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Circular business models for lithium-ion batteries - Stakeholders, barriers, and drivers

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ABSTRACT

Business models for the circular economy, or circular business models, is a growing field of research applied in various industries. Global sustainability trends, such as electrification of the transport sector and increased energy consumption from renewable sources, have led to rapid growth in the number of batteries produced, especially lithium-ion based batteries. Sustainable lifetime management, including end-of-life, needs development to avoid social and environmental harm and potentially to recapture economic value as the use of these batteries increases. Current research primarily focuses on technical and economic issues based on recycling and the second use of batteries rather than circular business models. This study's purpose is to explore the circular business models, drivers, barriers, and stakeholders required to enable value recapturing. The Delphi panel method was applied to communicate with battery experts from various disciplines. The study's findings reveal that the favored circular business model includes several circular strategies. According to the expert panel, the most critical driver is national and international regulations and policies; the most critical barrier is financial viability; the most critical stakeholders are governments and vehicle manufacturers.

1. Introduction

Governments, institutions, businesses, and consumers need to join forces as the global society moves towards increased sustainability to achieve meaningful targets such as the United Nation's (UN) Sustainable Development Goals (SDG) (United Nations, 2015). Working towards achieving these goals represents an opportunity to implement the Circular Economy (CE) and transition towards low-carbon societies. This transition relies on increasing renewable energy production on the supply side and electrification on the demand side, especially within the transport sector. Electrifying the transport sector inevitably requires an increase in battery energy storage systems' production capacity to supply an increasing share of electric vehicles (EV) (Winslow et al., 2018; Zhang et al., 2018). In 2019, the total global electric vehicle (excluding two- and three-wheelers) stock was already above 7 million vehicles and is estimated to increase to nearly 140 million by 2030, which implies 7% of the total vehicle fleet (IEA, 2020). Lithium-ion batteries (LIB) are the most-used energy storage system in EVs due to their high energy and power densities (Opitz et al., 2017). The EV demand is largely expected to continue contributing to growth in LIB production (Winslow et al., 2018). However, the increased use of LIBs comes with several challenges. They are hazardous, and their projected demand will increase the need for raw materials that may not be sustainably available. Hence, their increased use can cause environmental and social damage, and be economically challenging if not handled responsibly. CE implementation is critical to establish practicable, commercially viable, or financially profitable solutions in this field (Yang et al., 2021). Within a CE framework, for example, the second use of batteries can potentially reduce battery waste and contribute to future (renewable) energy storage needs (Ahmadi et al., 2014; European Commission, 2019; Kamath et al., 2020a). Implementing second use batteries and improving recycling rates will require overcoming economic and technical barriers. Companies can overcome these barriers by adopting Circular Business Models (CBM) and implementing circular strategies, such as second use, as part of their core business activities.

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Abbreviations

CBM Circular Business Model (–)
CE Circular Economy (–)
EOL End-of-Life (–)
EV Electric Vehicle (–)
LIB Lithium-ion Battery (–)
RQ Research Question (–)
SDG Sustainable Development Goal (–)
UN United Nations

Recent academic literature focuses on economic and technical studies of second use LIBs (Beverungen et al., 2017; Heymans et al., 2014; Martinez-Laserna et al., 2018) rather than on CBMs. Adopting a business model perspective would help us better understand how to enable an economically viable, circular use of batteries. Research on CBMs for LIBs is scarce and has relied on literature reviews and multiple-case studies (Jiao and Evans, 2016; Olsson et al., 2018; Reinhardt et al., 2020). As second use and recycling of EV LIBs have not reached industrial scale, these studies typically report from pilot studies or simulations based on available information. For example, Swain (2018) developed a theoretical analysis that suggests combining two cost-effective and environmentally sustainable processes, such as reverse osmosis and lithium carbonate precipitation, to recover lithium from wastewater that derives from the LIB recycling industry. While these studies provide us with an idea of what the alternative CBMs may be (and their key characteristics), we know little about which CBMs are likely to succeed, for what reasons, and which stakeholders will play a role in that. The value chains of LIBs are complex, consisting of several activities and stakeholders. To enhance CBMs for LIBs, it is necessary to consider several aspects as most activities are interconnected (e.g., LIB design affect dismantling complexity and costs in EOL). Research mapping LIB experts' opinions on CBMs and three additional vital aspects to enhance circular economy practice is currently lacking despite the large volumes of batteries that will be retired from EVs.

Appropriate CBMs will be essential for battery second use and recycling to become economically feasible. Simultaneously, to enhance, drivers for CBMs need to be empowered. Currently, there are several barriers for CBMs (Guldmann and Huulgaard, 2020) that need to be solved to proceed. Several stakeholders need to cooperate to enhance the drivers and overcome the barriers to recover value from spent LIBs. Therefore, the following Research Questions (RQ):

RQ1: What are the circular business models that have the highest potential in the context of lithium-ion battery lifetime management?

RQ2: What are the main drivers to develop circular business models in the lithium-ion battery market?

RQ3: What are the main barriers to develop circular business models in the lithium-ion battery market?

RQ4: Which stakeholders are crucial in empowering the drivers and overcoming the barriers?

A novel Delphi study was performed to answer the research questions; several assessment options were ranked by an expert panel based on their potential. This study has unveiled the applicable circular business models, drivers, barriers, and stakeholders needed for sustainable LIB lifetime management.

2. Lithium-ion battery value chain

A battery pack used in an EV comprises several components: the casing, electrical components (e.g., battery management system, converters, switches, wires, and sensors), and individual battery modules and cells. The battery pack is disassembled and processed by a battery handler when an EV battery reaches 70–80% of its initial capacity (Faessler et al., 2019; Keeli and Sharma, 2012). The battery handler can assess if the battery is suitable for second use applications or if the battery should be sent for recycling. The second use case batteries are repurposed on the battery pack, module, or cell level in an energy storage system. Typical second use applications are stationary energy storage applications that are usually less demanding than mobile energy storage applications (Reinhardt et al., 2017). A second use battery can be used until it reaches 60% of its initial capacity before it is finally sent for recycling (Cicconi et al., 2012).

If LIBs are consumed in a second application before recycling, the product and associated resources are further exploited over time compared to direct recycling materials after first use. Such circular practice may reduce the production of new LIBs (Rallo et al., 2020) and be environmentally beneficial (Kamath et al., 2020b). Spent batteries may also be more economically viable for stationary energy storage systems; however, they depend on several factors such as battery degradation mechanisms (Casals et al., 2017) and future market characteristics. Fig. 1 illustrates the LIB value chain, including the second use.

In 2018, recycling businesses estimated that 97 000 tons of LIBs would need to be recycled globally; however, the forecast for 2025 already predicts four times this amount (Melin, 2018). LIB recycling typically involves separating the casing and electrical components, and decommissioning the battery pack to modules and/or cells (Gaines, 2014). Many of these fractions are exported to Asia for further processing (Brandslet, 2019). Industrial LIB recycling processes are generally inefficient because not all materials are currently recovered (Heelan et al., 2016).

Exposure and release of battery materials such as nickel and cobalt into the environment should be avoided due to their carcinogenic and mutagenic nature (Banza et al., 2009; Chagnes and Pospiech, 2013). Environmental mitigation through material EOL management is thus the main incentive for developing circular battery value chains at the moment (Pagliaro and Meneguzzo, 2019). Fortunately, the 2020 EU Circular Economy Action Plan has a stated goal of "boosting the circular potential of all batteries" (European Commission, 2020). Asian countries like Japan, South Korea, and especially China have designed regulatory frameworks for materials recovery, such as the Chinese Policy on recycling technology of electric vehicle power battery (Yang et al., 2021). These efforts illustrate the importance of evaluating battery value chains from a sustainability and transparency perspective to strive for circularity. The EU Action Plan encourages CBM designs for battery second

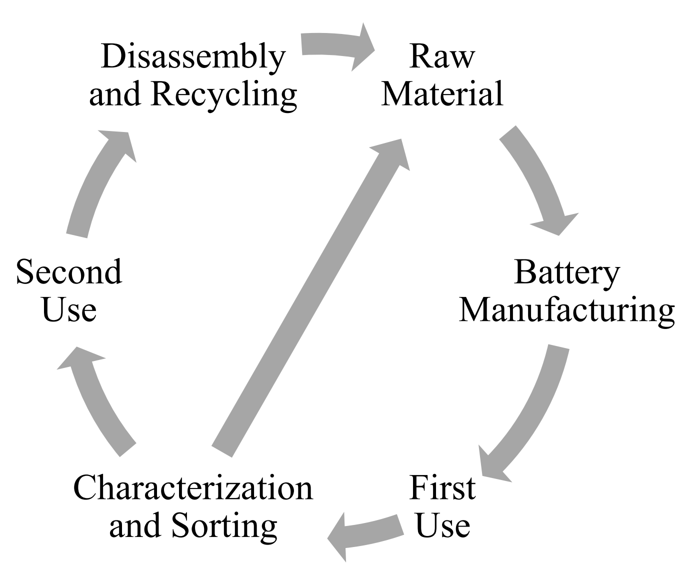

Fig. 1. Lithium-ion battery value chain of an electric vehicle including second use.

use, improved recycling practices, and ways to eliminate waste, emissions, and pollution in the value chain. Therefore, it is critical for the European and global battery markets to ensure that environmental and economic sustainability issues will be dealt with to push the battery market towards circularity (Bobba et al., 2018; Gaines, 2014; Melin, 2018).

3. Circular business models

The business model is an old concept (Drucker, 1954) revitalized during the last twenty years, catalyzed by the emergence of new technologies. Many authors have contributed to enriching this concept and have concluded that a business model's focus is on value creation, delivery, and value capture (Amit and Zott, 2001; Magretta, 2002; Shafer et al., 2005). From another perspective, BMs are links between new technologies and the market, being key to the diffusion and success of a technology (Chesbrough and Rosenbloom, 2002). Embedded in sustainable development, the discourse on CE adopted the business model concept. The CE aims to close the loops of materials and energy in biological and technical cycles to avoid exploiting raw materials, keeping the value of goods during their life cycle (Prieto-Sandoval et al., 2018). According to Salvador et al. (2020, p. 3) review, the CBMs are circular systems, economically viable (Bocken et al., 2016), regenerative in nature, which offer immediate solutions to immediate problems rather than sell products of permanent ownership (Antikainen and Valkokari, 2016). They intend to maintain resource value to the maximum, eliminating or reducing their leakage by closing, slowing, or narrowing their flows. Also, they argue that CBMs help reconcile resource efficiency with the creation of commercial value, capitalizing on both the environmental and economic value embedded in products (Bocken et al., 2016).

The innovation paths for CBMs have been presented through different typologies. Vermunt et al. (2019) identified four types of CBMs in terms of the 4Rs (reduce, reuse, recycle and recover) framework proposed in the EU Waste Framework Directive (European Commission, 2008; Kirchherr et al., 2018). These four models are 1) product-as-a-service, 2) product life extension, 3) resource recovery, and 4) circular supplies. Vermunt et al. (2019) reported that each model faces some barriers. The product-as-a-service model that focuses on leasing or performance models mainly faces organizational, financial, and market barriers. The product life extension model struggles with supply chain and market challenges, while the resource recovery model faces supply chain, market, and institutional barriers. The business models for circular supplies are mainly threatened by knowledge and technology, supply chain, and market barriers. A CBM can promote different loops: "closing loops, slowing loops, intensifying loops, narrowing loops and dematerializing loops" (Geissdoerfer et al., 2017). All contribute to a CE from an organizational level, and such a business model that creates value from waste is identified as a sustainable business model archetype (Bocken et al., 2014).

Olsson et al. (2018) proposed two types in the particular case of CBMs for electric vehicle batteries: 1) refurbishment after the first use, followed by second use in an EV in another market before final recycling, or 2) repackaging followed by second use in another application, followed by recycling. The study categorizes barriers to facilitating CBMs as technical, organizational, and cognitive. Several stakeholders in the battery value chain see the potential of second use for LIBs; however, a need exists to overcome the current challenges (Linder and Williander, 2017; Martinez-Laserna et al., 2018; Olsson et al., 2018). Three significant factors encourage businesses to seize these opportunities: battery ownership, inter-industry partnership, and policy support (Jiao and Evans, 2016).

4. Research methodology

The Delphi method is a systematic, anonymous, and iterative process for structuring a group communication process to obtain consensus between experts about a complex problem (Dalkey, 1969; Landeta, 1999; Linstone, Harold A. Turoff, 1975; Okoli and Pawlowski, 2004). It provides controlled feedback and a statistical response from the experts (Landeta, 1999). The response received guarantees the presence of each viewpoint in the result and reduces the pressure toward conformity. Several rounds (iterations) enable the experts to review their preliminary idea and understand the questions. Achieving a representative result by dynamic discussions requires 10 to 18 experts to respond (Okoli and Pawlowski, 2004).

The Delphi method comprised two online rounds. The second round was enhanced with opinions and consensus from multiple academics, practitioners, and CBM experts from different European and American countries. The panel was asked after the two rounds to provide additional comments regarding the responses in round two. The two online survey rounds were completed from March to April 2020, and the additional comments were collected in August 2020. The Delphi technique was chosen for three reasons. Firstly, this fast development phenomenon implies a high amount of knowledge exchange within the business ecosystems, which requires managerial resources. Secondly, the academic literature about CBMs for LIB EOL management is scarce; for example, a combined search in Web of Science about the topics "circular economy" AND "lithium" AND "business model*" yields only five papers, published from 2018 to (September) 2020. Finally, the Delphi panel method is suitable for research on framework development (Okoli and Pawlowski, 2004) to identify particular CBMs for the battery industry.

4.1. Expert recruitment and Delphi process

The Delphi panel was formed by contacting experts with profound knowledge via various channels and professional networks. The experts hold various professional backgrounds working in academia and businesses, with experience within sustainable transportation technologies, lithium- and traditional-batteries management, CBMs, and smart cities. The panel is also diverse in terms of demography, culture, and gender.

45 experts were invited to participate in the online Delphi panel. 21 participated in the first round, including men and women from different countries (Colombia, Finland, Italy, Mexico, Norway, Spain, and the USA). 9% were aged between 21 and 30 years, 30% between 31 and 40, 26% between 41 and 50, and 35% above 51 years. 44% had a master's degree and 38% a doctorate. 20 out of 21 experts confirmed they have more than five years of experience in LIBs and batteries, and nine have more than 20 years. 52% in the panel work in academies, research centers, and universities, 26% in business, 9% in governments and international institutions, 9% in non-governmental organizations, and 9% in other. In terms of profession, 44% identified as researchers, 26% managers, 18% consultants, 4% advisors, 4% engineers, and 4% professors. 12 of the experts finished the second round. The experts that responded to both rounds (12) have experience from Europe (11), South America (3), and North America (1). When establishing the expert list, the authors wanted a representative number to provide feedback. The surveys were sent to all experts listed and did not systematically exclude experts based on continent of origin to achieve equal share from Europe and America. The majority represents European expert opinions, as detailed in Table 1. The panel was additionally asked to provide comments completed by eight experts to justify some of the statistical responses. The Delphi process of this study is illustrated in Fig. 2.

LimeSurvey software was used to collect data in the two statistical rounds, and SurveyXact software was applied to gather the additional comments. These survey platforms were chosen because they allow for anonymous data collection, offer different question formats, provide automatic reports, and offer data security. After all, experts finished round one and two; a statistical report was provided showing the panel results, i.e., the mean of the group's ranking (Skulmoski et al., 2007).

Table 1
Second round experts' profile.

Expertise	Experience in Organizations	Experience in Countries	Level of Studies
Remanufacturing and recovery of lead and lithium-ion batteries, sustainable mobility	Rebattery, ULMA, MUISU	Spain, France, Latin America	Master/ postgraduate
Circular economy expert, sustainable development, and life cycle assessment consultant in electronics, mining, and oil industries	Consultancy firms, Apple	Mexico, Ecuador	PhD
Environmental health scientist	Public environmental protection agencies and research centers	USA	PhD
Business models and technological innovation expert, senior researcher	Industrial research centers	Multiple countries in Europe	PhD
Chemistry and materials sciences, including research on low CO_2 battery recycling	Universities	Finland	PhD
Battery and renewable energy expert	Hitachi ABB Power Grids, Nissan Energy engineering team, Saft	Spain, France	Master/ postgraduate
Energy and water technologies, including research on autonomous demand side management of electric vehicles in a distribution grid	Universities and research centers	Germany, Austria	Master/ postgraduate
Energy management algorithms for thermal and electrical systems and components	Universities and research centers	Austria	PhD
Smart cities and sustainable mobility	Universities and public organizations	Norway	Master/ postgraduate
Battery and power electronics (UPS) technologies, applications, and business	Consultancy firms	Finland, Ireland	Master/ postgraduate
Sustainable supply chain development in the renewable energy sector, and high-end technology solutions	Universities	Spain	PhD
Strategy, business models design, digital transformation	Universities, research centers and consultancy firms	Spain and Colombia	PhD

4.2. Data collection structure and performance

In the first round, the panel chose between options based on existing literature and were encouraged to add options if the given ones were not sufficient. In the second round, the panel observed the results of the scores from the first round prior to choosing between the options for the second time – this time including the experts' added options. Information of the overall results and remarks was presented in the second round and for the additional comments to promote the consensus or encourage personal reflection about the group answer. However, a potential barrier to reaching consensus is if individuals are influenced by self-interest (Hussler et al., 2011).

The Delphi was structured into four assessment categories with the options presented in 2. The first assessment category is dedicated to evaluating the potential viability of four CBM proposals and investigating other business models that allow the recovery of LIBs. This category's options are based on the CBMs (product-as-a-service model, product life extension, resource recovery, and circular supplies) proposed by Vermunt et al. (2019). The second category focuses on identifying the drivers that will enhance the recovery of LIBs. For the third category, the panel was asked about the importance of barriers that hinder the recovery of LIBs. The fourth category evaluated the influence of stakeholders who can facilitate or hinder the development of CBMs in the context of LIBs. The structure presented to the expert panel in the first round is illustrated in Table 2.

The degree of importance of these categories was assessed on a Likert scale from one to six. Other questions were designed to obtain an extended explanation and justification of the experts' ranking (Tapio et al., 2011), which allows for equality of all answers (Okoli and Pawlowski, 2004).

5. Results and discussion

This chapter presents the Delphi panel study results from the two rounds and the additional expert comments. The results are sorted and presented according to the four assessment categories described in Section 4.2. The results show the average value of each component within these categories. The panel used additional terms interchangeably with "second use" and "second life". This Section uses "reuse" to describe the process of repurposing spent EV batteries in stationary applications to avoid replacing the experts' words. The term "remanufacture" refers to the process of restoring a discarded EV battery and is used to describe the reuse of batteries in the same application for both first and second use. The experts also used the term "electric car" interchangeably with EV.

5.1. Circular business models for lithium-ion batteries

The experts were asked to assess the potential of four CBMs in the first round based on the business model typology (product-as-a-service model, product life extension, resource recovery, and circular supplies) proposed by Vermunt et al. (2019). They were also asked to propose

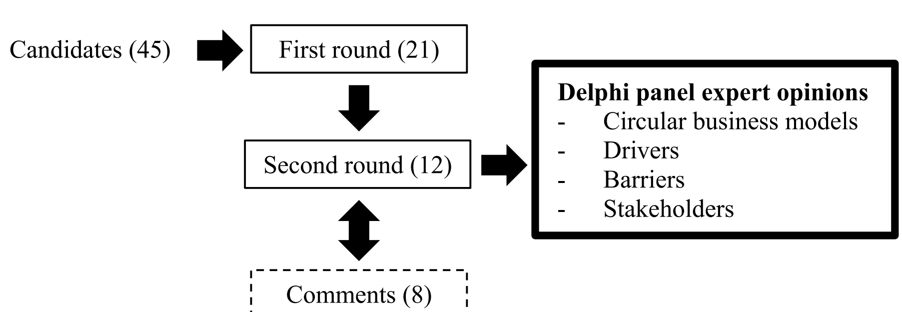

Fig. 2. The Delphi process including the number of experts participating in the surveys.

Table 2
Original Delphi panel structure prior to inputs from the expert panel.

Assessment category	Description and options	References
Circular business models for lithium-ion batteries	Potential of CBM to extend the use or recover the value from used lithium-ion batteries that have been discarded from EVs: • Product-as-a-service model • Product life extension by durable design, update services, remanufacture • Resource recovery of discarded materials • Circular supplies by using recyclable or biodegradable materials • Current circular practices for LIBs recovery in organizations and businesses (invitation for the panel to add)	(Merli and Preziosi, 2018; Nußholz, 2018; Vermunt et al., 2019)
Drivers for circular business models for lithium-ion batteries	Assessment and prioritization of drivers that encourage more efficient waste management of lithium-ion batteries: • National and international regulation and policies • Global difficulties in exploiting raw materials • Pollutant risk • Raw material availability • Second-hand material availability • Raw material production costs • Production and recovery technologies • Logistic and infrastructure development • Waste management costs • Potential applications of recycled products • Potential profits from repurposing or remanufacturing • Consumer behavior	(Balbuena and Wang, 2004; EYDE; NCE, 2019; Speirs and Contestabile, 2018; Yang et al., 2021)
Barriers for circular business models for lithium-ion batteries	Assessment and prioritization of barriers for recovering materials from lithium-ion batteries considering infrastructure, financial, legislation, technology, human talent, socio-cultural, and market barriers.	(Garcés-Ayerbe et al., 2019; Kirchherr et al., 2018; Ormazabal et al., 2018; Rizos et al., 2015; Vermunt et al., 2019; Yang et al., 2021)
Stakeholders for end-of-life management of lithium-ion batteries	Assessment and prioritization of stakeholders who may encourage the management of lithium-ion battery wastes: • Governments • Institutions • Research centers and universities • Car users and shoppers • Car producers • Public transport companies • Suppliers • Waste managers and recyclers	(Bocken et al., 2014; Del Río et al., 2016; Ellen MacArthur Foundation, 2015)

additional business models, which were added and ranked based on their potential in the second round. The majority of the proposed CBMs consisted of several EOL value chain activities, which indicate that a broader approach may be beneficial. Table 3 shows the average ranking rated by the experts from one to six based on the potential of each of the CBMs (1 means "no potential", 6 means "very high potential") and the associated standard deviations of the ranking.

More than half of the experts in the first round declared knowledge of organizations developing CBMs or technical applications to recover value from used LIBs. 13 experts out of 21 answered that they knew businesses reusing LIBs from EVs. Second use of LIBs and EV batteries is increasingly emphasized in research and at a regulatory level (European Commission, 2020b). 13 experts also responded that they are familiar with businesses, research centers, or any other organizations that improve the material sustainability of LIB components. Eight out of 21 confirmed that they are familiar with a business that offers battery performance as a service instead of battery ownership. Some experts indicate that ownership models should be designed for each application, dependent on, e.g., infrastructure and market characteristics. Martinez-Laserna et al. (2018) highlighted three potential EV battery ownership models: EV owner, EV manufacturer, or a third party. If one of the two latter owns the battery, there is likely a leasing agreement with the EV owner. Thus, contextual factors determine the ownership model.

As a result of the ranking, the most suitable business model, according to the experts, is "Remanufacture + reuse + recycle + waste management", comparable to a combined, flexible version of the two recognized CBMs by Olsson et al. (2018). The second was the "Product life extension by durable design, update services, remanufacture". These CBMs include several CE strategies (Blomsma et al., 2019) involving updating services and remanufacturing. Design for remanufacturing is recognized as an important effort and can include, for example, modular design, standard parts, and complexity reduction (Prendeville and Bocken, 2017).

The low standard deviation of the "Product life extension by durable design, update services, remanufacture" indicates a consensus among the experts on the importance of this CBM. However, the highest-ranked CBM shows more conflicting opinions regarding remanufacturing and reuse, which led to a higher standard deviation. The discrepancy is emphasized in the additional comments concerning the safety aspects of remanufacturing and reuse and the potential for economic viability. "Resource recovery of discarded materials" was ranked as the third-highest CBM, indicating that direct recycling is the most appropriate EOL path in some cases. However, new LIB recycling processes need to be commercialized to upscale the recovery of valuable materials more

Table 3
Circular business model potential to recapture value from spent lithium-ion batteries from electric vehicles.

Circular Business Model	Proposed by the Panel	Average Ranking	Standard Deviation
Remanufacture + reuse + recycle + waste management	X	5.08	1.11
Product life extension by durable design, update services, remanufacture		4.83	0.80
Resource recovery of discarded materials		4.67	0.94
Vertical integration of lithium-ion battery production + recycling	X	4.67	1.31
Product life extension + product as-a-service model to ensure that the product can be remanufactured after use	X	4.33	1.11
Product-as-a-service model		4.08	0.86
Circular supplies by using recyclable or biodegradable materials		4.00	1.00
Reuse without any upgrading process	X	4.00	1.47

efficiently to enhance the recycling system's economic viability (Heelan et al., 2016).

Two out of the four CBMs proposed by the expert panel were a combination of existing CBMs (Merli and Preziosi, 2018; Nuβholz, 2018; Vermunt et al., 2019). The other two proposed are new to the LIB context, although the "reuse without any upgrading process" did not receive high ranking. Similarly, Olsson et al. (2018) included refurbishment or repackaging for both CBMs for spent EV batteries. "Vertical integration of LIB production (+recycling)", however, is identified as a CBM with potential. This finding correlates with Jiao and Evans (2016) significant factor inter-industry partnership to encourage businesses to reuse EV batteries.

Answering the first research question, "*What are the circular business models that have the highest potential in the context of lithium-ion battery lifetime management?",* the circular business models with the highest potential are "Remanufacture + reuse + recycle + disposal", followed by "Product life extension by durable design, update services, remanufacture". Both include product life extension and reuse; however, the share of LIBs that will be reused or repurposed before recycling is uncertain. There are a few assumptions but no consensus. The following sections discuss the drivers and barriers that will affect this.

As a reaction to the need for knowledge concerning the global COVID-19 pandemic, the experts were additionally asked to consider the usefulness of LIBs during crisis and isolation scenarios. Table 4 shows the average ranking based on a rating scale from one to six based on the level of agreement (1 means "completely disagree", 6 means "completely agree").

Most experts agreed with the statement that "Reuse of lithium-ion batteries is an excellent choice in crisis and isolation scenarios". Back-up power systems for the hospital, telecom and military uses, and solar energy accumulation were suggested as potential applications. The panel further emphasized that the COVID-19 pandemic has slowed down public and shared transportation development and adoption. Public and shared transportation is generally seen to reduce the number of passenger vehicles and hence, as a possible counterforce to the growing demand for EVs.

5.2. Drivers for circular business models for lithium-ion batteries

Based on current research, twelve drivers for upscaling CBMs for LIBs were suggested to the panel. The experts were asked to assess the importance of each driver on a Likert scale from 1 to 6 (1 means "not important at all", 6 means "very important"). The experts proposed two additional drivers (Environmental values: saving this planet for next generations and Economic benefits). Table 5 shows the resulting average rankings and associated standard deviations.

The average rating and the standard deviation varied for some drivers. For example, most experts agreed on the importance of the driver "Raw material availability", whereas they disagreed on "Consumer behavior", reflected in the corresponding standard deviations. The significant variation can be explained by the different backgrounds and interests of the individual experts. Both organizational and individual values may affect responses (Hussler et al., 2011). The panel stressed that regulations, policies, and economic factors are the main drivers for all circular practices, such as reuse and recycling. Experts are concerned about LIB-appropriate waste management systems because they are in different development stages in different countries. However, if partnerships abroad are established, spent batteries can be exported to countries with appropriate waste management systems, although costs will increase. The panel agreed that it is challenging to rank the most important driver because several are critical to successfully establishing CBMs.

Table 4
Reuse of lithium-ion batteries in crisis and isolation scenarios.

The relevance of reuse in crisis scenarios	Average Ranking	Standard Deviation
Reuse of lithium-ion batteries is an excellent choice in crisis and isolation scenarios	4.67	0.94

Table 5
Drivers for circular business models of lithium-ion batteries.

Drivers for Circular Business Models	Proposed by the Panel	Average Ranking	Standard Deviation
National and international regulation and policies		5.58	0.76
Economic benefits	X	5.25	0.60
Potential profits from reuse or remanufacturing		5.17	0.55
Raw material availability		5.08	0.49
Raw material production costs		5.08	0.64
Production and recovery technologies		5.08	1.32
Global difficulties in exploiting raw materials		5.00	0.41
Second-hand material availability		4.75	1.09
Logistic and infrastructure development		4.75	1.23
Waste management costs		4.58	0.86
Potential applications of recycled products		4.58	1.11
Environmental Values: saving this planet for next generations	X	4.00	1.35
Pollutant risk		3.92	1.04
Consumer behavior		3.83	1.46

A strong consensus agreed that the most important driver is "National and international regulation and policies". This implies that governments and institutions can incentivize businesses and consumers to adapt to CBMs. The panel emphasized that appropriate regulations and policies are required at national and international levels to commercialize the reuse of LIBs (Jiao and Evans, 2016). Furthermore, the experts proposed the following policymaking focus: obligatory recycling with clear responsibilities across the value chain, targets for collection, research on potential economic benefits, and logistics and infrastructure development.

One expert proposed the "Economic benefits" driver in the first round, and it gained prominence in the following round as the second most important driver. Economic drivers for CBMs are internal drivers such as revenue growth from recovering value, and additional opportunities for innovation in the organization (Mont et al., 2017). An interesting comment was made regarding reuse practice by the automotive industry. The expert argued that reuse is currently driven by the lack of alternative EOL treatments, not by economic viability. The driver "Consumer behavior" was ranked the lowest, which implies that consumers have limited power and knowledge to drive CBMs. Consumer preferences is a part of external market pressures on businesses (Mont et al., 2017).

In comparison with drivers identified in CE research in general,de Jesus (2018) found that the drivers most frequently mentioned in academic literature is 1) economic/financial/market; 2) institutional/regulatory; 3) social/cultural; and 4) technical. Applying these categories in our context, the authors found that for CBM for LIBs, the following is ranked as the most important: 1) institutional/regulatory; 2) economic/financial/market; 3) technical; and 4) social/cultural. The difference points at the importance of the context when choosing CBM and the special context of the LIB as a technology and as an application.

Answering the second research question, "*What are the main drivers to develop circular business models in the lithium-ion battery market?",* "National and international regulation and policies" followed by "Economic benefits" are considered the main drivers for developing CBMs in the LIB market. However, several drivers were highly ranked based on their importance. The findings imply that a high uncertainty exists about which CBM(s) will be upscaled because several factors will affect future success. Battery price was raised as something that could determine if a battery is remanufactured, reused, or recycled. The issue concerns a second use LIBs potential to compete with the continually decreased price of a new battery (Martinez-Laserna et al., 2018; Zhang et al., 2020). Raw material availability and production costs will be cooperating factors, as the expert panel proposed. Nevertheless, retired LIBs require circular business models to outcompete primary-produced batteries.

5.3. Barriers for circular business models for lithium-ion batteries

Some barriers prevent a circular practice, such as enabling commercial repurposing of spent EV batteries. Seven barriers were proposed to the panel, based on current research. They were subsequently assessed for their significance on a Likert scale from 1 to 6 (1 means "not important at all", 6 means "very important"). One additional barrier, proposed by the experts in the first round, was added (Transportation cost of hazardous materials) to the second-round ranking. Table 6 shows the resulting average rankings and associated standard deviations.

The experts stress that similar to the drivers' findings, most barriers are linked; therefore, identifying a sole dominant barrier is not expected to occur. The highest-rated barrier was "Financial", reflecting challenges such as incentives and financial viability. The uncertainty of the profitability is also recognized by existing research, illustrating sensitivity to second use LIB price, battery aging (lifetime), discount rate, and efficiency (Kamath et al., 2020a; Rallo et al., 2020). "Technology" was ranked as the second most important and includes safety concerns, indicated in the additional comments. The experts additionally expressed that a legal framework would support a transparent and predictable market. Barriers related to "Socio-cultural" and "Human talent" are rated lower. No consensus exists regarding "Human talent" - if the people's skills and knowledge on circular practice on batteries are already available today. One expert pointed out that this talent will be available when needed; in contrast, another argued that it should be developed today.

Guldmann and Huulgaard (2020) found that most CBM innovation barriers were at the organizational level in their multiple-case study. In contrast, the barriers ranked the highest by the Delphi panel experts are at the market and institutional- or value chain levels. The barriers at the employee and organizational level (human talent and socio-cultural) are ranked the lowest. "Financial", however, is related to several levels. This comparison indicates that circular practice of LIBs mainly requires system-level innovation and change to overcome current barriers.

Answering the third research question, "*What are the main barriers to develop circular business models in the lithium-ion battery market?",* "Financial" followed by "Technology" are considered the main barriers to developing CBMs in the LIB market. The experts highlighted the importance of considering remanufacturing or refurbishing processes to technically enable the LIB to meet customer needs in the second use application (e.g., establish a new battery management system). This is also reflected in the "remanufacture" activity included in the preferred CBM.

Table 6
Barriers importance for circular business models of lithium-ion batteries.

Barriers for Circular Business Models	Proposed by the Panel	Average Ranking	Standard Deviation
Financial		5.42	0.65
Technology		4.92	1.19
Lack of technical standards		4.58	0.86
Infrastructure		4.58	1.11
Transportation cost of hazardous materials	X	4.50	0.87
Market		4.42	1.38
Legislation		4.33	1.03
Human talent		3.42	1.32
Socio-cultural		2.83	0.69

5.4. Stakeholders for end-of-life management of lithium-ion batteries

Several stakeholders must cooperate to recover value from spent lithium-ion batteries, a practice that is applicable in a broader circular economy context (Parida et al., 2019). The experts assessed and ranked the relevant stakeholders on a Likert scale from 1 to 6 (1 means "not important at all", 6 means "very important") in this section. The panel suggested two additional stakeholders during the first round (Battery cell manufacturers and raw material producers, and Renewable energy companies).

Table 7 shows the resulting average rankings and associated standard deviations.

The ranking showed that the most important stakeholders for LIB EOL management are governments and battery-related businesses because they develop applicable standards and regulations and have crucial knowledge for optimal battery waste management.

Overall, "Governments" are considered the most important stakeholder, followed by "Car producers". The panel argues that these two stakeholders must collaborate to steer EOL management by introducing appropriate regulations. One comment was related to the EU Battery Directive regarding its importance for incorporating circular economy principles, eco-design, the economic impact on companies, and potential job creation. The following regulative tools were suggested: standardization with strict requirements, taxes, tax reduction in the initial phase, binding collection, recycling targets with sanctions, legislation for reuse of LIBs, and innovation support. One expert argued that the focus should be on studying the economic potential to reduce governmental efforts. "Waste managers and recyclers", as well as "Battery cell manufacturers and raw material producers", are highly ranked due to their knowledge that is needed to develop battery standards for practices such as improved recycling. "Car users and shoppers" was the lowest-ranked stakeholder and was not considered critical to EOL management. The experts stated that most consumers focus on the market battery price rather than on the quality or potentially hazardous materials a battery contains. According to one expert, some consumers are likely to purchase a battery for reuse or remanufacturing if the technical standard is guaranteed.

The panel agreed that cooperation among the different stakeholders is required. Earlier research illustrates that existing partnerships and dependencies can hinder new (circular) practice (Boons and Lüdeke--Freund, 2013) if a traditional, linear approach exists within the stakeholder network. Several stakeholders need to collaborate to manage a circular practice (Mont et al., 2017).

The panel was asked for final comments about who should be managing the LIB collection; the experts suggested professional logistics companies, recyclers, and manufacturers because they have the

Table 7
Stakeholders' importance for lithium-ion batteries' end-of-life management.

Stakeholders	Proposed by the Panel	Average Ranking	Standard Deviation
Governments		5.77	0.42
Car producers		5.17	0.80
Battery cell manufacturers and raw material producers	X	5.08	1.04
Waste managers and recyclers		5.08	1.04
Research centers and universities		4.42	0.95
Suppliers		4.33	0.85
Industrial/business associations and clusters		3.92	1.26
Institutions		3.75	1.09
Renewable energy companies	X	3.58	1.38
Public transport companies		3.50	1.04
Car users and shoppers		3.00	1.15

appropriate knowledge and can meet high environmental standards. Furthermore, these stakeholders are more capable of generating economically viable businesses due to high battery volumes.

Answering the fourth research question, "*Which stakeholders are crucial in empowering the drivers and overcoming the barriers?",* "Governments" followed by "Car producers" are interpreted as the most important stakeholders to empower the drivers and overcome the barriers mainly due to the regulative tools' importance to upscaling circular business models.

6. Conclusion

The Delphi study method was used to identify circular business models for spent lithium-ion batteries, along with the key drivers, barriers, and stakeholders to consider. The invited expert panel shared valuable experience and knowledge. Findings map vital aspects to better cope with the complexity of circular economy for lithium-ion batteries. This rapidly changing phenomenon requires clarity, supporting policies, and context-sensitive business activities. Appropriate waste management systems, including logistics and infrastructure development, must be adapted to recover the valuable materials incorporated in batteries as their volume increases.

6.1. Theoretical contributions

Circular business models are vital parts of the circular economy framework to enable economically viable recapturing of value. This study proposes context-adapted, circular business models and ranks them based on their potential for feasible lifetime management of spent lithium-ion batteries. Previously, Olsson et al. (2018) identified two circular business models for spent electric vehicle batteries (such as lithium-ion batteries) through interviews. This study ranks several circular business models and unveil the most important drivers, barriers, and stakeholders for upscaling circular business models through the Delphi panel method. The results support Jiao and Evans (2016) three important factors to encourage businesses to invest in second use battery practice: inter-industry partnership, battery ownership, and policy support.

Circular business model research (Merli and Preziosi, 2018; Nuβholz, 2018; Vermunt et al., 2019) was applied to structure this Delphi panel study. Findings reveal, however, that it is beneficial to combine circular business models for spent lithium-ion batteries. Furthermore, which circular business model(s) will have the most success depends on market characteristics, infrastructure, involved stakeholders, and regulatory involvement.

Drivers and barriers identified in earlier work were appropriate to apply in the context of this study. Applying Guldmann and Huulgaard (2020) categories of barriers for circular business models innovation, the market and institutional- and value chain level barriers are currently ranked the most important for spent lithium-ion batteries. Additionally, Guldmann and Huulgaard's (2020) other two categories, organizational and employee barriers, heavily depend on the market and institutional- and value chain level barriers. Hence the importance of system-level change and stakeholder cooperation is crucial to overcome the barriers of CBMs for LIBs.

6.2. Managerial and policy implications

Circular business models can facilitate organizations to recapture economic value from spent lithium-ion batteries while potentially reducing environmental impacts. The three with the highest potential to recover economic value from lithium-ion batteries found are 1) Remanufacture + reuse + recycle + waste management (disposal), 2) Product life extension by durable design, update services, remanufacture, and 3) Resource recovery of discarded materials. It may be interesting for managers to compare their existing business models with these findings and to consider these options when they are about to start innovating their business models in a circular direction. Together with the panel, we found that it may be beneficial to hold a broader view of the circular business models, often involving several end-of-life value chain activities. Nevertheless, the most appropriate circular business model depends on the context. Our study still gives a better understanding of which contextual factors to look at (e.g., in terms of drivers and barriers). The results also indicated that raw material prices and availability may accelerate interest in applying particular circular business models, which is a crucial matter to consider for companies that have not yet seen an incentive to implement CBMs.

Results related to the drivers showed that national and international regulations and policies and economic benefits are the most critical to upscale circular business models. The most critical barriers are related to the financial aspects, technologies, and lack of technical standards. However, the panel commented that technological solutions for a lithium-ion battery circular economy could be found if the financial barriers are solved. Regarding stakeholders, governments and institutions were ranked the highest by the experts. Nevertheless, it is emphasized that managers who bring battery-containing products to the market should closely cooperate with them to develop regulations with clear responsibilities.

As regulations and economic factors are ranked the highest by the expert panel, this is a clear indication that currently, the circular economy practice of spent lithium-ion batteries needs development at a system level in parallel with the growth of spent battery volumes.

6.3. Limitations and further research

The presented study is a baseline study for circular business models for sustainable end-of-life management of spent lithium-ion batteries. Future research should focus on more in-depth analyses of the assessment categories presented, for example, by studying the value creation and capture in circular business models to upscale the remanufacturing and second use practices of lithium-ion batteries, including empirical data analysis. The rated results additionally require further investigations, such as specifying the regulations needed and assessing environmental sustainability.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author, [BW]. The data are not publicly available due to their containing information that could compromise the privacy of research participants.

CRediT authorship contribution statement

Benedikte Wrålsen: Investigation, Writing – original draft, Writing – review & editing, Project administration, Conceptualization. **Vanessa Prieto-Sandoval:** Methodology, Formal analysis, Writing – original draft, Conceptualization. **Andres Mejia-Villa:** Resources, Writing – review & editing, Visualization, Conceptualization. **Reyn O'Born:** Term, Project administration, Conceptualization. **Magnus Hellström:** Validation, Writing – review & editing, Conceptualization. **Bernhard Faessler:** Resources, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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