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Circular Business Models for Extended EV Battery Life

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Abstract: In the near future, a large volume of electric vehicle (EV) batteries will reach their end-of-life in EVs. However, they may still retain capacity that could be used in a second life, e.g., for a second use in an EV, or for home electricity storage, thus becoming part of the circular economy instead of becoming waste. The aim of this paper is to explore second life of EV batteries to provide an understanding of how the battery value chain and related business models can become more circular. We apply qualitative research methods and draw on data from interviews and workshops with stakeholders, to identify barriers to and opportunities for second use of EV batteries. New business models are conceptualized, in which increased economic viability of second life and recycling and increased business opportunities for stakeholders may lead to reduced resource consumption. The results show that although several stakeholders see potential in second life, there are several barriers, many of which are of an organizational and cognitive nature. The paper concludes that actors along the battery value chain should set up new collaborations with other actors to be able to benefit from creating new business opportunities and developing new business models together.

Keywords: electric vehicles; reuse; recycling; electricity storage; business models; circular economy

1. Introduction

In July 2018, there were over 55,000 electric vehicles (EVs) in Sweden [1]. Worldwide, the number exceeds 3 million and is expected to increase to between 125 million and 220 million by 2030 [2]. Vehicle original equipment manufacturers (OEMs) have ambitious goals to transform their fleets. For example, as of 2019, Volvo Cars will no longer launch vehicles that are driven solely by internal combustion engines, transforming their portfolio into one based on hybrids and plug-in EVs. Buses and other heavier vehicles are also becoming increasingly electrified.

While EVs are expected to reduce the climate impact and pollution problems of transport, many of the materials used in the batteries are toxic and rare and might thus reduce the sustainability performance of EVs in impact categories such as human toxicity, acidification and eutrophication potential [3–6]. Extending the battery life cycle is therefore a crucial aspect in improving EVs' contribution to overall sustainable development. By 2025, 250,000 metric tons of EV lithium-ion batteries (LIBs) are expected to have reached end-of-life [7]. In this context, end-of-life means that the batteries are no longer considered useful in a vehicle, but they still retain 70–80% capacity. Being able to make use of that capacity, and only then recycle the batteries, might lead to big sustainability improvements.

Capturing the value that is left in a product after use is the cornerstone of circular economy. Through direct reuse, refurbishment, remanufacturing, and/or recycling, waste can be eliminated [8]. Remanufacturing and reuse slow down the resource cycle by extending products' life while recycling closes the resource loop [9,10]. The processes of reuse and recycling are complementary to each other, and the largest sustainability benefit can be reached if EV batteries are first reused and then recycled.

There are currently a number of established businesses on the market, such as Spiers New Technologies Inc (SNT), a US-based provider of "4R" services (repair, remanufacturing, refurbishing and repurposing) for advanced battery packs used in hybrid and electric vehicles. However, a look at the market also reveals a number of recent businesses created by established car manufacturers. While many car manufacturers have conducted pilots, only a few, such as Nissan and Renault, have launched their second-life businesses. Nissan and Renault have launched brands (XStorage Home Systems and Powervault respectively) in the household energy storage market and focus on private households with solar panels in the UK as their core customer segment. Moreover, a number of third-party entrepreneurs are attempting to establish second life battery businesses. For example, the start-up company Freewire Technologies develops portable EV charging stations, and Relectrify, a start-up based in Australia, focuses on battery management systems to squeeze more value out of used batteries and facilitate the transition of batteries into a second life in residential solar storage, commercial peak-shaving, grid support and beyond.

To enable the transition to a circular economy, with reuse and recycling, specific product designs and business models are required [9]. When transitioning from linear to circular product logics, business models and value chains need to become circular in order to create value and satisfy customer and stakeholder needs sufficiently [11]. However, while technological solutions are advancing, economic and regulatory aspects have not yet been able to provide sufficient framework and incentives for a circular economy with slowed and closed EV battery cycles. There is not enough understanding of how companies can create business models that facilitate a circular economy [12].

1.1. Aim and Scope

In this paper, second life of EV LIBs is studied through interviews and workshops with stakeholders to provide an understanding of how the battery value chain and related business models can become more circular. An illustration of the value chain, as referred to in this paper, is provided in Figure 1. The value chain starts with design and manufacturing. After first life, the battery's health and capacity are checked to see if it can be used in a different vehicle or in a stationary application or if it needs to be recycled directly. If a second life is possible, the battery is refurbished. Depending on the battery and the application, refurbishment can include different processes.

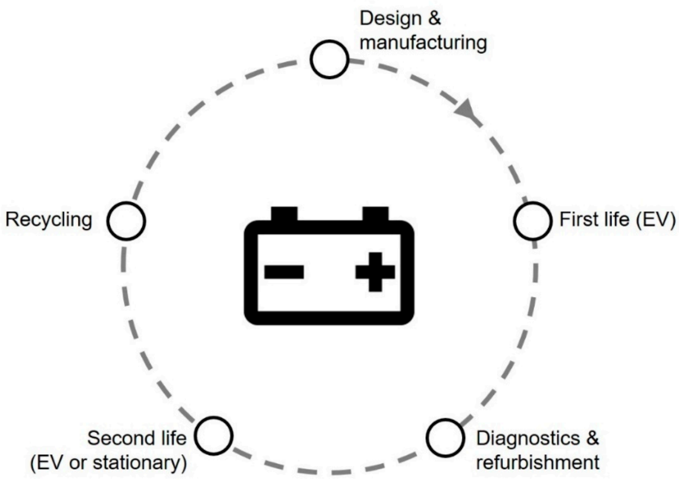

Figure 1. The circular EV battery value chain.

The aim of the paper is to contribute to the ongoing discussion on the circular economy by identifying barriers to and opportunities for second use of EV batteries, and by exploring business models in which increased economic viability of second use and increased business opportunities for stakeholders will lead to reduced resource consumption.

Second use of EV batteries is an issue of global interest, but this study is centered around Swedish and European actors and conditions. The EV market is growing in Sweden, there are national actors in all parts of the battery value chain, European Union (EU) legislation applies, and a large-scale second-life demonstration project (https://www.riksbyggen.se/globalassets/1-media-riksbyggen/2-bostad/bostadsratter/vastra-gotaland/brf-viva/lagring-av-el-i-begagnade-bussbatterier-i-riksbyggen-brf-viva.pdf) in Gothenburg, Sweden's second largest city, is drawing interest among several stakeholders. Thus, a study with a mainly Swedish scope can be considered to be of general interest.

1.2. Background

1.2.1. Theoretical Background on Business Models

The business model is the logic of the firm for how it creates and captures value in a specific business. With technological advancements and new emerging businesses and markets, the business model has recently been viewed as a source of innovation, albeit complementary to traditional types of innovation such as product, process, or organizational [13].

Innovation of the business model is increasingly highlighted as equally important as the idea or the technology that enables the innovation, meaning that new ideas and technologies cannot generate a competitive advantage without a fitting business model. New products, services and technologies can be commercialized through different business models and accordingly may drive different performances [14]. Therefore, the business model has become popular as a source of competitive advantage for the firm [15,16]. Business model innovation may manifest both in terms of renewal of existing business models [17–19] or as a means for competing with multiple business models [20–22].

Innovation of the business model may involve changes in one or multiple business model components and their links to one another, and it is therefore generally viewed as a complex, emergent, and uncertain process [23,24]. Despite many advantages of business model innovation highlighted in literature, firms may face substantial challenges and barriers towards working with change and transformation of their business models and in many instances, they are prone to failure.

Organizational barriers may manifest in different forms: Resistance to allocation of resources to the new business model, especially if the new business model creates conflicts with existing assets and capabilities [14,25,26]; lock-in that is manifested in switching costs to the new business model for customers or other stakeholders [27]; complications of developing a new business model in parallel to existing one(s) [28] and management of multiple business models [21]; inertia due to uncertainty about the effectiveness of new business models [29] and anticipating performance implications of the new business model ex ante [30].

Cognitive barriers [31] are related to: Filtering out ideas which are not in line with the dominant logic due to managerial cognition that hinders envisioning alternative business models and understanding the opportunity inherent in business model innovation [14,32]; lack of top management leadership to envision business model innovation and to figure out the required structures, capabilities and processes for the new business model [18,33]. Realizing a need for change in the business model is not only related to the top management leadership. It is also related to the distribution of authority and decision making in the management team. In companies where middle managers have decision-making authority and delegation for cooperation with external parties, the likelihood of sensing the need for business model innovation is higher [34].

1.2.2. Technical Background on EV Batteries and Recycling

Battery packs are made up of modules, with any number of cells, and a battery management system (BMS) [35]. They have different shapes, and different chemistries. Some chemistries have higher specific power (more suited to power delivery, e.g., lithium iron phosphate (LFP)), others have higher specific energy (better for energy storage, e.g., lithium cobalt oxide (LCO)). Supply issues of individual substances could impede production. For example, there is a so-called bottleneck of cobalt because both mining and refining occur in only a few places, a couple of which are politically unstable (such as the Democratic Republic of Congo). In addition, cobalt is a bi-product or co-product of gold and copper, making production of it dependent on those markets [36]. Nickel-heavy chemistries that utilize less cobalt, such as lithium nickel manganese cobalt oxide (NMC), are however expected to increase [37].

The batteries reach the end of their functional first life once they have lost 20% to 30% of their capacity [38]. When this exactly is depends on many factors, including:

- Consumer behavior when charging and discharging, and other usage patterns such as driving styles [39,40].
- Technical specifications of the battery, including the powertrain efficiency [41].
- Climate, in specifically high or low temperatures [40].

Sweden and the EU have legislation that requires recycling, and there is a growing interest in establishing systems for collection and management of used LIBs internationally [7]. Recycling technologies can be roughly categorized in three techniques: Hydrometallurgical, pyrometallurgical and mechanical processes [42]. In most cases, a combination of these recycling techniques is used [7].

Hydrometallurgy is a chemistry-specific leaching-intensive process that can recover lithium, aluminum, and other high-value materials [43]. The process is preceded by a mechanical separation and crushing of batteries [42]. A solvent is added to the crushed batteries, and this mixture is filtered. Acid is then used to separate metals [35]. Either precipitation using an alkaline solution or electrolysis is used to recover the metals from the leach solution [42].

Pyrometallurgy is a thermal treatment process, that includes pyrolysis, smelting, distillation, and refining [42]. High-value materials such as nickel, cobalt and copper can be recovered [43]. Batteries are shredded and slowly heated, after which plastics and solvents are burned in pyrolysis, where organic material is decomposed [42]. The remainder is smelted in a furnace and combined with limestone to create slag [43]. Metals are then separated through distillation [42]. Nickel, cobalt, and copper are recovered, while lithium and manganese usually end up in slag [35].

Literature concludes that with ‘state of the art’ recycling, a large fraction of materials can be recovered: Over 90% of lithium, cobalt, manganese, nickel, copper and aluminum [44,45]. In current practice, however, recycling rates are much lower [45,46].

1.3. Disposition

In Section 2, the methodology used in the study is presented along with the material that the results are derived from. Section 3 presents results, and Section 4 provides an analysis of what the results mean for circular business models and a discussion on the requirements for circular business models to develop. Section 5 concludes the paper.

2. Methodology and Material

To understand the various aspects of circular business models for EV batteries, background material was gathered. A scientific literature study was performed to gather data about battery manufacturing, second life and recycling. Desk research was performed, on three themes: Technology scanning, market analysis and stakeholder and network analyses; all with respect to EV batteries, second life and recycling. The material from this initial research phase was then used to plan the interviews and the stakeholder workshops that are the main sources of data in this paper. In addition, informal phone and email conversations with respondents have been used as input.

2.1. Interviews

This paper mainly builds on data gathered in 20 interviews with EV battery experts from 16 Swedish or global stakeholders in the battery value chain. The interviews were semi-structured, with a tailored interview guide for each stakeholder. Common topics were barriers and opportunities for second life and/or recycling of EV LIBs, possible business models for more circular value chains, battery design, and perspectives on standards and regulation. Most of the interviews were done by phone, and some in person. They lasted between 30 and 90 min and were recorded and transcribed. All interviews had one or two respondents. The interviews were done in Swedish or English. Quotes from interviews in Swedish have been translated with the aim of capturing the essence of the respondent's statement. Table 1 shows the different categories of stakeholders represented in the study. All respondents are kept anonymous, as it would not add value to the paper to specify the companies or agencies that were interviewed.

Table 1. Stakeholders participating in interviews and workshops.

Stakeholder in the Battery Value Chain	Number of Interviewed Stakeholders
Battery manufacturers	1
OEMs	4
Energy storage suppliers involved in repurposing for second life	3
Energy companies	2
Recycling industries	2
Government agencies	2
Other experts	2

First, several interviews were strategically planned to include actors in different parts of the value chain, which was mapped during the initial desk research. The respondents were asked what stakeholders they believed would be valuable to interview, and some of their suggestions were then contacted and interviewed. This process continued. Such "snowball sampling" was administered so that newfound aspects could be identified along the way. This may mean that some aspects are less explored than they ought to be, and others may not have appeared at all. Despite this potential limitation, the goal to interview stakeholders from all parts of the value chain and obtain a view of barriers and opportunities from each stakeholder, was reached. There is an emphasis on interviews with OEMs, as they manufacture and sell the EVs that the batteries in question come from and thus have an interest to participate in studies like this one. Finding battery manufacturers with time to spare for an interview about second life proved difficult, which is why only one interview could be conducted in that segment.

2.2. Workshops

Two workshops were conducted with interviewees. The idea behind the workshops was to find solutions to the barriers found in the interviews, to identify pathways to make the most of the potential of extended EV-battery life cycles, and to discuss strategies and business models to achieve circular value chains. The first workshop focused on further understanding the main barriers identified in the interviews. The second workshop was designed for problem-solving; categorizing the identified barriers, exploring relationships between the different categories, and identifying the most critical barriers. During the workshops, it became clear that rather than finding solutions, the barriers to second life and recycling needed to be explored further. By documenting the discussions among the stakeholders, the workshops provided material that complements the interviews with regard to barriers to a more circular value chain, relationships between stakeholders, and views on legislation.

2.3. Data Analysis

The material from the interviews and the workshops were analyzed using content analysis. First, recurring categories were identified: Battery design, business models, costs, collaboration, logistics, producer responsibility, safety, standardization. Then, these categories were explored with respect to the different points of view of the stakeholders. Thus, common perceptions of barriers and opportunities could be identified. This material was then analyzed from a business model perspective, using theory presented in the next section.

3. Opportunities and Barriers

3.1. Opportunities for Second Life

From our perspective, second life makes complete sense, if you can bring the cost right down and bring up the life [of the battery]. (Energy storage supplier)

3.1.1. Actors Who can Create Business Solutions

Second use of EV batteries is often seen as an opportunity to delay disposal and recycling, which currently present burdens for OEMs, as well as an opportunity to squeeze value out of existing resources. Today's low volumes mean that the possibilities of such a business are small, but in the next few years volumes of LIBs on the market are expected to increase greatly. According to an industry expert, EV OEMs will have what it takes to seize a big part of the expanding energy storage market. They have the knowledge of their batteries and the best chance of maintaining or reestablishing control of the LIBs in their EVs.

Recycling industries also see new opportunities, in making themselves natural intermediaries between the vehicle end-user or OEM and a second life for the battery. Recycling actors already receive end-of-life vehicles, shred, sort and sell materials, and have facilities and a large network of dismantlers that can manage disposal of EVs. In order for a second-life battery to be useful, it however needs some degree of repurposing. A number of third-party entrepreneurs are currently attempting to establish second-life battery businesses, with repurposing at the heart of their business models. Some energy storage suppliers also work with second-life batteries, refurbishing them for new applications.

3.1.2. Applications for Second-Life Batteries

The desk research and interviews show that there are several possible applications for second-life batteries, which are listed in Table 2. Using batteries to store renewable electricity is gaining interest, and there are several demonstration projects where second-life batteries are used for this application. Using batteries for power demand reduction, thus being able to reduce transmission capacity and costs, is another area of increasing interest.

Table 2. Possible applications for second-life batteries.

Application	Actors	Comments
Storage of solar or wind power	Households, property owners	Small or large scale, off-grid or grid-connected
Peak shaving	Industries	Reducing power demand
EV charging	Property owners, grid owners	Reducing power demand at time of charging
Increased grid capability and stability	Grid owners	Instead of installing larger cables, or to avoid fluctuation
Backup	Industries, property owners	In case of electricity loss
Electricity trading	Electricity companies	Having a battery farm for electricity trading
Vehicle propulsion	Vehicle manufacturers	E.g., ferries, forklifts

3.1.3. Benefits of a Second-Life Battery

A second-life battery has several benefits. Its extended life means that as much usefulness as possible is gained from a product that otherwise is rejected when 75–80% capacity remains. Studies show that capacity drops linearly down to 80% and then drops at a faster rate (e.g., ref. [47]). Some respondents emphasized that the battery might not be very useful after its first life in an EV, and several respondents commented on the uncertainty that surrounds the capacity drop after first life. Second life in a different application other than an EV has not been studied. Given that the battery is used under other circumstances, it could be useful for a long time.

> *When buying a battery from a manufacturer for a vehicle, one wants assurance that the battery performs well in that particular application. There are requirements for the manufacturer, of what performance is required of the cells. But then other things [than first life] are not studied. It would be interesting to perform tests and see what the battery can do after 75%, or 80% [capacity], as that is somewhat unknown. (OEM)*

A second-life battery can be considered a "good enough" product at a fair price for certain customers. For example, home storage of solar power produced in a household might require some charging during the day and some discharging in the evening. The requirements are very different from those of a vehicle, where the battery must also handle high power (In vehicles, requirements for high power rates and power bursts could also be met by supercapacitors [48–50]).

> *One of the major errors, I would say, is that the second usage company, they see it as if they get a bad product. / . . . / But it's not. For the usage that they need, it's a product that is OK, it's going to be cheaper than if they buy the 100% health, not used battery, and they just need to make their business around it. / . . . / Buying a 100% [capacity] battery for their usage would be an overkill, they would overpay. I think they will need to see it more as an opportunity to / . . . / find [what] that they need for the right price. (OEM)*

A second-life LIB might also be considered a safe product, as it is built for demanding conditions and has been tested thoroughly during its life in the vehicle. The repurposing process is demanding, as each cell needs to be controlled and the BMS needs to be set up to fit the battery's new surroundings and application, but then a second-life installation might actually be safer than batteries dedicated for home storage.

> *[When assembling electricity storage using second life], the battery pack is manufactured with extremely high quality and tested in the car for five, ten, fifteen years. [It] has worked really, really well. So you remove it [from the car], measure so you know that the pack is alright [for further use], and hopefully you have the BMS and temperature sensors and everything you need to keep it safe. Then you assemble [the storage installation] and put it in a quiet room that does not vibrate and where temperatures don't reach −40 or +85 degrees [Celsius]. That will be a very comfortable place for the battery compared to what it has experienced in the previous ten years. In this aspect, I believe that second-life batteries ought to be very, very safe to use in an electrical installation. (Government agency)*

3.2. Barriers to Second Life and Recycling

> *Without significant development we would struggle to see how [second-life batteries] could efficiently compete based on a number of factors e.g., warranty, reliability, service specification levels, cost per throughput / . . . / in a number of grid related applications. The battery market is in a state of flux and the actual [issue] of second life batteries (in volumes) [is] many years [in the future]. (Energy company)*

3.2.1. Technical Challenges

Despite the apparent reuse value remaining in the imminent piles of batteries, there are aspects that challenge the idea of reuse. EV LIBs are made by many different manufacturers with many different constructions, which include variations in number and type of cell, physical shape and chemistry. LIBs are not labelled with their specific chemistry, so neither third-party battery refurbishers nor recycling actors know which kind of LIBs they receive. In addition, each LIB has a tailored BMS which regulates critical functions of the battery. This means that large costs are often associated with repurposing. Standardization of diagnostics, health monitoring, packing and labeling could simplify the process, but as common standards could interfere with competition between manufacturers this is a sensitive issue.

Transport is another troublesome issue, as used LIBs can be considered to be hazardous waste. That means that transport is costly and highly regulated. Some logistics firms will not transport used LIBs, and air freight is not allowed at all. This is of course a problem for recycling as well as for second life. According to multiple respondents, transport is generally the most expensive part of battery recycling. This brings up the question of where markets are located - for EVs, for second-life solutions and for recycling. One respondent means that there might be a need for a global second-life LIB market, as for example there may be many EVs in Sweden but a low use for stationary electricity storage. The second-life batteries from Swedish EVs could be more valuable elsewhere.

3.2.2. Legislation to Ensure Recycling of LIBs

The European Union's Battery Directive [51] states that 50% of the weight of an EV LIB shall be recycled. According to the Swedish Environment Protection Agency, in Sweden that is obtained. However, current legislation does not create incentives for further recycling, which could be achieved for example by specifying recycling requirements.

> *Lithium, cobalt, nickel / . . . / are the important metals to recycle but the weight of them [is] just a fraction of the whole module, so there has to be an update on how to define / . . . / the demands on the recyclability of the batteries. (OEM)*

The actor that puts the battery on the market has producer responsibility, i.e., responsibility for providing a system for collection and recycling when the battery becomes waste. That responsibility can be transferred if the battery turns into a new product, with a new function or under a new brand. It is not always entirely clear which actor has the producer responsibility, and uncertainty about legal issues could discourage actors from engaging in second-life endeavors. In a workshop discussion with representatives from OEMs, recycling industry and the research community, legislation and responsibility were discussed as main issues to be clarified to stimulate more circular business models. Other respondents worry that EV batteries might be lost if given a second life—that with too many actors involved in the value chain, batteries might not end up in recycling at all.

3.2.3. Uncertainties

Despite the potential for second life to be a good fit for several applications that are less demanding than an EV, there is currently no market for second life. Partly, that is because EV sales have been low until recently. But according to respondents, it is also very much due to uncertainty about the future: which LIB chemistries will be used, what will new batteries cost, and how will second-life batteries perform in different applications?

Some respondents argue that it would be better to recycle used EV batteries directly, instead of giving them a second life. The rationale is that with the expected technology development, the raw material would be put to better use in a new battery.

> *It is a no-brainer, understanding that batteries need to return [to the manufacturer] for recycling of metals. (Battery manufacturer)*

However, due to uncertainty about future battery volumes and chemistries, investments in recycling processes are not easily accomplished. New battery chemistries are developed and produced, energy density is improving, and battery prices are falling. The cost and availability of different materials affect battery prices, but also the content of batteries. Resource concerns and recycling challenges depend on what materials are used. The cost of virgin-material batteries and the technological development affect the profitability of recycling and the demand for recycled material.

What I see, is that recycling companies are not prepared, at this point, to [make] large investments in technologies for recycling for example lithium until they see that the market prices, the commodity prices encourage that type of technology, because it's a very large investment. / . . . / The recycling industry is following, quite closely, the OEMs. No one is really willing to take the risk of developing a large-scale infrastructure or technology for a certain type of battery chemistry when the battery chemistries themselves are actually changing. So this is one of those Catch 22 situations, who is going to be the first to take the initiative. (OEM)

4. A Business Model Perspective on Second Life and Recycling

4.1. Barriers for Circular Business Models

Analyzing the challenges and barriers for second life and recycling of EV LIBs from a business model perspective, they can be categorized along three aggregate dimensions: Cognitive, organizational, and technological, as shown in Table 3.

Table 3. Overview of barriers to second life, in a business model perspective.

	Cognitive Barriers	Organizational Barriers	Technological Barriers
Second life	Lack of interest in second life applications that are conflicting with the existing business models.	Regulatory uncertainties in relation to producer responsibility and the definition of the product during the second life.	Lack of standardization beyond the cell level, and in module and pack levels.
	Not realizing the potential value in second use in the existing market(s).	Not investing in collection of existing batteries due to low volumes.	Lack of knowledge on the remaining capacity after first life.
		Lack of collaboration along the value chain.	
Recycling	Aligning investments with previous business models based on selling raw materials.	Risk of investment in large scale automated processes when future technology advancements are uncertain.	Variations in number and type of cell, physical shape and chemistry.

Cognitive barriers are related to decision makers being uncertain about how promising future business models centered on second life will be. They may be reluctant to invest in new business models that conflict with their up-and-running businesses due to potential mismatches with the company's long-term strategies. *Organizational barriers* are related to adaptations needed to support development and scaling of new business models that cannot be supported with existing resources and capabilities and which require new ways of working, new flow of resources, and information, new processes and structures, etcetera. *Technological barriers* are exogenous and are related to lack of standardization in design of new batteries beyond the cell level, which makes preparing them for second life and recycling costly and complex, and to the uncertainty of how they will perform after first life (with respect to capacity loss).

Several barriers are related to the cognitive and organizational dimensions rather than the technological dimension. This is an interesting finding, which stands in contrast with the current practical and research focus which highly attends to the technological dimensions and overlooks cognitive and organizational barriers in utilizing the technological advances. Understanding the relationships between different types of barriers, and whether certain barriers (e.g., technological) are antecedents to other types of barriers (e.g., organizational), is probably necessary in order to better understand how to achieve a circular EV battery value chain.

4.2. Four Business Model Scenarios

In the following section, four different scenarios to adopt circular economy principles for potential business models are conceptualized; see Figure 2 for an overview. These business models are different in relation to *customer value proposition* and the *value network* they require to function in [12]. The customer value proposition determines the positioning of companies in the market according to their customer segments, customer relationships, and distribution channels [31,52]. The value network defines the ways through which companies interact within their ecosystems and reorganize their own internal activities.

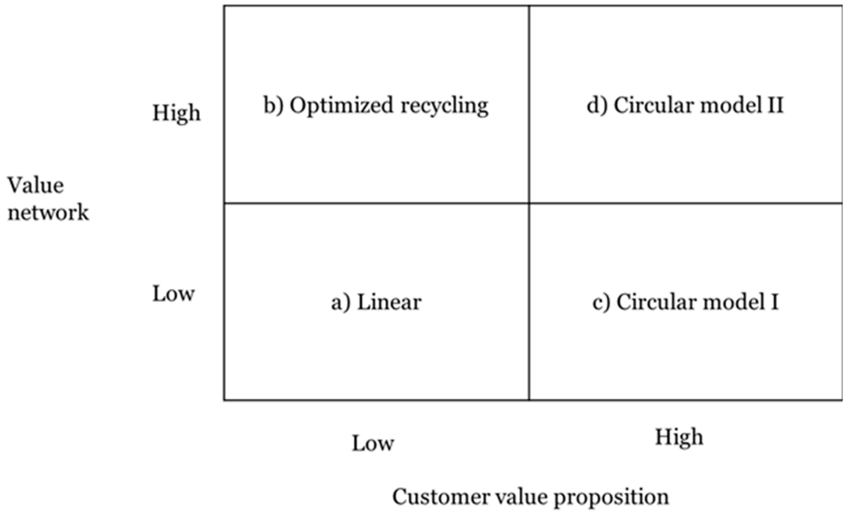

Figure 2. Four business model concepts.

(a) Linear model: Battery production and use in vehicle + currently practiced recycling

Model (a) is the closest to the situation as is today. The OEM uses customized modules and packs for the first use in their cars. The close partnerships that the OEM has with dismantlers allows them to collect almost all batteries for recycling after first use. Removal of the batteries from the EVs and unpacking (i.e., opening up the battery packs to separate the modules from other components and packing materials) can be performed by certified workshops certified by the OEM or by the dismantlers, before transport to recycling actors which perform recycling processes. Alternatively, the dismantler could simply be a collection point for the battery, before being transported to recycling actors which operate both unpacking and recycling processes.

(b) Optimized recycling: Battery production and use in vehicle + state of the art recycling

With close collaboration between the OEM and the recycling company, the recycling actor can collect removed batteries from the cars after their first use, from workshops or dismantlers. In this scenario the recycling company performs both unpacking and recycling in an automated process which allows handling of large volumes of batteries with different designs. Moving towards this scenario requires investments from the recycling actors in scalable and automated recycling processes. This is currently perceived to be of high uncertainty given that such processes need to match future battery designs and chemistries which are not yet well defined.

(c) Circular model I: Battery production and use in vehicle + repair and refurbishing for second use in vehicle in the same or a new market + state of the art recycling.

After the first use in a vehicle, diagnostics are performed by workshops or dismantlers, to decide whether the batteries are in good condition and have capacity for reuse in a car. The certified workshop, which is directly in communication with the OEM, performs refurbishment and repair of the battery which is then placed in a car in the same or a new market (e.g., with less intensive driving demands). Model (c) is already under test with an OEM that has fleet operators as their main customer segment. The OEM has a take-back system in place for collection of the cars after a period of use, refurbishment of the batteries and then putting the car in a market which requires less intensive driving for its second use.

(d) Circular model II: Battery production and use in vehicle + repackaging and second life in a different application + state of the art recycling

After the first use in a vehicle, an early diagnosis is performed by dismantlers to decide whether the batteries have capacity for reuse in a car, whether they are fit for refurbishment, repacking and transportation for use in second-life applications (e.g., home electricity storage), or if they should be recycled. Based on this decision the battery may enter different flows. This process can decrease handling and transportation costs by assuring that the batteries will end up in the right place after their first use. For a transition to a second life, the battery needs to be repacked and the BMS needs to be adjusted or even replaced, which are additional activities that need to be incorporated in the business model. Model (d) is currently under test by a new venture, which designs and manufactures smart energy storage systems for households. The company has recently started a partnership with an OEM to reuse their EV LIBs in home energy storage units. This partnership is estimated to reduce the production costs of home energy storage (as provided by this new venture) by 30%.

This last scenario, model (d), would require the highest degree of collaboration among the different stakeholders in the value network, including the OEM, dismantlers, recycling actors and second-life actors. A reflection from the second stakeholder workshop is that the greatest uncertainties around this scenario concern the product definition and how this may change during transition from first to second use. This is related to which legislation might apply. For instance, two EU directives may apply to a used EV LIB: The Battery Directive [51] and the End-of-life Vehicles Directive [53]. For successful collaborations, there should be no ambiguity of product definition and applicable legislation.

4.3. Future Knowledge Development

As the previous sections show, there are several barriers to second use of EV batteries and even to improved recycling processes. Some barriers are of a technological nature, others have to do with interpretation and application of legislation, and yet others are related to the many uncertainties regarding second life of EV batteries. The analysis shows that with regard to business models, it is clear that many of the barriers are organizational or cognitive. This implies that for circular business models to become a reality, the actors in the EV battery value chain are required to take active roles. For them to be able to do that, it seems that they need better information. Some questions that arise when trying to establish a circular value chain are:

- What is the value of a second-life battery?
- How does a used EV battery perform in different stationary applications?
- For how long can a second-life battery be expected to be useful?
- What is the value of recycled battery materials?
- How should legislation be interpreted throughout a circular value chain?
- How can it be made clear who has producer responsibility at different stages?
- What are the consequences of second life, with regard to ecological and social sustainability?

It is likely that actors need answers to these questions in order to establish a strategy for battery second life. This study has demonstrated that there is currently not enough knowledge for even hypothetical answers to be provided, so further research is required in several areas. There is a lot of ongoing research, for example in the area of technical improvement of recycling processes. However, that research needs to be connected to technical, organizational and economic perspectives on battery production and use, in order to capture which strategies might hold more value. There are also several ongoing second-life demonstration projects. Research should follow them closely in order to learn about the potential and difficulties of using EV batteries in different environments. For circular business models to gain popularity, actual data on the value and environmental and social benefits are likely required. Research that builds on this study and delves deeper into understanding what barriers exist for different circular business models could be beneficial for actors along the value chain who wish to explore opportunities related to second life. Furthermore, research needs to approach the application of different directives with regard to producer responsibility and the safety of battery handling. This study shows that uncertainty about how to interpret legal documents could discourage actors from exploring circular business models. Perhaps even more importantly, clear definitions of producer responsibility at any given time are vital for ensuring that a battery will end up in recycling no matter how many stakeholders have been involved in its value chain.

5. Concluding Remarks

There is potential for actors throughout the battery value chain to explore the use of EV batteries in second-life applications. Once the batteries reach end-of-life, there is also potential for recycling processes to salvage more materials than occurs today. Enhanced recycling could have rather big environmental benefits. The paper shows that some actors consider second-life EV LIBs as potentially safe products, with reasonable economic value, that fit the requirements of electricity storage for a wide range of actors. There are business opportunities all along the value chain: OEMs might benefit from selling the used battery to a second-life actor instead of paying for disposal; battery refurbishers might grow their businesses, adapting used EV LIBs for second life in other applications; energy storage providers might offer solutions with smaller ecological footprints; recyclers might use their expertise in collecting and dismantling as part of the process from first life to second, and to recycle sought-after metals.

Yet, there are several barriers to both second life and improved recycling. In this paper, barriers are characterized as cognitive, organizational or technological. There are the cognitive barriers of not being very interested in new business models, or not finding enough value in second-life solutions; the organizational barriers related to investment risks and legal issues; and the technological barriers of a general lack of design standards and uncertainty in capacity loss after first life. These barriers may be alleviated by collaboration between actors in different parts of the value chain, sharing their expertise and learning from others.

OEMs naturally optimize batteries for first life, not for use thereafter. However, if OEMs were to collaborate with battery refurbishers, second-life users and recyclers from the start, it might be possible to find ways to simplify the path to second life and recycling, to make transfer through the value chain less costly and to learn how and when second life adds value. By such collaborations, informal standardizations could develop. Collaborations might also make it easier for recyclers to predict future volumes of batteries and their chemistries. By including battery manufacturers in collaborations, requirements for recycled material to be used in battery production might be illuminated, thus possibly reducing the risk of investments in recycling processes. Collaborations throughout the value chain could likely simplify the issue of determining producer responsibility at different parts of the battery's life cycle, thus reducing the risk of batteries getting lost and not being recycled at end of life.

The recommendation for stakeholders is thus that they seek collaboration with other actors in the battery value chain, in order to be able to explore new business opportunities and develop new business models together. Moreover, for society to achieve goals related to battery reuse and recycling, stimulating collaboration in battery value chains could be a good complement to stimuli focused on technology development.

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