the total weight of the battery is recycled. Furthermore, by 2030, guarantee that a given percentage of several EV battery materials must be recycled [14]. Future recycling initiatives will affect LIB volumes that will first be repurposed before recycling or directly recycling after consumption. This EOL system is complex and influenced by several factors, such as demand for and prices of virgin raw materials, and increasingly by demand and prices for secondary raw materials.

Furthermore, another unpredictable factor to second use LIB volumes is that the car dismantlers possess the LIBs when the EV consumers sold or delivered it to them. This can be a risk for the predictability of the ecosystem as they ultimately choose the customer. Additionally, a small share of dismantlers sells it to individuals/ organizations without experience and skills to handle the LIBs, which can be a safety risk and resulting reputation damage for the whole ecosystem. The insurance company chooses which car dismantler to sell the cars to when there is a defect.

One daring source estimated (based on personal belief) that, with future spent LIB volumes, the share of retired batteries repurposed will be around 20-30%, but not above 50%.

The LIB battery pack is built up of modules, and the modules consist of cells. Spent LIBs can be repurposed at the pack, module, or cell level. Sources suggested by the informants to access second use batteries at pack, module, or cell level are shown in Table 6**.**

Table 6: Sources to access second use of electric vehicle batteries.

Source of second use battery	**Who controls the battery**
When the battery has a defect before the warranty is expired	Car importer or insurance company
When the electric vehicle reaches end-of-life, and the warranty is expired	Electric vehicle owner, car- or battery dismantler
Damaged batteries are typically sent to a battery dismantler in Norway	Battery dismantler
Spent LIBs sold and exported abroad	Car- or battery dismantler

Table 8 presents the requirements for sustainable collection practice and actors that can fulfill these. Thus, who should be collecting the spent LIBs. The requirements and actors are based on what was mentioned in the Delphi panel study.

Table 7: Who should manage the collection of spent LIBs, according to the expert panel.

Requirements for sustainable collection practice	**Actors that fulfill these**
• Knowledge • High battery volumes to achieve economically viable businesses • Meet high environmental standards	• Professional logistics companies • Recyclers • Manufacturers

When the volumes of spent LIBs are available on the market is another dimension. Sources recently indicate that the EV battery capacity will sustain longer than previously expected. However, consumer preferences can also influence when the EV is retired and, thus, when the battery is.

6.5.2 Responsibility and risk

Current regulations in Europe on extended producer responsibility make EV manufacturers who put the LIBs on the market responsible for managing and recycling battery waste after consumption. Therefore, there are currently a few unsolved issues regarding responsibility in the LIB second use practice:

- Who should be responsible for the quality and security of second use LIBs?
- Who will pay the cost of recycling after the second use?

Potential solutions:

- A repurposed LIB is no longer considered waste. The repurposer who puts the battery pack on the second use market will be responsible for it during and after second use.
- A contract that withdraws responsibility from EV manufacturer.
- EV manufacturer partly- or wholly-owns one or more subsidiaries that manages the second use value chain, reusing and repurposing their EV batteries.
- Shift from EV owner to EV manufacturer owner or adopt a hybrid battery ownership model (Figure 14), i.e., the manufacturer manages a financially safe second use value chain with minimized risk. This requires increased control over the batteries and a quality assurance system. It may also involve individual battery identifiers, e.g., QR codes.

If the battery value chain contributes to enabling second use of LIBs, there is a risk for battery cell manufacturers to experience that the spent LIBs "cannibalize" sales. That is if spent LIBs can sincerely compete with new. As a result, battery cell manufacturers may experience decreased demand for new batteries [10]. However, this claim is uncertain as the demand for LIBs is expected to increase substantially [2], and second use batteries can lead to higher consumption of batteries rather than replacing new ones[4] [43]. This depends, among other factors, on future battery prices and consumer behavior.

6.5.3 Economic viability

Several sources are uncertain if a second use battery pack can compete with a new one. The price of new versus spent LIBs is one of the most frequently highlighted factors that will affect the share of spent LIBs repurposed or sent directly to recycling. Figure 18 shows the result from a multi-scenario simulation study by Zhang et al. [44] that looked at the net present value (in a million Chinese Yuan) of second use EV batteries and new over time. As illustrated, the costs of new EV batteries are expected to decrease.

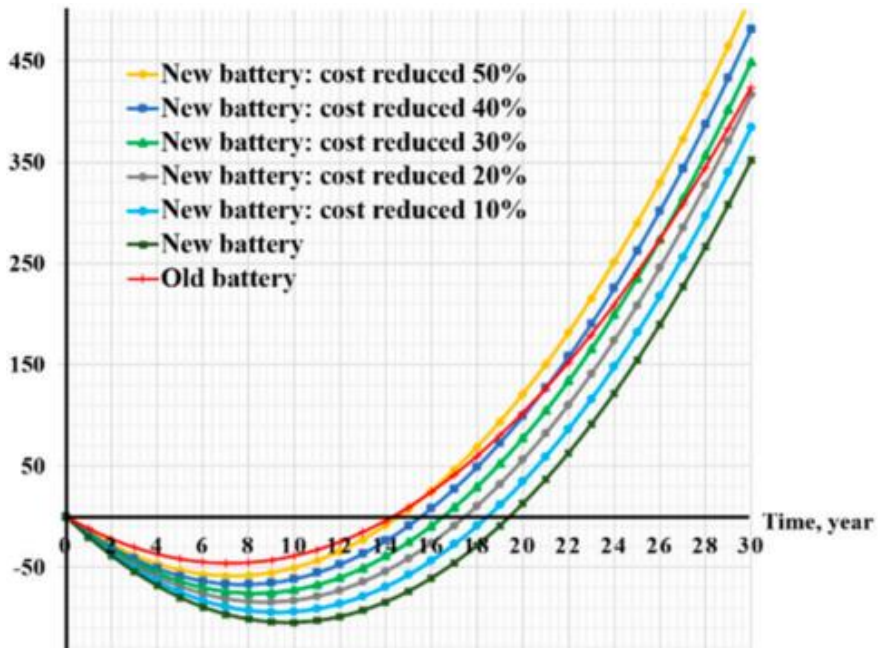


Figure 18: Comparison of net present value (in a million Chinese Yuan) of second use and new battery energy storage system over time (adapted from Zhang et al., 2020).

Costs of processing spent batteries must be minimized to compete with new batteries. One of the sources argued that 50% of all second use LIB costs are related to dismantling processes and the battery management system. Thus, reusing or repurposing the entire battery pack rather than dismantling it to a module or cell level can save costs. However, this requires cooperation with the EV manufacturer to access battery data from the battery management system.

Stationary energy storage systems connected to the grid are in many cases not considered as profitable in Norway as in other countries with higher electricity prices and fluctuations in prices. Also, the fee of

[4] The inability of secondary products to replace new, in addition to price effects that will further enhance the effect, are recognized as "circular economy rebound" by Zink and Geyer [43].

connecting to the grid is a cost that needs to be accounted for when investigating the economic viability of grid-connected energy storage systems [45]. As a result, several (or most) of the current second use projects in Norway are not commercial but encouraged by R&D. However, a few projects in Norway were motivated by profit. One example mentioned was a ferry on the west coast that found it cheaper to install a battery pack of retired EV batteries to access electricity compared to connecting to the grid.

Currently, the demand from other European countries is considered higher than the supply of spent EV batteries. One example was mentioned, where an actor abroad desired a contract agreement to secure the supply of spent EV batteries from Norway. In this case, similar to the ferry case, it was considered cheaper to invest in a battery storage system compared to connecting to the grid. This benefit was even more apparent when the actor would have to expand grid infrastructure to access electricity.

In conclusion, the economic viability of second use LIBs in the future is challenging to predict as the EOL system depends on several unknown factors. Nevertheless, second use batteries must compete with new on price. The majority of the sources argue that regulations that enhance the economic viability of second use practice are needed. However, there is currently a consensus among stakeholders and the European Commission that second use of batteries will be driven by market forces and not regulations [13].

7 Further research

In this report, the business ecosystem models are explorative studies that are dynamic over time as they develop and shape future business opportunities and challenges. These ecosystems included actors at a firm-level and did not include system changers such as regulators (e.g., EU and national government agencies) and research institutions. This approach, however, may be added or integrated into future work on ecosystem modeling.

EU's new regulatory framework for batteries was released in December 2020 and contained regulations that may affect the proposed business ecosystems and circular business models. For example, as LIB recycling targets are changed to percentage per material instead of total battery weight, this may impact dependencies and risks among the ecosystem actors. An update of the ecosystems can be done after the new regulatory framework is processed by industry to compare them before and after its implementation to detect effects of regulations. To further enhance the robustness and details of the ecosystems proposed, future research can also conduct quantitative surveys to receive further valuable inputs from project partners and informants.

An ongoing study, including techno-economic assessments, is relevant to work package 2 in terms of the economic viability of repurposing EV LIBs. This simulation study includes a case company and assesses potential profits given different conditions (e.g., location and climate) for two grid-connected battery energy storage systems.

Future research will also consider the environmental aspect of second use and recycling processes. Firstly, a systematic literature review will be done to identify existing relevant studies assessing the environmental impacts of such a circular practice. This will include an overview of existing (and future) recycling technologies from a climate- and environmental perspective. Furthermore, the mechanisms involved will be studied using a Life Cycle Assessment (LCA) approach to attain a system understanding of environmental impacts. For example, this will include the consideration of what (if any) a second use battery can substitute. Attained insights from this and other BATMAN reports will be a valuable basis for this research. A quantitative LCA study may also be relevant.

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Another version of this report for the internal use within the BATMAN consortium exists.

9 Sources

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