A Circular Economy in Electric Vehicle Batteries

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A European Perspective

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Abstract

Title: A Circular Economy in Electric Vehicle Batteries – A European Perspective

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Electrification of the automotive industry is an imperative for achieving the sustainability goals of various multilateral agreements. Battery electric vehicles (BEVs) have advantages over internal combustion engines, but lithium-ion batteries, the major component of the BEV powertrain, have significant environmental footprints. Circular economy concepts can mitigate these negative impacts and externalities via closed loop resource systems and second life applications for lifetime extension. The Circular Economy is still in its infancy, but regulation and moves towards decarbonization are strong drivers.

This thesis discusses how second life applications associated with the Circular Economy are hindered by technical and economic factors. They compete with closed loop ambitions of recycling activities and market opportunities in the energy storage area are immature. In particular, less than 20-30% of batteries will have a second life. According to experts, battery recycling may become more tenable as increasing numbers of spent batteries enter the market.

Scenario planning has shown that the prognosis for Circular Economy in electric vehicle batteries 5 to 10 years from now is optimistic. This scenario is characterized by the highest adoption of Circular Economy levels possible at this time. A consumer survey indicated that consumers fully support the transition to a Circular Economy and are not an impediment to this transition.

Keywords:
Circular Economy, Sustainability, Electrification, Automotive Industry, Battery Industry, Lithium-ion Battery, Scenario Planning

Sumário

Título: Uma Economia Circular em Baterias de Veículos Elétricos - Uma Perspetiva Europeia

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A eletrificação da indústria automóvel é um imperativo para atingir os objetivos de sustentabilidade de vários acordos multilaterais. Os veículos elétricos a bateria (BEV) têm vantagens sobre os motores de combustão interna, mas as baterias de iões de lítio, o principal componente do grupo motopropulsor BEV, têm pegadas ambientais consideráveis. Os conceitos de economia circular podem mitigar estes impactos negativos e externalidades através de sistemas de recursos de circuito fechado e aplicações de segunda vida para extensão da vida útil. A Economia Circular está ainda a dar os seus primeiros passos, mas a regulação e os movimentos no sentido da descarbonização são fortes impulsionadores.

Esta tese discute como as aplicações de segunda vida associadas à Economia Circular são dificultadas por fatores técnicos e económicos. Confrontam-se com as ambições de circularidade nas atividades de reciclagem e as oportunidades de mercado na área do armazenamento de energia são pouco desenvolvidas. Em particular, menos de 20-30% das baterias terão uma segunda vida útil. Segundo os peritos, a reciclagem de baterias pode tornar-se mais sustentável à medida que um número cada vez maior de baterias usadas entra no mercado.

O planeamento do cenário revelou que o prognóstico para a Economia Circular em baterias de veículos elétricos daqui a 5 a 10 anos é otimista. Este cenário é caracterizado pela maior adoção possível dos níveis da Economia Circular no presente momento. Um inquérito aos consumidores indicou que estes apoiam plenamente a transição para uma Economia Circular e não são um impedimento a esta transição.

Palavras-chave:
Economia Circular, Sustentabilidade, Eletrificação, Indústria Automóvel, Indústria de Bateria, Bateria de iões de lítio, Planeamento de Cenários

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I. List of Abbreviations

BEV	Battery Electric Vehicle
CE	Circular Economy
CRMs	Critical Raw Materials
EC	European Commission
EGD	European Green Deal
EMF	Ellen MacArthur Foundation
EoL	End-of-Life
ICE	Internal Combustion Engine
JRC	Joint Research Centre
LIB	Lithium-ion Battery
SDG	Sustainable Development Goals
SoH	State-of-Health
SRM	Secondary Raw Materials
WEF	World Economic Forum

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1. Introduction

Electrification of the mobility sector is a major contributor for achieving the goals of the Paris Agreement (WEF, 2019). To this end, the automotive industry is transitioning from the internal combustion engine to electrification of the powertrain and an estimated 60% of vehicles sold in 2030 in Europe will be electrified (Niese et al., 2020). Decarbonization of the automotive sector by the electrification of the powertrain is critical for EU CO2 reduction (DI Persio et al., 2020).

Lithium-ion battery technology is expected to be the dominant model for this decade (Armand et al., 2020; EEA, 2018). The EU is strongly dependent on imported raw materials like cobalt and lithium where the supply side is geographically concentrated and insecure (DI Persio et al., 2020). Additionally, the EV industry must manage the end of first life problem of batteries – from economic as well as environmental standpoints. As part of the European Green Deal (EDG) EU regulations have been updated regarding the battery life cycle to ensure that batteries "should be repurposed, remanufactured or recycled, feeding valuable materials back into the economy" (EC, 2020e).

A circular economy (CE) approach can help secure access to Secondary Raw Materials (SRM) and reducing carbon footprints of EVs (DI Persio et al., 2020). On a global level, a circular battery value chain could reduce emissions by 30%, creating 10 million new jobs and unleashing 150 billion euros of value until 2030 (WEF, 2019).

Electric vehicles CE in Europe is in its infancy with "limited […] information on the recycling of EV batteries [because] very few batteries have reached their end-of-life" yet (Drabik & Rizos, 2018, p. 15). The end-of-first-life (EoL) is when a battery has 70 to 80% of capacity left (Hill et al., 2019). In 2011, the first year of EV sales in Europe, only 20,000 EVs were sold compared to over 1.4 million in 2020 (IEA, 2021a). Given an average lifespan of 8 to 10 years, a critical mass of batteries has yet to reach EoL. Europe is projected to reach over 1.1 million EoL batteries in 2030, and over 2.5 million in 2035 (Drabik & Rizos, 2018).

Second-life applications expand the life cycle of the battery and reduce carbon footprints (DI Persio et al., 2020; Reinhardt et al., 2019). As second-life enables life extension, this is more environmentally sound than immediate recycling (Reinhardt et al., 2019; WEF, 2019). However, the economic attractiveness of use cases is uncertain (DI Persio et al., 2020; Niese et al., 2020). There are no regulations set yet but political stakeholders are aiming for a legal framework to facilitate second-life applications (Drabik & Rizos, 2018).

1.1. Academic & Managerial Relevance

Though some scholars argue for second-life applications since they extend battery life (Reinhardt et al., 2019), others stress technological challenges and lack of clear regulatory directives (Bobba et al., 2018). Although, major stakeholders like the European Commission seek a future CE approach, there is no clear setup. However, successful management of economic and environmental implications of electrified powertrains is critical for all CE stakeholders.

The current research gap warrants further academic study (Reinhardt et al., 2019). Furthermore, since development of second-life applications will also affect recycling, CE future scenarios will affect electric vehicles 5 to 10 years from now. This research will help stakeholders identify potential key factors influencing CE and its business models.

This thesis addresses the following research questions:

1) How will second-life applications for electric vehicle batteries likely play out within the framework of a Circular Economy?

2) What is the prognosis for a Circular Economy in electric vehicle batteries 5 to 10 years from now?

2. Literature Review

This section begins by reviewing literature on the automotive industry. Next, the concept of CE is described. Finally, a theoretical picture of CE in electric vehicle batteries will be discussed from a European perspective.

2.1 Automotive Industry

Europe's automotive industry is historically large and important. This sector accounts for roughly 7% of the EU's GDP and provides direct and indirect jobs to 13.8 million Europeans (EC, 2021a; McKinsey Center for Future Mobility, 2019). During the last decade, the automotive industry has faced significant changes. New market entrants, technological changes, regulatory policies, and shifting consumer behavior are causing structural changes (Ferràs-Hernández et al., 2017) with major trends captured by the acronym ACES: autonomous driving, connectivity, electrification, and shared mobility (Möller et al., 2019).

With respect to transformative ACES trends, automotive firms are urged to assess their future positioning (Möller et al., 2019). As Teece (2007) argues, achieving sustainable competitive advantages for a company demands dynamic capabilities to adapt and renew business models.

2.1.1 Electrification

Road transport accounts for 20% of EU's total carbon emission (ICCT, 2021). Electrification is a key phenomenon under the Paris Agreement, so the internal combustion engine (ICE) is becoming obsolete. The European Commission has several policies like the Regulation (EU) 2019/631, starting in 2021, which aims for 15% CO2 emissions reduction from 2025 onwards and 37.5% from 2030 (Regulation (EU) 2019/631, 2019).

In July 2021, the EU presented the "Fit for 55 package" to cut emissions by at least 55%[1] (previously 40%) by 2030 to achieve climate neutrality by 2050. In 2035, new cars must be emissions free (Fit for 55, 2021) and experts assume only EVs will conform to this requirement (ACEA, 2021). Automakers like Volkswagen already announced ending sales of ICEs in Europe by 2035 (Reuters, 2021b).

Since BEVs have no direct tailpipes, carbon footprints now pertain to the production phase (Aichberger & Jungmeier, 2020; Hill et al., 2020). Therefore, a lifecycle perspective best assesses production and use phases of BEVs (Hill et al., 2020) overing extraction of raw materials, manufacturing of components and vehicle assembly during life and end-of-life; and a Well-to-Well (WTW) analysis entails assessing fuel or electricity used to power the vehicle. WTW includes environmental impact of producing and distributing energy (WTT) and the environmental impact of driving (TTW) (Hill et al., 2020).

Based on WEF (2021) data, material emissions of a BEV can be 1.5 to 2 times higher than an ICE with battery production accounting for 40% of emissions.[2] Aichberger and Jungmeier (2020) found that GHG emissions from battery production to drive one km are an average of 20 g CO2-eq/km[3] for a 30 kWh battery pack[4]. The WEF and McKinsey (2020) posit that with higher numbers of EVs, production emissions as a proportion of lifecycle emissions will increase from 18% in 2020 to 35% in 2030 and 60% in 2050. Also, indirect emissions from

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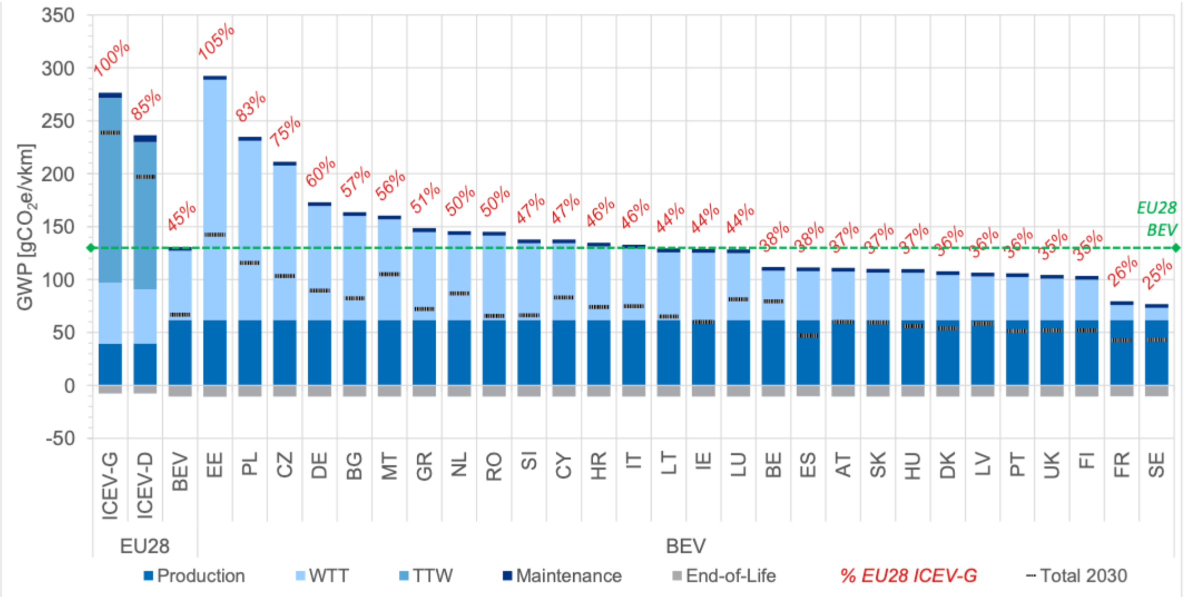
[1] Compared to 1990.
[2] See appendix A.
[3] 9 g CO2-eq/km in the Q25%-quantile (200,000 km) and 47 CO2-eq/km in the Q75%-quantile (150,000 km).
[4] Battery lifetime for the average value is 180,000 km.

electricity generation depend significantly on energy sources (Aichberger & Jungmeier, 2020; Hill et al., 2020).



Notes: Results shown for the lower medium car in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years. 2020 BEV battery of 58 kWh, with 300km WLTP range (and with 64 kWh and 460 km WLTP electric range for 2030); an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for BEVs.

Figure 1: Comparison of lifecycle GWP impacts of ICEs and BEVs
(Hill et al., 2020, p. 9)

The vehicular landscape can be divided into five categories: i) battery electric vehicles (BEVs) entirely powered by an electric motor and an on-board battery; ii) Plug-in hybrid electric vehicles (PEHVs) powered together or separately by an electric motor and an ICE; iii) Range extended electric vehicles (REEVs) where a combustion engine is used to power or recharge the electric motor; iv) Hybrid electric vehicles (HEVs) combining ICE and an electric motor that assists the conventional engine; v) Fuel cell electric vehicles (FCEVs) entirely propelled by electricity which is provided by a fuel cell stack that uses hydrogen (EEA, 2018).

The BEV powertrain[5] accounts for about 50% of a vehicle's value while the battery pack constitutes over 70%. In comparison, an ICE powertrain makes up 20% of the vehicle's value (Cornet et al., 2019). Moreover, a BEV consists of only 200 parts while an ICE has about 1400. This is an 86% reduction in parts (Erich & Witteveen, 2017). Thus, the battery pack is the most important component of a BEV from an economic and engineering perspective. The different setups of BEVs to ICEs can be found in appendix B.

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[5] Assuming a 50 kWh battery.

Globally, sales of EVs will jump from 3.1 million in 2020 to 8.5-13 million in 2025 and 26 million units in 2030 (BloombergNEF, 2021; IEA, 2021a). The total size of the global EV fleet is projected to increase from 11 million in 2020 to 116 million (BloombergNEF, 2021) to 125 million (IEA, 2021a) by 2030. The IEA projection considers the impact of existing and announced policies (figure 2). Europe is the fastest growing market, annual new EV[6] registrations reached almost 1.4 million which accounts for a market share of 10% and have more than doubled compared to 2019 (EEA, 2020; IEA, 2021a). Recent analyses outline that EV sales are increasing faster than expected due strict government mandates as well as purchasing incentives. According to EY (2021), the tipping point in Europe could be reached in 2028. Volvo and Ford will only sell EVs from 2030 in Europe, Volkswagen aims for 70% and Daimler for 50% sales of EVs in 2030 (IEA, 2021a).[7]

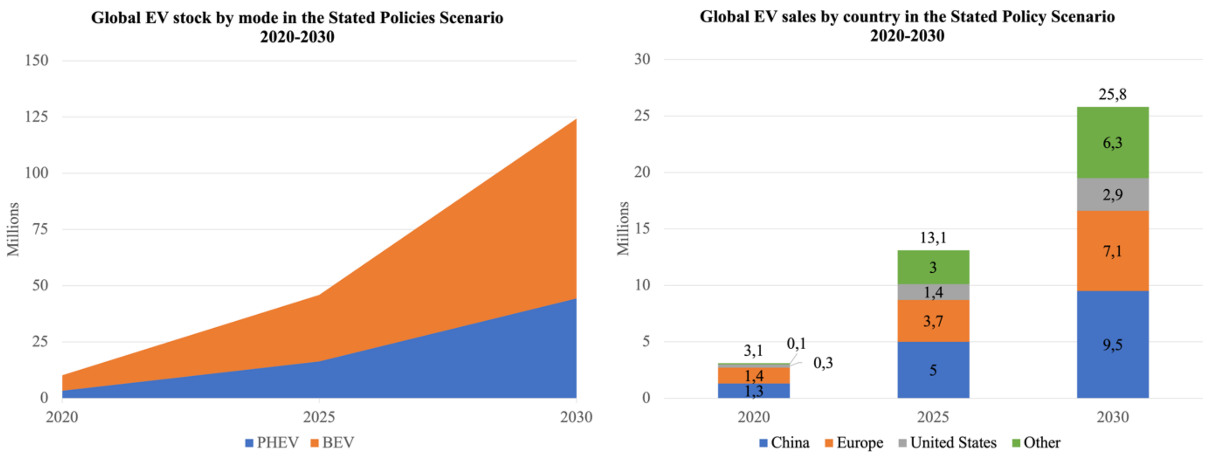

Figure 2: Global EV stock and sales 2020-2030
(own illustration based on IEA, 2021a)

2.1.2 Battery value chain and lithium-ion battery technology

Advances in traction battery technology are accelerating development of EVs (Deng et al., 2020). Within different battery technologies, lithium-ion batteries (LIBs) have become the dominant model (Azevedo et al., 2018; Deng et al., 2020; WEF, 2019). Key resources for this are aluminum, cobalt, copper, graphite, manganese, nickel, and lithium. Cobalt, graphite and lithium are categorized as critical raw materials (CRMs) by the EU (EC, 2020a, 2020c) having high economic importance while also being vulnerable to supply disruptions (European Commission, 2017; Helbig et al., 2018). With demand increasing, this creates challenges since

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[6] BEVs and PHEVs.
[7] See appendix C.

resources are concentrated in specific geographies like the DRC (50% of global cobalt mine reserves) and Chile, Argentina, Australia, and China (99% of global lithium reserves) (EC, 2020a; WEF, 2019). Social risks like hazardous working conditions are also a concern in the DRC's mining industry (WEF, 2019).

Battery value chain

The battery value chain starts with mining and refining of raw and processed materials. Manufacturing processes concerning the cell and the battery pack are part of the production process. When the battery reaches end-of-life, it is recycled to recover metals and aspects of its chemistry (Hill et al., 2019).

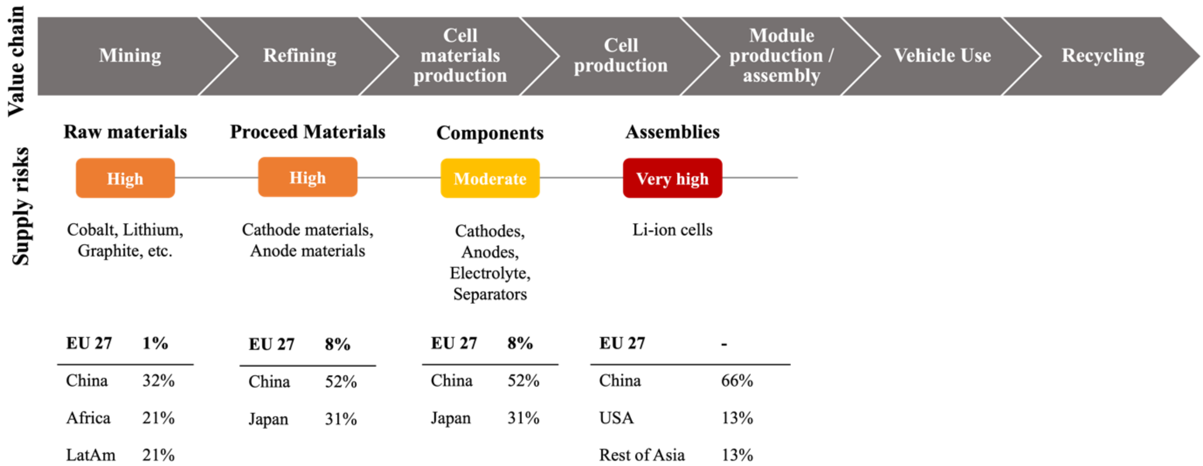

Figure 3: Battery value chain and supply risks
(own illustration based on EC, 2020a; Lebedeva et al., 2016; Niese et al., 2020)

Global cell manufacturing capacity in 2020 was 500 GWh; 73% was in China, 13% in the rest of Asia, and 5.4% in Europe. As the market grows to up to 3,000 GWh by 2030, Europe's share increases to 17% (~500 GWh) and China and the rest of Asia's market share shrinks to 67 (~2000 GWh) and 4% (120 GWh) respectively (EC, 2020b; Moores, 2021). Asian companies are a strong presence in the European battery manufacturing market: 4 out of 5 cells for the top 5 EV models 2020[8] sold in Europe were produced by Asian manufactures in Europe. All cathodes are produced in China, South Korea, or Japan (Mathieu, 2021).

Lithium-ion batteries

The main components of an EV battery are the cell, the module, and the pack. Starting from the bottom up, the battery cell is the smallest unit. The battery module is a battery assembly in a

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[8] Renault ZOE, Tesla Model 3 (cell from USA), VW ID.3, Hyundai Kona, Audi e-tron.

frame which combines a fixed number of cells. The module protects the cells from external shocks, heat, or vibration. A battery pack is the whole battery system installed in an EV. It consists of modules and a battery management system (BMS) with software for controlling and cooling (SAMSUNG SDI, 2021). The average capacity of LIBs was 42 kWh in 2017 and it is expected to double to 86 kWh in 2030 (Baars et al., 2021).

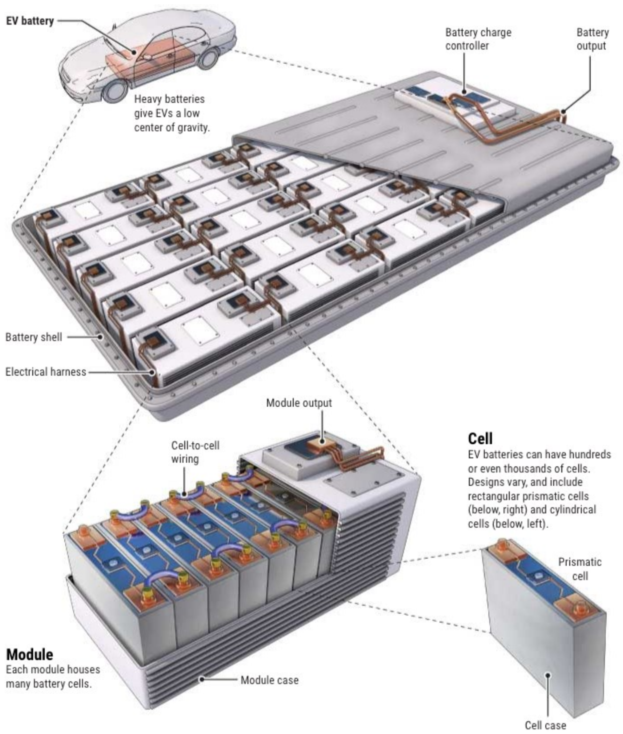

Figure 4: EV battery - from cell to pack
(modified from Morse, 2021, p. 780)

Battery cell

The battery cell is one of the costliest elements due to the high proportion of valuable materials and energy intensive production (Dai et al., 2019). The battery cell contains three main parts: a cathode, an anode, and a liquid electrolyte.

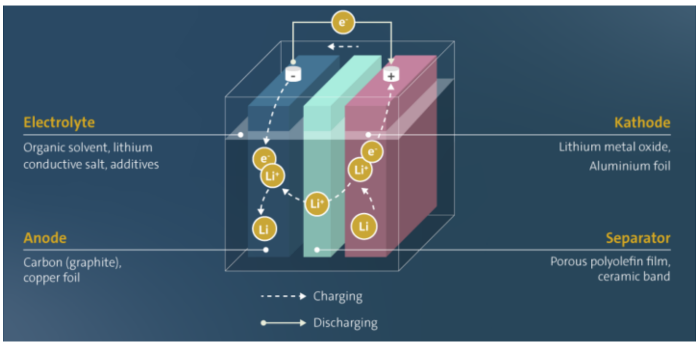

Figure 5: Lithium-ion battery cell
(Volkswagen AG, 2019)

The cathode is the most expensive component in a cell. Cathode materials compromise at least 60% of the total costs of cathodes as it contains the most valuable materials - lithium, cobalt and nickel (Diekmann et al., 2017; Shabbir et al., 2018; Wentker et al., 2019). Within the anode, copper and graphite are used as primary materials (Diekmann et al., 2017).

Figure 6 illustrates the general composition of a lithium-ion battery which can vary with different battery types.

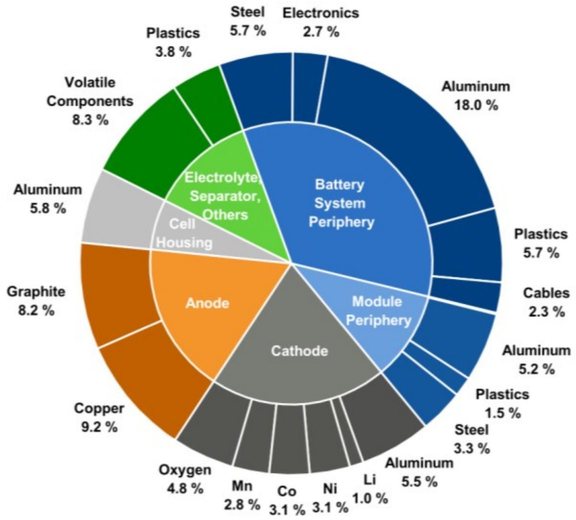

Figure 6: Generic composition of lithium-ion batteries
(Diekmann et al., 2017, p. A6185)

Battery chemistry

The three main types of lithium-ion cells are nickel-cobalt-aluminum (NCA), lithium-iron-phosphate (LFP), and nickel-manganese-cobalt (NMC). There are also lesser-used lithium-manganese-oxide (LMO) batteries (Ding et al., 2019). NMC and NCA batteries are typically nickel rich and include cobalt (Ding et al., 2019). Appendix E and F provide an overview of metal compositions and performance attributes.

NMC batteries accounted for around 80% global market share in 2020 and may rise to 90% by 2030 (acatech et al., 2020; Faraday, 2020). However, relatively dated LFP batteries are facing upwind due to technological improvements that diminish this outlook. LFPs find place in low-cost entry models while NMCs are used in longer-range models (McKinsey, 2021; Reuters, 2021a). This follows the trend towards low-cobalt and nickel-rich batteries such as NMC 811[9] (Armand et al., 2020; Chen et al., 2019; Ding et al., 2019). Moreover, advanced technologies

[9] Stoichiometric ratio of the composition: NMC 811 = 80% nickel, 10% manganese, 10% cobalt.

like solid-state (SSB), lithium-sulfur (Li-S), and lithium-air (Li-Air) batteries have received considerable attention (Aurbach et al., 2016; Ding et al., 2019; Randau et al., 2020).[10] Li-S and Li-Air batteries would reduce the dependency on cobalt and nickel (Xu et al., 2020). However, these technologies are at lab scale (Duffner et al., 2021; Janek & Zeier, 2016) compared to large-scale production of LIBs and investments in further plants (Duffner et al., 2020; Mauler et al., 2021). Sodium-ion cells could be another cheaper and less toxic technology (Vaalma et al., 2018) but there is low likelihood of commercialization within this decade (Baars et al., 2021). According to Armand et al. (2020, p. 16) LIBs remain the battery technology for the "near- to mid-term future".

Supply and demand of materials

With demand for vehicles and batteries rising, the WEF and McKinsey (2019) predict GWh for batteries in Europe will increase over 3.5 times between 2018 and 2030.

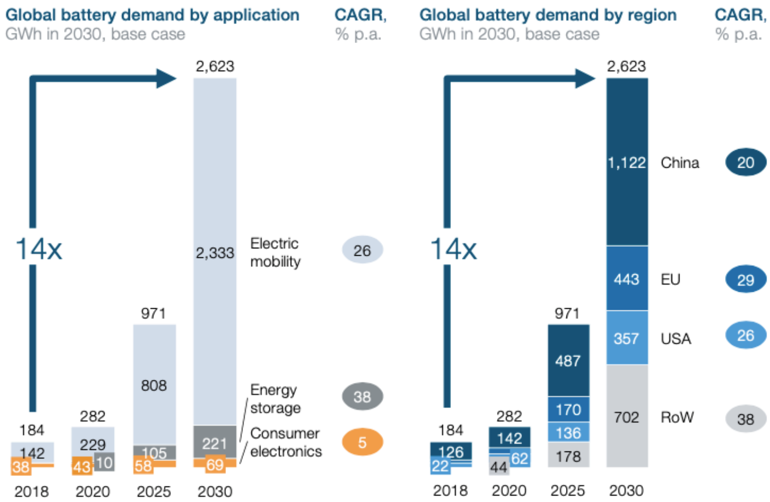

Figure 7: Global battery demand (in GWh) by application and region (WEF, 2019, p. 18)

Xu et al. (2020) found that future lithium and cobalt requirements could outgrow current global production capacities before 2025[11]. Another analysis found that half of the lithium and cobalt supply could be exhausted by 2030 (IEA, 2021b). The EU estimates need for lithium will increase 7-18 times and for cobalt 2-5 times by 2030 (EC, 2021b). Lithium reserves are sufficient but commercialization of all capacities might face economic, environmental, and

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[10] Appendix G and H show an outlook and overview of the technology developments.

[11] See appendix J.

geographic constrains (Gallucci, 2021). The demand for nickel and cobalt is strongly influenced by battery chemistry scenarios (Xu et al., 2020).

Costs

Battery pricing has reduced significantly with costs per kWh decreasing from USD 1,000 in 2010 to USD 150 in 2018. Moreover, it is predicted that EVs will reach a tipping point of USD 100 per kWh when EVs will be cheaper than ICE cars after 2025 (Azevedo et al., 2018). Mauler et al. (2021) forecast 132 USD per kWh for 2030.[12]

Regarding the battery life cycle, battery replacement occurs when capacity falls below 70-80% (state-of-health (SOH)) compromising reliability (Hill et al., 2019; Niese et al., 2020). Studies estimate that his SoH is reached after 8-10 years which is defined as EoL (Karabelli et al., 2020).

2.2 Circular Economy

The concept of the Circular Economy (CE) gained interest over the last 5 to 10 years and it is now a widely discussed term among policymakers, scholars, and environmental economists (Geisendorf & Pietrulla, 2018; Reike et al., 2018). There is no single definition for CE (Korhonen et al., 2018; Reike et al., 2018; Tonelli & Cristoni, 2019). Despite varying definitions, the concept is: an alternative model to production and consumption, decoupling resources from economic growth and focusing on sustainable development (EC, 2015; EMF, 2013, 2015; Geissdoerfer et al., 2017; Ghisellini et al., 2016; McKinsey, 2015; Reike et al., 2018; UNEP, 2012).

Drivers

Although proposing CE as a new economic paradigm would be an overstatement, rising environmental challenges are engendering interest driven by three concerns: climate change, scarcity of raw materials and price volatility, and structural inefficiencies associated with the current economic model (EMF, 2013; Tonelli & Cristoni, 2019). Esposito, Tse, and Soufani sum the matter up: “In the linear economy we risk the threat of running out of natural capital on the planet, our home” (2017, p. 9).

[12] See appendix I.

The political debate around CE in the EU traces to discussions of waste management during the eighties and nineties. In 2008, the EU Waste Directive sought to harmonize an EU-wide waste and recyclables management program. These regulations were reformed by Circular Economy Package in 2015 (Weber & Stuchtey, 2019).

The financial sector recognizes CE approaches as a value creation opportunity. Since 2019, assets under management in funds with a focus on CE have grown 26-fold to a total of 8 USD billion (Bocconi University et al., 2021). Integrating CE models support the way firms address environmental, social and, governance (ESG) issues (Bocconi University et al., 2021; EMF, 2020) and makes them more attractive in capital markets (Cheng et al., 2014; Dhaliwal et al., 2011).

2.2.1 School of thoughts and principles

The genesis of the concept, circular material flows, started decades ago and root CE in different schools of thought (EMF, 2013; Geisendorf & Pietrulla, 2018). Although CE is timely and relevant, few management scholars have employed the concept (Lathi et al., 2018).

A key definition was formulated by the Ellen MacArthur Foundation (EMF): “A Circular Economy is one of that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times distinguishing between technical and biological cycles” (EMF, 2015, p. 2). While influential, some argue this definition does not provide sufficient macroeconomic content (Geisendorf & Pietrulla, 2018).

Early work of Carson in 1964 (2002), Boulding (1966) and Commoners (Commoner, 1971), built a foundation for recognizing ecological issues and the notion that pollution and waste are undesirable (Bocken et al., 2016).

An initial theoretical foundation out of industrial ecology and was set by Ayres (1994). “The goal of the system should optimize the use of energy and materials, minimize pollution and waste, and consider environmental impact […]” (Geisendorf & Pietrulla, 2018, p. 775). McDonough and Braungart (2002) emphasized the importance of closing “technical” and “biological” loops in the cradle-to-cradle (C2C) rather than the cradle-to-grave or linear consumption model (Bocken et al., 2016). Stahel (1994, 2010) further distinguished between recycling of materials and the reuse of goods (Bocken et al., 2016). The aim is to maximize use value of products and minimize material input and used energy (Geisendorf & Pietrulla, 2018).

Bocken (2016, p. 309) introduced the term of i) “slowing resource loops: through the design of long-life goods and product life extension […]” and extension of the utilization period; ii) “closing resource loops: through recycling […]”; iii) “resource efficiency or narrowing resource flows, aimed at using fewer resources per product”.

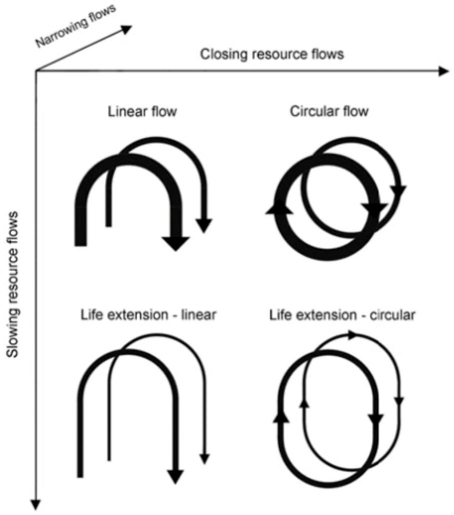

Figure 8: Categorization of linear and circular approaches for reducing resource use (Bocken et al., 2016, p. 309)

Another key idea is transforming the linear consumption model of “make-use-dispose”, into the three Rs principle, “reduce-reuse-recycle” (EMF, 2013; Ghisellini et al., 2016; Lathi et al., 2018). As part of the production principle, the input of primary energy, raw materials and waste should be minimized by improving production efficiencies and consumption processes (Ghisellini et al., 2016). The reuse principle aims to salvage products or components for the same purpose whereas the recycling principle refers to recovery of waste of organic materials and their transformation into other products, materials or substances (Ghisellini et al., 2016). CE often merely refers to the recycling principle, potentially a lesser sustainable solution compared to reduction and reuse (Ghisellini et al., 2016; W. R. Stahel, 2013).

2.3 Circular Economy in electric vehicle batteries in Europe

CE in electric vehicle batteries can also create additional added value such as cost savings, job security, and increased economic resilience. So-called “closing the loop” helps achieve Paris climate goals and decouples resources from prosperity (acatech et al., 2020). Successfully implementing CE could lead to a potential 40% carbon footprint reduction and 20% lower cost for batteries by 2030 (WEF, 2019).

Through this, the EU aims “to create a competitive and sustainable battery manufacturing industry in Europe” (EC, 2018, p. 2). Potential environmental gains could be attenuated if there is no sustainable management of EV batteries at the end of their first life (Ahuja et al., 2020; Hill et al., 2019; Niese et al., 2020; WEF, 2019).

In the final analysis, CE is a holistic phenomenon and encompasses the entire EV. Thus, components like the plastic from the car body become part of CE, too. The scope of this work pertains only to traction batteries used in electric vehicles.

2.3.1 Transition from linear consumption to a Circular Economy

Traditional car manufacturing tends to proceed on the linear economic model: "vehicles are developed and produced, delivered to the customer and disposed at the end of life" (AUDI AG, 2019, p. 63). This follows the "make-use-dispose" paradigm whereas CE builds on the 3 Rs: "reduce-reuse-recycle".

Compared to a linear system, CE approaches the battery from a lifecycle perspective (acatech et al., 2020), and prefers cradle-to-cradle over cradle-to-grave for flows of materials (Bocken et al., 2016; Braungart et al., 2008). Key elements of a transition to CE are i) closed-loop material cycles and ii) lifetime extensions (acatech et al., 2020; Buchert et al., 2019):

i) To achieve closed-loop material cycles, effective and efficient recycling, and resource recovery are critical in combination with high collection rates. In the case of lithium-ion batteries used in consumer electronics, collection rates are low and more than 50% end up in landfills or incinerators. Another feature in a CE is that resource efficiency is expressed as a reduction of virgin materials, called non-circular resource consumption per year (WEF & Accenture, 2020). In a future scenario, recycling in a CE could provide up to 10 to 13% of battery materials in 2030 (acatech et al., 2020; Buchert et al., 2019; Xu et al., 2020) and up to 40% by 2050 (Öko-Institut, 2017; WEF, 2019; Xu et al., 2020).

ii) Extending battery life is a way to slow resource loops (Bocken et al., 2016). Different EoL pathways are possible such as repair, refurbishment, reuse (second life) before proceeding to recycling. Introducing additional stages to the lifecycle, instead of a direct-to-recycling approach, mitigates high CO2 emissions associated with battery production over the extended lifetime (acatech et al., 2020; Chen et al., 2019).

With CE, the shift to renewable energy sources in the production process, as well as for charging cars, is fundamental (acatech et al., 2020; Bocken et al., 2016; WEF, 2019). Also, decoupling economic growth from resource consumption and increased recycling will create

15 new jobs per 1.000 BEVs that go into recycling (WEF, 2019). CE in electric vehicle batteries further promotes several UN Sustainable Development Goals (SDGs) – e.g., SDG 8: Decent Work and Economic Growth and SDG 12: Responsible Consumption and Production (Weber & Stuchtey, 2019).

2.3.2 Circular view on the EV battery value chain and end-of-first-life options

The Joint Research Centre (JRC), the European Commission's science and knowledge service, published an applied model (Hill et al., 2019).

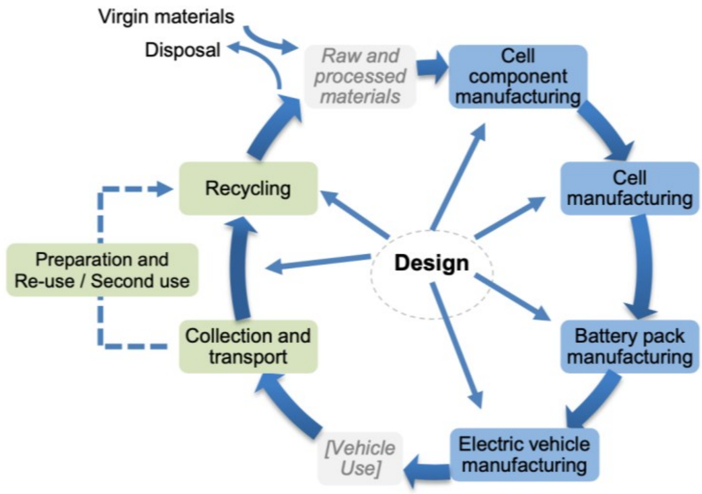

Figure 9: Circular view on the EV battery value chain (Hill et al., 2019, p. 7)

Further investigation of end-of-first-life activities is needed which gives rise to the research questions of this thesis. Although, in a European context the final endpoint should be recycling, interest in reuse potential or repurposing is increasing due to economic and resource efficiency concerns as well as for perceived environmental benefits (Hill et al., 2019). Quantity and capacity of EoL batteries are estimated by Drabik & Rizos (2018) in table 1.

	2030	2035	2040
Quantity	1,163,500	2,596,100	5,380,000
Capacity (MWh)	46,540	103,844	215,200

Table 1: Quantity and capacity of EoL batteries – forecasts for 2030, 2035, and 2040 (Drabik & Rizos, 2018 based on BloombergNEF, 2017; Casals et al., 2017; Curry, 2017; Myall et al., 2018; Neubauer et al., 2015)

There are different EoL pathways including re-use, re-purposing, re-manufacturing, all of which slow the loop (Bocken et al., 2016). However, the definitions for these are not always consistent (Ardente et al., 2018). Here the following definitions from JRC and figure 10 will be used (Hill et al., 2019, p. 20).

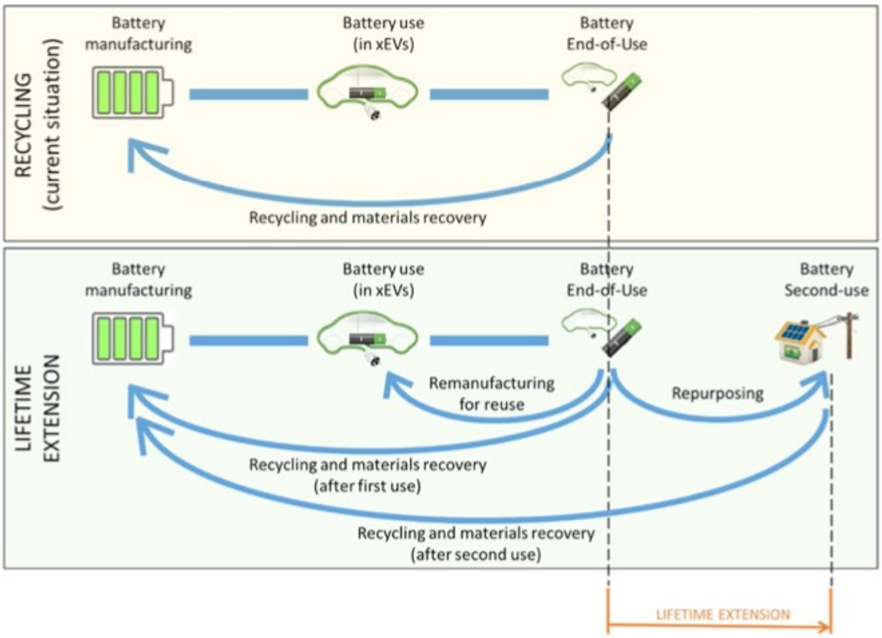

Figure 10: End-of-life patterns
(Bobba et al., 2019, p. 280)

Remanufacturing/refurbishment/reconditioning/repair

Remanufacturing is defined as "[…] all different stages of getting batteries ready for either re-use or repurposing for second use […]" (Hill et al., 2019, p. 20).

Re-use

Re-use is defined as "[…] complete or partial re-use of the battery for the original purpose […]" (Hill et al., 2019, p. 20). Although re-use offers environmental and economic benefits, technical, regulatory and safety concerns exceed achievable benefits (Kampker et al., 2016).

Re-purposing ("second-use")

Repurposing is interchangeable with "second-use" and defined as "[…] complete or partial re-use of the battery for a different purpose/application, […] will also require an element of remanufacturing […]" (Hill et al., 2019, p. 20). Since a second-use of a battery entails extending product life, it contributes strongly towards CE in terms of mitigating carbon investment incurred to produce the battery (Niese et al., 2020; Reinhardt et al., 2019). It slows down resource loops (Bocken et al., 2016) which consequently leads to a delay in recycling (Chen et al., 2019). This is useful for products with high environmental impacts of the production phase (Dominish et al., 2018) which applies to LIBs due to their embedded emissions. *Further analyses can be found in chapter 4.3.*

Recycling

Recycling includes "reprocessing of waste materials, for either the original purpose or a different purpose" (EEA, 2018, p. 47) to close resource loops (Bocken et al., 2016). It reduces the need for primary (virgin) materials by replacing them with secondary (recycled) materials (Ellingsen & Hung, 2018; Hill et al., 2019) which have a lower environmental impact (Bigum et al., 2012). On average, recycling can reduce 20 kg CO2-eq/kWh compared to virgin materials in production (Aichberger & Jungmeier, 2020). In the potential case of bottlenecks in CRMs supply, recycling can secure access to secondary materials for the domestic battery production (Abdelbaky et al., 2021; Baars et al., 2021).

The recycling process typically starts with collection of LIBs. Depending on further chemical treatment, mechanical pre-treatments like discharging of the battery pack, dismantling of the battery module, and disassembling the spent LIBs occur (Yun et al., 2018). The main recycling techniques for lithium-ion batteries are i) pyrometallurgy, ii) hydrometallurgy, and iii) direct recycling (Diekmann et al., 2017; Harper et al., 2019):

i) Pyrometallurgy recovery uses high temperatures to smelt batteries to produce metallic alloy faction, slag, matte, and gases (Brückner et al., 2020; Chen et al., 2019). The process can handle LIBs without pre-treatment (Morse, 2021). Hydrometallurgical processes are used to further separate the metal alloy (Brückner et al., 2020; Chen et al., 2019). Currently, this process is mostly used at industrial scale in Europe and North America due to the simple process but has high energy consumption (Chen et al., 2019; Mossali et al., 2020).

ii) Hydrometallurgy recovery applies aqueous solutions to leach targeted metals from cathode material (Brückner et al., 2020; Harper et al., 2019). It obtains materials more readily compared to burning but uses chemicals that pose health risks (Brückner et al., 2020; Morse, 2021). The technology is primarily deployed in China (Chen et al., 2019).

iii) Direct recycling is the removal of cathode or anode material from the electrode for reconditioning and re-use purposes (Harper et al., 2019). The process includes physical separation which faces economic and technical challenges (Chen et al., 2019).

Figure 11 illustrates the recycling pathways with materials recovered (Xu et al., 2020).

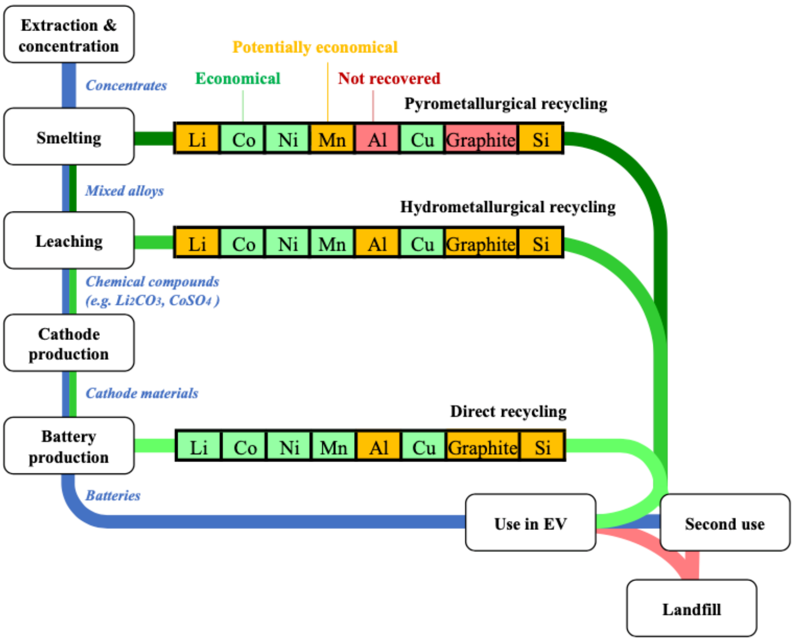

Figure 11: Overview of recycling scenarios and recycled materials (Xu et al., 2020, p. 5)

Recycling activities primarily target high-priced metals in the cathode such as cobalt and nickel and miss materials like lithium and graphite (Harper et al., 2019) where value of the material drives the recycling effort (Heelan et al., 2016; Hill et al., 2019; Niese et al., 2020). Metals used in a LFP battery are worth only half of those in an NCM due to the nickel portion (Niese et al., 2020). There is increasing pressure to improve recycling since the battery industry aims to avoid cobalt in near future (Chen et al., 2019; Xu et al., 2020). Lithium is 100% recyclable but recycling is only viable if prices are high and recycling occurs at scale (Mossali et al., 2020; Rahman & Afroz, 2017; Velazquez et al., 2019). Kirchherr et al. (2018) highlight the issue of low prices for virgin materials in closed loop while Beaudet et al. (2020) point out that price does not account for environmental externalities.

Recycling presently is plagued by low collection rates of batteries, immature technology, and low volumes of EoL batteries in the market (Beaudet et al., 2020; Chen et al., 2019). Technological innovation such as increased automation and higher standardization by design for recycling are potential opportunities (Harper et al., 2019). Future recycling activities could also be spurred by regulation including collection rates and recovery targets (Beaudet et al., 2020; Chen et al., 2019; Dunn et al., 2021) – like the new Battery Directive.

Uncertainty pertaining to the evolving chemical composition of cathodes is impeding capital investment in appropriate infrastructure (Chen et al., 2019; Heelan et al., 2016). In 2018, global recycling capacities were concentrated in China with 68% while Europe had a share of around 5% (Roland Berger, 2019).

2.3.3 European Union's circular economy activities and policies

Coherent policy action is needed to coordinate industry activities and to provide guidance for the transition. "Policy action can mitigate barriers and strengthen drivers of automotive circularity […] and is needed to overcome hurdles" (WEF & SYSTEMIQ, 2021). Given this, the EU is actively seeking and promoting a transition to CE.

The European Green Deal (EGD) and Circular Economy Action Plan

The EDG seeks to transform the EU into a resource-efficient and competitive economy for a sustainable future (The European Green Deal, 2019). As integral part of the EDG, the Circular Economy Action Plan defines the battery and vehicle value chain as key product value chains for circular potentials and sustainability (EC, 2020d).

Proposal for a new Battery Directive (repealing Directive 2006/66/EC)

In 2020, the EU proposed a new Battery Directive to replace the previous version.[13] The Directive covers not only EoL but also the production, use phase, GHG emissions and responsible sourcing. The Directive further includes clear targets for collection rates, recycling efficiency rates and recovery rates (COM(2020) 798 Final, 2020).

Measure	Ambition
Minimum recycling efficiency rates (LIBs)	2025: 65% 2030: 70%
Recovery rates for individual materials	2026: cobalt 90%, copper 90%, nickel 90%, lithium 35% 2030: cobalt 95%, copper 95%, nickel 95%, lithium 70%
Recycled content in LIB	2030: batteries contain minimum share of cobalt (12%), lithium (4%), nickel (4%) recovered from waste
Extended producer Responsibility (EPR)	EV batteries included in EPR, producers are responsible for waste management
Support	information/labelling, carbon footprint targets, electronic exchange system, and Battery Passport

Table 2: Key measures of the Proposal for a new Battery Directive
(own illustration based on COM(2020) 798 Final, 2020; WEF & SYSTEMIQ, 2021)

[13] In August 2021, the proposal is not finalized and is still ongoing.

3. Methodology

The following section outlines the research methodology used in this thesis. The chapter further describes research design as well as data collection which was conducted to gain the required insights to answer the RQ's.

3.1 Research Design

Primary and secondary data were collected with a semi-structured interview approach along with the literature review from the previous section. Expert interviews are an accepted approach to gain insights (Saunders et al., 2016). A survey was conducted to investigate the consumer perspective.

Scenario analysis was implemented in line with the strategic planning tool of Schoemaker (1995) positing three different scenarios – optimistic case, base case, and conservative case.

3.2 Data Collection

3.2.1 Primary data collection – Expert interviews

The semi-structured interviews allowed for open-ended questions (Galletta, 2013) with experts from different areas chosen for their expertise, work experience, and position of their company in the battery value chain. A diverse array of experts was interviewed. However, it was not possible to acquire an expert from the mining sector. Interviews were conducted via Zoom and Microsoft teams and casted between 45 and 60 minutes.

#	Role / Position	Years of experience	Country	Company Type	Reason for choice of interviewee
A	Head of European Battery Marketing	10+ years	DE	Leading chemical company with 40-60 billion revenues	Professional expert in battery market and environmental catalyst research
B	Manager Sustainability Practice	10+ years	DE	International consultancy with 40-60 billion revenues	Strong expertise in Circular Economy and corporate strategy in automotive industry
C	Engineering Manager Mechatronics	15+ years	DE	Automotive engineering company, revenue NA	Battery professional with competences in normative legislation
D	Founder and Chair	5+ years	GB	Battery consultancy with advisory and lab services, revenue NA	PhD in lithium-ion batteries, Global Shaper, and fellow of the WEF
E	Head of Strategy	5+ years	SE/ DE	Cell producer and recycling company, revenue NA	Topical expert in battery industry and Circular Economy

F	Vice President Policy	10+ years	US/ CH	Battery technology service company, revenue NA	Previous Lead of the WEF Circular Car Initiative and thought leader in CE
G	Senior Consultant	3+ years	DE	Leading international automaker with 160-260 billion revenues	Professional experience in strategic battery value chain and CE projects
H	Lead Sustainable Strategies	5+ years	GB/ DE	System change company, revenue NA	Deep expertise on Circular Economy in battery and mobility industry
I	Partner	20+ years	GB/ DE	Financial services with focus on sustainable investments, revenue NA	Specialist in second life applications, and WEF Future Energy Council member
J	Manager	9+ years	DE	Strategy and operations consultancy with 150-250 million revenues	Expert on battery technologies and the battery market

Table 3: Overview of interview experts

After the interviews, qualitative content analysis (QCA) was used to analyze results (Mayring, 2015). Within content analysis the categorization procedure is important (Krippendorf, 2004). According to Mayring (2015), an inductive approach is favorable for QCA. The categories were built during the content analysis of the collected qualitive material.

3.2.2 Primary data collection – Survey

Consumers play a vital role supporting or impeding the consumption process (Gallaud & Laperche, 2016). For successful energy transition, consumers need to be on board (Lenzen et al., 2007) and it is crucial to understand negative perceptions of recycled products that influence purchasing habits (Calvo-Porral & Lévy-Mangin, 2020). Environmental concerns also shape consumer attitudes and purchasing choices (Netwon et al., 2015; Testa et al., 2020; Trivedi et al., 2018). From sustainable packaging studies it is known that perception of sustainability and real performance based on life-cycle- assessments can be misaligned (Boesen et al., 2019; Testa et al., 2020). Finally, lack of consumer interest and awareness is a major barrier for CE models (Kirchherr et al., 2018).

The questionnaire analyzed 7 different categories: environmental concerns, sustainability perception of BEVs and LIBs, recycling knowledge, support of CE practices, and intentions in the purchasing decision. In total, 255 responses were collected. The survey was published on Amazon MTurk, Linkedin and social media channels.

3.2.3 Secondary data collection

Secondary data was obtained from academic journals and leading research institutes, NGOs, consultancies, and bodies such as the World Economic Forum. To understand governmental activities and upcoming policy directives, official websites and sources from the European Commission as well as multinational and national project research like the Circular Economy Imitative Germany were used.

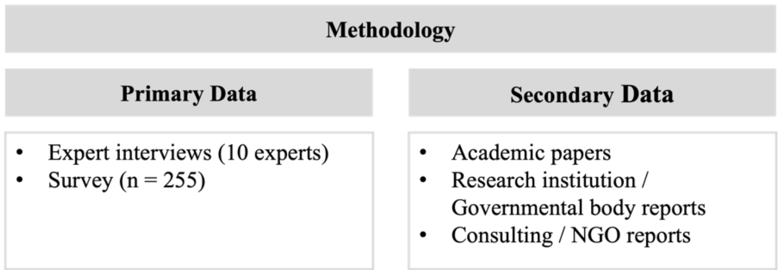

Figure 12: Methodology

4. Analysis & Findings

4.1 Expert interviews

Interview findings were clustered into 8 different categories derived from the expert interviews.

Transformation of the automotive industry

The need for decarbonization drives electrification (all Experts). The transition towards electrification is a strong change of strategies and business models for automakers (Experts A & I). With this transition, access to raw materials has become a challenge for the whole industry (Experts A & C). Automotive companies are realizing that the battery is the key component of the car rather than a commodity (Experts A, C, I). Although the industry is being disrupted, electrification offers new business opportunities for vertical integration that compensate for layoffs (Experts A, C, I). The battery industry is currently controlled by Asian players and European companies are lagging (Experts A, C, E, F, H-J).

Insights: Industry transformation	A	B	C	D	E	F	G	H	I	J	Ratio
Transformation is driven by decarbonization	X	X	X	X	X	X	X	X	X	X	10/10
Battery industry controlled by Asian players	X		X		X	X		X	X	X	7/10
Battery becomes key component	X		X						X		3/10
New opportunities to compensate layoffs	X		X						X		3/10

Table 4: Interview insights: Industry transformation

Circular Economy role & goals

CE is a critical lever to reduce carbon emissions (all Experts). Experts A, D, E, F, J highlighted the need to address battery emissions occurring during the production phase. Due to resource constraints, maximum resource usage is necessary, and CE should focus on resource efficiency

(Experts A, B, D-J). The goal is to reduce the need for virgin materials (Experts A, F, H) and have a closed loop (Experts A, B, I). The design for reuse and recycling must be considered from the beginning (Experts C, D, F, I) which needs a shift in mindset in the industry and from the consumer (Experts F & I). Moreover, experts emphasized that CE should also contribute to SDGs (Experts B, D, E, G, H, J). Creation of jobs is another goal and benefit of CE (Experts G & J). CE driven by consumers was only mentioned by one expert (Expert J).

Insights: CE role & goals	A	B	C	D	E	F	G	H	I	J	Ratio
Strong lever for decarbonization	X	X	X	X	X	X	X	X	X	X	10/10
Increased resource efficiency	X	X		X	X	X	X	X	X	X	9/10
Support of SDG goals		X		X	X		X	X		X	6/10
Securing raw material supply	X	X						X	X	X	5/10
Design for reuse and recycling			X	X		X	X		X		5/10
Reduce cost		X			X			X	X		4/10
Fulfilling consumer requirements										X	1/10

Table 5: Interview insights: CE role and goals

Second life applications

In terms of circularity, second life applications should always be at EoL of a battery (Experts A, D, E, F, I). There is a considerable opportunity to increase resource efficiency (Experts A, C, D, E, F, H, I). In the future, second life must be considered in the design phase (Experts C, D, F, G, I). The market is currently small and immature (Experts A, C, D, E, F, G, I). Industrial applications like stationary energy storage are the most prevalent use cases (Experts A, C, D, E, I) and support transition to renewable energy by peak shaving (Experts C, D, E, I). Safety concerns mitigate usage in residential applications (Experts C, D, H, J).

Second life applications can also be a hedging instrument against volatile resource availability and price swings (Experts A, D, E, F, G, I) since they provide flexibility about when to bring materials back into the cycle. Therefore, the market for second life applications is strongly dependent on raw material markets (Expert A & J). It is also in competition with recycling which brings materials directly back into production (Experts A, D, J). Expert B argued that second life is only a bridging solution until recycling technologies become more efficient.

The largest issue for second life applications appears to be competition with new batteries relative to price, technology, and reliability (all Experts). Battery design can be an issue since first generation batteries were not made for reuse (Experts A, F, G, I). Due to lack of data and information sharing, ignorance about battery health is another strong barrier (Experts A, C, D, F, G, H, I). Innovative solutions like battery swapping, e.g., offered by the US startup Ample, could be a strong use case if it gains traction (Expert F & H).

Although, most experts argued in favor of second life in terms of circularity, projections about the extent of second life for batteries in 5 to 10 years differed. All experts highlighted those assumptions are being made under conditions of high uncertainty and are more of a vision than a projection.

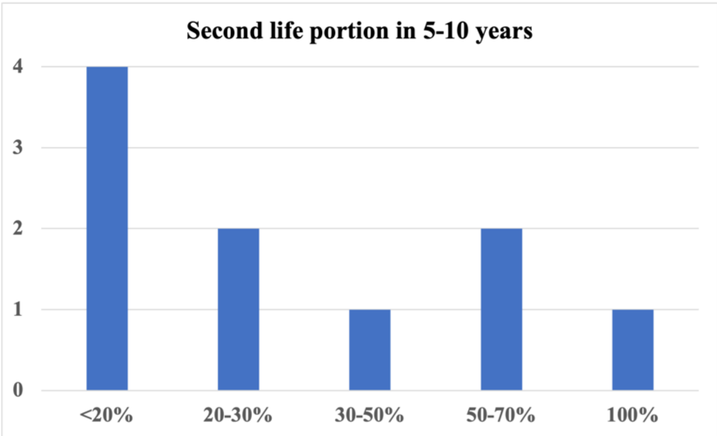

Figure 13: Interview insights: second life portion

Insights: Second life applications	A	B	C	D	E	F	G	H	I	J	Ratio
Competition with new batteries as issue	X	X	X	X	X	X	X	X	X	X	10/10
Favor in terms of circularity	X			X	X	X	X	X	X	X	8/10
Small and immature market	X		X	X	X	X	X		X		7/10
Lack of SoH data as issue	X		X	X		X	X	X	X		7/10
Increase resource efficiency	X			X	X	X		X	X		6/10
Hedging instrument for raw materials	X			X	X	X	X		X		6/10
Considered second life in design phase			X	X		X	X		X		5/10

Table 6: Interview insights: Second life

Recycling

Recycling of LIBs in Europe currently is at a low level due to limited EoL batteries in the market (Expert A, H, J). Infrastructure is currently in the ramp-up phase but also needs large investments (Experts A, E, H, I, J) but there is uncertainty regarding regulation and future chemistries (Expert A, C, D, H-J). Recycling of LIBs is capital and energy intensive (Experts A, F, I, J) which makes it a low margin business (Expert A). The business case for recycling is not yet clear (Experts A, C, D, I) and highly depends on raw material markets (Experts A, F, I & J). Experts F & H criticized recycling of LIBs under CE principles as it always implicates material losses and energy intensive processes. Recycling should be a final recourse (Experts F, H, I).

Regulation will be a further driver by setting recycling targets (Experts A & J). The strategic focus for European companies could also change as the need for recycled materials rises to fulfill regulatory mandates. Currently, the largest recycling capacities are located in Asia (Expert J). Larger capacity recycling will start from 2030 onwards (Experts A, G, I) but will not be at scale (Experts H & J).

Insights: Recycling	A	B	C	D	E	F	G	H	I	J	Ratio
High uncertainty regarding regulation and future chemistries	X		X	X				X	X	X	6/10
Needs large investments	X				X			X	X	X	5/10
Business case is unclear	X		X	X					X		4/10
Strongly dependent on raw material prices	X					X			X	X	4/10

Table 7: Interview insights: Recycling

Battery value chain

The battery value chain is very complex and international (Experts A, F, I) where large parts are located in Asia or under the control of Asian companies (Experts H & J). In the traditional world of ICEs, automakers had a low degree of integration across the value chain and relied on high levels of outsourcing (Experts E, F, H, I, J). As the battery becomes an integral part, automakers must move towards vertical integration to better understand the market and gain more control (Experts A, D, G, I).

Automakers will become cell producers (Experts C, E, G, I) as they need competencies inhouse and do not want to rely on cell companies (Expert I). Mining and refining will remain untouched as it is considered a “dirty business” (Expert G). Different players, such as automakers, cell manufacturers, cell component manufacturers, and independent recyclers, are engaged in recycling (Niese et al., 2020). Access to recycled materials will be critical in the future due to regulation (Experts A, E, I, J; Melin et al., 2021).

There will be large players who will try to monopolize most of the value chain (Experts A, D, E, J). Partnerships and joint ventures will play a prominent role as automakers need external cell know-how (Experts A, D, E, I). The model of collaboration is changing due to higher power of cell companies and increased need for tighter cooperation to define future technologies (Experts A, E). Partnerships are also needed for capital intense investments in infrastructure like the example of Volkswagen and Northvolt (Experts A, E, G, I). Local clusters could be a dominant form to avoid transportation costs (Expert H).

Insights: Battery value chain	A	B	C	D	E	F	G	H	I	J	Ratio
Traditionally automakers relied highly on outsourcing					X	X		X	X	X	5/10
Automakers must vertically integrate to better understand and control the market	X			X			X		X		4/10
Partnerships are needed for large investments	X				X		X		X		4/10
Access to recycled material is critical	X				X				X	X	4/10

Table 8: Interview insights: Battery value chain

Regulation

Regulators play a vital role in the transition towards CE in EV batteries (all Experts). They should set aggressive targets to push industry (Experts A, C, E, G, F, I, J) but regulations should be workable (Experts A, C, E, F) and not disrupt underlying fundamentals of the industry (Expert F). Regulators should set a clear framework to reduce uncertainty (Experts A, D, E, G, I). The role of the regulator is not limited to the market, its main duty is to fight climate change, a responsibility related to caring for citizens (Experts E, H, I, J).

An important goal for the industry is setting up a level-playing field (Experts D, H, I, J). Regulator has to secure international competitiveness (Expert G). Regulations can also be flouted in the global economy and might also strengthen non-European competitors or even increase the reliance on them (Expert I; Melin et al., 2021). Expert E highlighted that regulatory activities mostly occur in the EU and need to be conducted also at the federal level.

The Proposal of a New Battery Directive was named as most important regulation (Experts A, C, D, E, H, G). The Battery Passport was frequently mentioned with regards to data and information sharing (Experts C, D, H, E, I).

Insights: Regulation	A	B	C	D	E	F	G	H	I	J	Ratio
Regulators play vital role	X	X	X	X	X	X	X	X	X	X	10/10
Should set aggressive targets	X		X		X	X	X		X	X	7/10
Regulator should reduce uncertainty	X			X	X		X		X		5/10
Goal is to set level-playing field				X				X	X	X	4/10

Table 9: Interview insights: Regulation

Challenges & barriers

A large challenge for transition to CE entails uncertainty related to investing where there is no strong industry and technology visibility (Experts A, B, C, E, F, G, H, J). This also implicates lack of scale of the industry (Experts A, B, E, G, H). Missing guidance from regulators is another barrier (Experts A, C, G, H).

European companies are lagging behind their Asian counterparts in terms of knowledge and capacity (Experts A, C, E, I). The first generation of batteries returning now were not designed for second life and recycling (Experts C & I). Lack of access to data on the battery SoH makes batteries less attractive for second life (Experts C & D). The future gap in supply and demand mitigates CE activities (Experts A, E, G, I, J). Access to renewable energies is not matching demand and presents a hurdle for emissions reduction (Experts A, B, D).

The focus on collaborative action in the industry slows down activity (Experts C & H) – "one company has to do the large investments like Tesla" (Expert H).

Insights: Challenges & barriers	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**Ratio**
Uncertainty hampers investments	X	X	X		X	X	X	X		X	8/10
Missing guidance from regulator	X		X				X	X	X		5/10
Lack of scale	X	X			X		X	X			5/10
Gap in supply and demand mitigates CE	X				X		X		X	X	5/10
European companies lagging behind	X		X		X				X		4/10

Table 10: Interview insights: Challenges & barriers

Enabler & accelerator

Regulations that provide clear pathways for the future were identified as a strong enabler (Experts A, C-I). This requires incentives for investments to build up necessary infrastructure (Experts A, D, E, I).

Faster traction for EVs could strongly accelerate the market (Experts F-I). Data and information sharing as well as collaborative platforms can be enablers for CE activities and simplify second life applications (Experts C, D, E, F, G). Standardization of battery design and the industry could also enable second life applications and reduce uncertainty surrounding recycling (Experts A, B, C, G, I). Increasing access to renewable energy is another accelerator (Experts A, B, I).

Putting circular products and services on a level playing field with non-circular products could be a strong accelerator for CE (Expert F). Cross-industry partnerships, E.g., between the mobility and energy industry, could help set expectations and requirements for products in different life phases as they transit between industries (Expert G).

Insights: Enabler & accelerator	A	B	C	D	E	F	G	H	I	J	Ratio
Regulation that provides guidance	X		X	X	X	X	X	X	X		8/10
Faster EV traction		X				X	X	X	X		5/10
Higher standardization	X	X	X				X		X		5/10
Incentives for investments	X			X	X				X		4/10

Table 11: Interview insights: Enabler & accelerator

Future CE in EV batteries

According to all experts, a CE in electric vehicle batteries will strongly contribute to reduced carbon emissions and resource efficiency in 5 to 10 years. Expert B highlighted "what is technically possible will be done". However, the industry will still face uncertainties regarding market and technology development (Experts A & J). Since the industry is still in the ramp up phase, infrastructure decisions have to be made now (Experts A, E, J).

New and upcoming regulations as well as policies will be overall supportive for the industry (Experts B, D, E, F, G, I) but also create some drawbacks (Experts F & J) and might be adjusted (Expert J).

The industry will be able to reduce need for virgin materials by covering material demand with recycled material in 2030 (Experts A, B, D, E, F, G, H, J) by around 10% which will increase strongly up to 40% by 2040 (Expert H; acatech et al., 2020). Companies will also consider second life and recycling in the design phase (Experts D, G, H, I). Battery design will become more standardized but still with considerable variety present (Experts A, D, F, G, I). Uncertainties regarding recycling economics continue and are dependent on raw material markets and technology development (Expert J). The experts predicted that on average less than 20-30% of batteries will be used for a second life. However, innovative business models like battery swapping may gain traction (Experts F, G, I). The European battery industry will also become less dependent on Asian companies (Experts A, B, D, H, I). Sales of EVs could be higher than expected and may strongly accelerate (Expert H).

Consumers will become more ecologically responsible (Experts D & H). Expectations for reuse in terms of second life applications will rise (Experts F & H). Car ownership will still be important for individuals (Experts C, G, H, I, J) but battery ownership could follow different business models (Experts B, G, H).

Some experts highlighted that CE will significantly advance from 2040 onwards when EVs are at scale (Experts H & J).

Insights: Future CE	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**Ratio**
Need for virgin materials will be reduced	X	X		X	X	X	X	X		X	8/10
Upcoming regulations will be supportive		X		X	X	X	X		X		6/10
Design will become more standardized	X			X		X	X		X		5/10
Europe will become more independent	X	X		X				X	X		5/10
Car ownership will still be important			X				X	X	X	X	5/10
Second life will be considered by design				X			X	X	X		4/10

Table 12: Interview insights: Future CE

4.2 Survey data analysis

From the 255 responses obtained, 200 were used after 55 results were excluded due to incomplete answers or failed verification.

Demographics

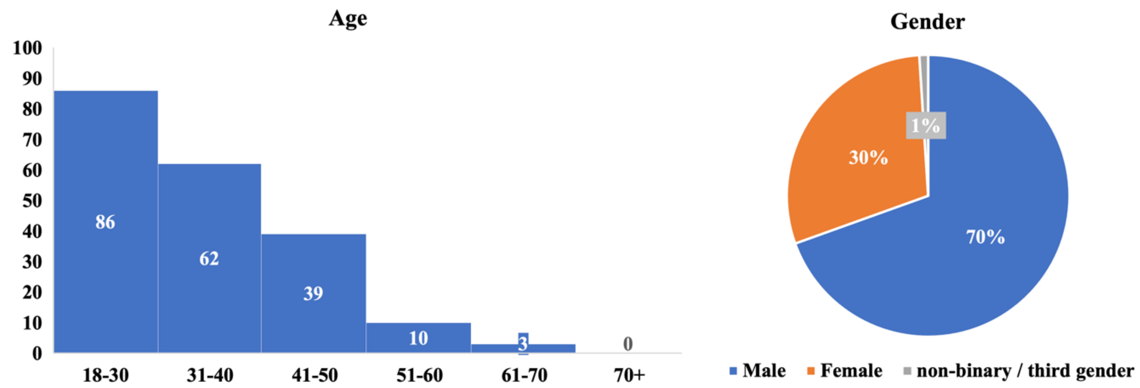

Figure 14: Survey: Age and gender

Planned BEV purchase

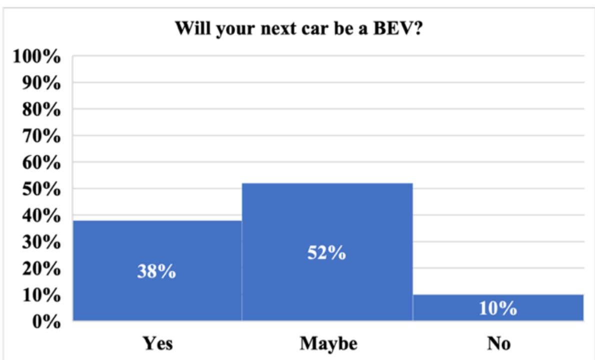

Table 13: Survey: Planned BEV purchase

A five point Likert scale to enable analysis (Croasmun & Ostrom, 2011; Joshi et al., 2015) was used ranging from "strongly disagree" = 1 to "strongly agree" = 5.

Environmental concern

Likert scale 1-5	Strongly not concerned (1)	Not concerned	Neutral	Concerned	Highly concerned (5)	Mean
Carbon emissions and climate warming	1%	5%	12%	36%	47%	4,22
Consumption of natural resources	2%	4%	7%	40%	47%	4,26
Waste of resources	2%	4%	5%	45%	46%	4,28

Table 14: Survey: Environmental concern

CE awareness and theoretical support

128 (56%) participants had previously heard the term Circular Economy, while 72 (36%) had never heard about it.

Likert scale 1-5	Not familiar at all (1)	Slightly familiar	Moderately familiar	Very familiar	Extremely familiar (5)	Mean
Circular Economy	28%	20%	24%	21%	8%	2,6
Sustainability	3%	8%	19%	43%	29%	3,88
Likert scale 1-5	**Strongly disagree (1)**	**Somewhat disagree**	**Neither nor disagree**	**Somewhat disagree**	**Strongly agree (5)**	
Economic model is based on "make-waste-dispose"	3%	7%	14%	51%	25%	3,88
Economic model should be based on "reduce-reuse-recycle"	1%	5%	9%	33%	53%	4,32

Table 15: Survey: CE awareness and theoretical support

BEV sustainability perception

The majority of the participants had not driven a BEV (59%) while 41% had driven a BEV.

Likert scale 1-5	Strongly disagree (1)	Somewhat disagree	Neither nor disagree	Somewhat disagree	Strongly agree (5)	Mean
Rides with BEVs have lower carbon emissions compared to ICEs	1%	5%	8%	48%	40%	4,22
Likert scale 1-5	**BEV much higher than ICE (1)**	**BEV higher than ICE**	**Same**	**ICE higher than BEV**	**ICE much higher than BEV (5)**	**Mean**
Total lifecycle emissions	5%	13%	13%	45%	25%	3,74
Material emissions	11%	26%	22%	30%	12%	3,06

Table 16: Survey: BEV sustainability perception

Battery sustainability perception

On average, the participants estimated that 41-60% the total BEV emissions are related to production of the battery pack (appendix Y).

Likert scale 1-5	Strongly disagree (1)	Somewhat disagree	Neither nor disagree	Somewhat disagree	Strongly agree (5)	Mean
Manufacturing process has large environmental footprint	1%	9%	20%	46%	25%	3,84
Supply risk for critical resources	2%	7%	21%	51%	21%	3,82
Violations of human rights	4%	16%	24%	37%	21%	3,55
Negative environmental impact from resource extraction	3%	15%	16%	46%	22%	3,7

Table 17: Survey: Battery sustainability perception

Recycling

The majority of the participants estimated recycling efficiency for battery packs of 41-60% in 2025 and 61-80% in 2030. For the material recovery rates for lithium, participants responded on average 41-60% for 2025 and 61-80% for 2030. For the material recovery rates of cobalt, most participants answered 41-60% for 2025 and 61-80% as well as 81-100% for 2030. An illustration of the results can be found in appendix Z and AA.

Support of CE goals and concepts

Likert scale 1-5	Strongly disagree (1)	Somewhat disagree	Neither nor disagree	Somewhat disagree	Strongly agree (5)	Mean
Set aggressive Circular Economy targets for the industry and require them	4%	5%	17%	46%	29%	3,9
Having full transparency about the life cycle emissions of the BEV	2%	6%	16%	40%	37%	4,04
European battery production should aim to increase the % of material demand covered by recycled material	3%	4%	10%	39%	46%	4,21
A battery should be reused for other applications before it goes into recycling	3%	3%	16%	33%	47%	4,18

Table 18: Survey: Support of CE goals and concepts

Intensions in the purchasing decision

Likert scale 1-5	Strongly disagree (1)	Somewhat disagree	Neither nor disagree	Somewhat disagree	Strongly agree (5)	Mean
Sustainability image of car brand has strong impact on buying decision	3%	9%	18%	53%	19%	3,75
Sustainability of BEV has strong impact on buying decision	2%	8%	12%	45%	35%	4,02
More recycled material in a battery, make buying a BEV more likely	4%	7%	19%	42%	29%	3,86
Higher circularity in a battery, make buying a BEV more likely	1%	5%	14%	48%	33%	4,07
Prefer to buy a BEV where I have full transparency about life cycle emissions	2%	3%	14%	45%	37%	4,11

Table 19: Survey: Intensions in the purchasing decision

4.3 Second life prognosis – Findings from the literature

Given their residual capacity of 70-80%, LIBs can be used for less energy-demanding applications like stationary energy storage (SES) in commercial, industrial, and residential applications (Haram et al., 2021; Martinez-Laserna et al., 2018; Reid & Julve, 2016) for another 7-10 years (Haram et al., 2021). BMW, Daimler, and Renault are testing second life applications for renewable energy storage, peak shaving, and fast charging (Ahmadi et al., 2014; Niese et al., 2020; Reinhardt et al., 2019). The Renault Group is collaborating with an SES provider to set up a second life energy storage plant for grid operations with a capacity of 1.2 MWh to provide renewable energy storage (Renault Group, 2020).

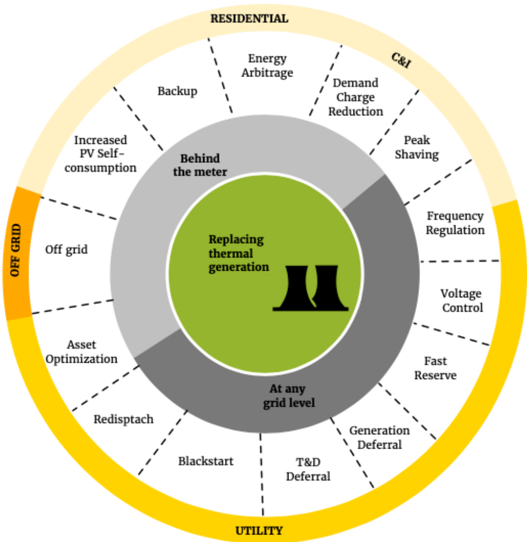

Figure 15: Second life energy use cases
(Reid & Julve, 2016, p. 16)

Bobba et al. (2019) illustrates batteries available for second life in Europe for two scenarios: REP20 = 20% second life; REP70 = 70% second life. Due to the scenario, 3 to 12 GWh could be derived in 2030.

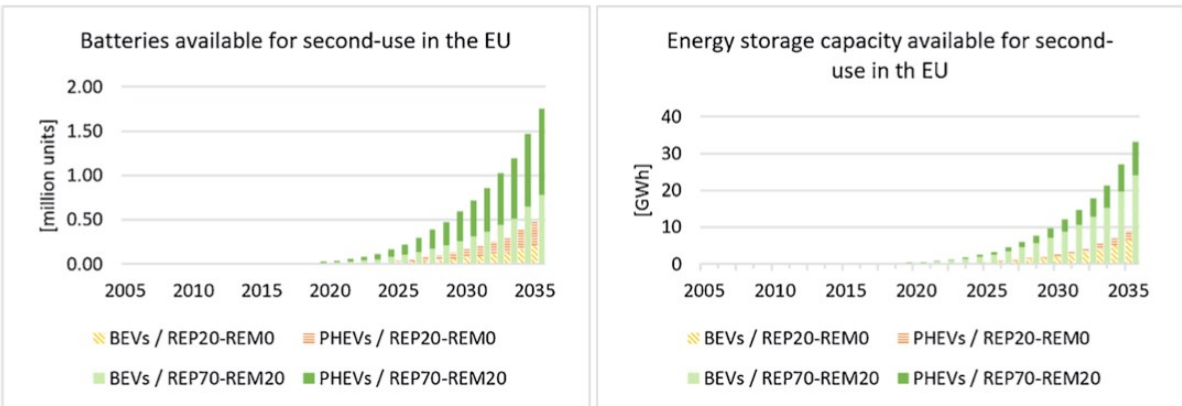

Figure 16: Batteries available for second life in Europe
(Bobba et al., 2019, p. 287)

While the European market developed from 0.6 GWh in 2015 to 2.6 GWh in 2018 (EASE, 2018), 4 GWh (Büscher et al., 2017) to 11 GWh (EU, 2018) are estimated for 2026. Potential for second life batteries in SES is limited by lack of demand and the market is still immature (Geth et al., 2015; Malhotra et al., 2016; Telaretti & Dusonchet, 2017) but could grow faster than expected since it is important for successful energy transition (Figgener et al., 2020; IRENA, 2017).

The second life concept is associated with uncertainty and is still developing (Martinez-Laserna et al., 2018; Niese et al., 2020). Studies suggest prices from 44 to 180 $/kWh are needed for profitability and 8 to 12-year-old batteries would command this price compared to new batteries priced at 132 $/kWh in 2030 (Martinez-Laserna et al., 2018; Mauler et al., 2021). Several studies suggest second life can be economically viable (Ambrose et al., 2014; Debnath et al., 2014; Neubauer et al., 2015). Retired batteries compete with new battery technologies which would offer increased performance (Haram et al., 2021; Niese et al., 2020).

There are unknowns about LIB aging performance which could affect reliability (Martinez-Laserna et al., 2018). This could also lead to safety concerns which constrains the use in residential applications (Haram et al., 2021; Martinez-Laserna et al., 2018). Another concern is lack of data on the usage profile in first life (Elkind, 2014; Zhu et al., 2021) which could be addressed by battery passports that contain life-cycle information (Global Battery Alliance, 2020). Second life LIBs seem to be capable of fulfilling the demand of SES (Martinez-Laserna et al., 2018).

It is undisputed that second life applications can mitigate the environmental footprints of LIBs and reduce the need for new batteries (Ahmadi et al., 2014; Martinez-Laserna et al., 2018). According to Richa et al. (2017) using a second life LIBs in SES could reduce gross energy demand and global warming potential by 15 to 70%. As an affordable option for SES, second life LIBs can also promote the transition to renewable energies (Bobba et al., 2019; Reid & Julve, 2016).

Sending LIBs into a second life consequently delays materials entering recycling (Baars et al., 2021; Bobba et al., 2018; Xu et al., 2020). Xu et al. (2020) highlight the impact of second life applications on material recovery and closed loop performance in figure 17. Baars et al. (2021) mention that current EU policy frameworks favor secondary materials.

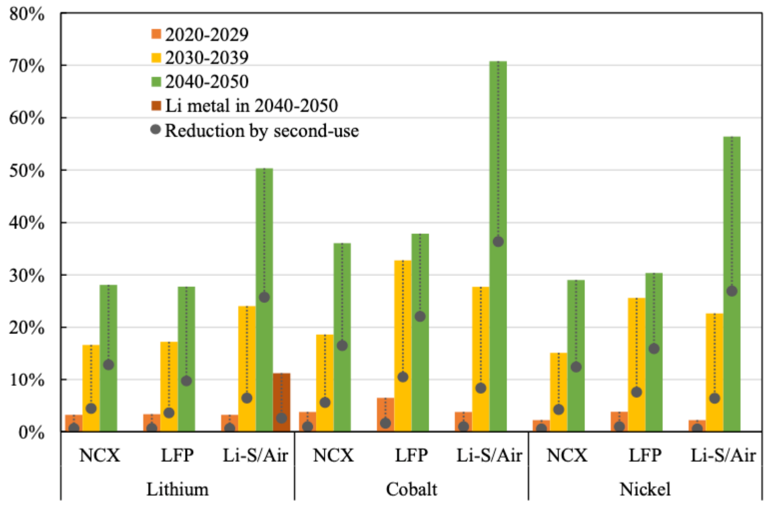

Figure 17: Recycling potentials and second life impact (Xu et al., 2020, p. 6)

Further, Baars et al. (2021) argue that new batteries for SES applications might be more viable due to the barriers of second life uses. Bobba et al. (2019) outline that second life can be used to delay the recycling process until it is more efficient.

5. Discussion

5.1 Second life applications in the circular economy framework

The first research question of this thesis was how second-life applications for electric vehicle batteries will likely play out within the framework of a CE. The discussion around second life applications is controversial. They can yield significant environmental benefits compared to the use of new batteries, but economic and technical feasibilities remain uncertain.

Market opportunities for second life LIBs are mainly related to SES. This market is dynamic due to the rise of forms of renewable energy in Europe. However, applications might be limited to industrial and commercial use cases due to safety concerns for residential areas, a point confirmed by literature and interview experts. Assessment of SoH is cost and labor-intensive, but a battery passport could simplify the process. Additionally, new battery generations might consider second life in the design phase.

Practically, second life applications can be used as a hedging instrument against volatile raw material markets. Companies gain flexibility since they choose when to bring back materials into the cycle. Slowing down of resources competes with the large material demand of a fast-growing industry and the closed loop recycling concept. This dilemma is exacerbated by future regulatory requirements for recycled content in batteries. The delay of recycling in the near term by second life can be an opportunity until recycling is more efficient.

To conclude, second life applications and CE are endorsed in theory, but may have limitations in practice since industry structures and mechanisms are not mature. Regulatory pressure might push direct-to-recycling pathways in the near future, but industry activities and innovative business models are more likely to promote second life applications in the long term and could create a robust recycling market by 2040. Insights from expert interviews, the in-depth analysis, and Niese et al. (2020), suggest that a second life proportion under 20-30% seems likely.

5.2 Consumer perspective

Consumers were generally concerned about the environment while they are less familiar with CE than sustainability since over one-third had never heard the term CE. But support for CE principles regarding policies, transparency, and circularity is high (Table 18).

Regarding the perception of the sustainability of a BEV, almost two-thirds of consumers underestimated material emissions, but the vast majority sees rides with BEV as having lower emissions compared to an ICE (Table 16). There is a strong awareness regarding negative environmental and social impacts of battery manufacturing (Table 17). Consumers overestimated the material recovery rates for lithium while they underestimated material rates for cobalt (appendix Z). The material demand covered by recycling in 2030 was strongly overestimated (appendix AA). It shows that consumers have higher expectations regarding recycling performance. A misalignment in the perception of sustainability and real life cycle assessment performance was observed which is in line with Boesen et al. (2019).

Concerning purchasing intentions, higher rates of recycled material and circularity correlated with higher likelihood of buying decisions. Greater circularity was more favorably considered than battery recycled content (Table 19) as people appear to perceive recycled products as having lower quality (Calvo-Porral & Lévy-Mangin, 2020). Although, there were strong purchasing intentions pertaining to sustainability and CE (Table 19), more than half of the consumers were still uncertain if their next car will be a BEV (Table 13).

Contrary to Kircherr et al. (2018) a lack of interest and awareness could not be identified. Consumers expressed strong affinity towards environmental concerns, critical perceptions of the battery production as well as awareness of CE principles. Considering the complexity, low levels of understanding can rather be linked to an education deficit rather than lack of interest.

To conclude, consumers have high awareness and concern regarding BEV batteries, tend to accept circular products, and therefore are not a barrier for accomplishing transition towards CE. The implication is that circularity appears as business opportunity, but people must be educated regarding quality of recycled materials. Moreover, highlighting BEVs' sustainability benefits could shift buying decisions of undecided consumers.

5.3 A future circular economy in electric vehicle batteries

This section considers three different scenarios: conservative, base case, and optimistic. In the initial assessment, all scenarios were assigned equal probabilities. After identifying different stakeholders and analyzing interrelations of uncertainties, new likelihoods for each scenario were adapted. All analyses are based on the findings of the expert interviews, the consumer survey, and the literature review.

5.3.1 Stakeholder definition

According to Schoemaker (1995), identifying major stakeholders is an important element for understanding different interests, mutual affections and influencing factors.

Primary stakeholder

Primary stakeholders are actors who can directly shape and influence the future of a CE in EV batteries by their actions and their decisions.

Regulators: The institutional power of regulators allows them to create policy to reach overall goals such as the GHG emissions reduction. Regulators have a direct influence on the future of a CE in EV batteries as they already set market objectives.

Automotive companies: Typically, automakers design and sell cars. In the case of EVs, automakers have to secure access to battery cells and are responsible for the waste management. Large automakers can integrate parts of battery cell production and recycling.

Recycling companies: These companies play an important role in a CE since they provide the technology and processes for a closed loop. Recyclers have interest in batteries with valuable metals to have profitable operations. The recycling rates and capacities are essential factors for the availability of SRMs.

Cell producers: Cells are the most critical and valuable part of battery packs. Cell producers are key suppliers for automakers and have to secure access to CRMs. Their interest is in developing new technologies and optimizing battery performance while lowering cost which indirectly affects the consumer.

Consumers: The demand of EVs is driven by consumers which could lead to slow or accelerated market growth. Changing consumer behavior and increasing relevance of sustainability can shape the buying decision. Consumers' acceptance of circular products is indispensable.

Secondary stakeholder

Secondary stakeholders are indirectly affected by market actions. They may shape relationships with primary stakeholders.

Governments: These entities are responsible for implementing European directives. The national legislation and bureaucracy have an impact on the economy. They can also create incentives for investment and support research as well as cross-industry collaboration.

Influencers

Influencers can affect the adaption of concepts in terms of traction and direction.

Media: This player provides news and information to consumers. Media coverage can influence consumers' perception and highlight issues.

NGOs and networks: These organizations create thought leadership and outline best practices for future industry pictures. They might have close collaborations with industry partners but can also be publicly funded.

5.3.2 Uncertainties

According to all experts, second life is important in CE but there is uncertainty about forces related to both the supply and demand side of the market. Recycling is a nascent phenomenon and new technologies are needed (Expert C, D, I). Large investments are required to ramp-up infrastructure that are hampered by regulatory and technological uncertainties (Expert A, C, D, H, I, J). Future batteries with reduced proportions of high-value materials could put further pressure on recycling (Expert A, C, D, J) while second life applications could become more attractive to delay recycling. EV traction might be faster than expected due to high penetration rates and falling costs (Expert H). Hence, a potential gap in supply and demand could arise for CRMs like lithium which could indeed hamper EV sales (Expert E & J). This would strengthen the role of recycling to secure access to those materials but mitigate CE activities (Expert A, E, G, J).

Assessing correlations between uncertainties entailed looking at “yes” answers and how the relation could be positive (+), negative (-) or zero (0). To provide an example: U_1 affects the chance of a “yes” for U_2, the correlation is positive and vice versa (Schoemaker, 1995).

Key uncertainties

U_1 = Will EV traction be faster than expected?
U_2 = Will regulation provide guidance and reduce uncertainty?
U_3 = Will recycling become economically attractive?
U_4 = Will second life applications create a viable market?
U_5 = Will European infrastructure rise at scale?
U_6 = Will future battery technologies reduce use of cobalt and other high-value materials?
U_7 = Will there be a gap between supply and demand of CRMs?

Regulation	U_2			
Market	U_1	U_3	U_4	U_7
Industry	U_5			
Technology	U_6			

Correlation matrix

	U_1	U_2	U_3	U_4	U_5	U_6	U_7
U_1		0	+	+	+	0	+
U_2			+	+	+	0	0
U_3				-	+	-	+
U_4					0	+	-
U_5						0	+
U_6							-

Figure 18: Scenario planning - key uncertainties and correlation matrix

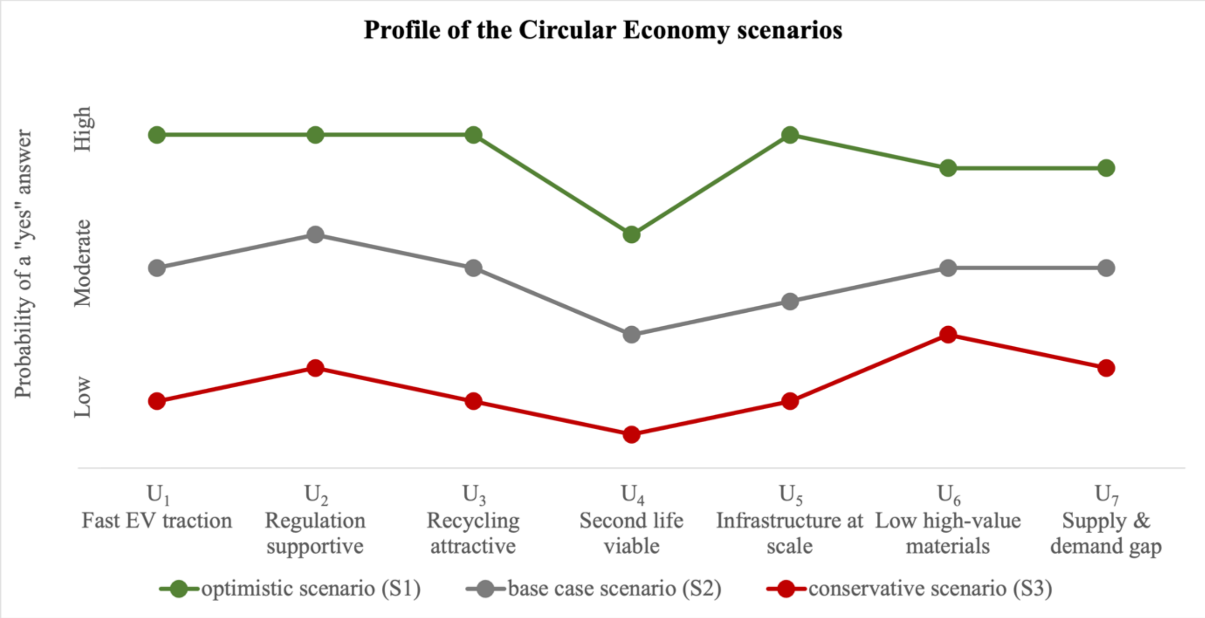

Figure 19: Profile of Circular Economy scenarios

5.3.3 Scenarios for Circular Economy in electric vehicle batteries development

All interview experts were optimistic about the future CE in EV batteries related to strong awareness in the industry. On the one side, enablers like regulations were assessed as very positive (Expert D, E, H, J). Strong commitments of automakers to electrification, shifting consumer preferences and decreasing cost of batteries could fasten EV traction (Expert E & H). This includes expectations of large investments since new joint ventures were already formed (Expert A & E). On the other side, some critical challenges endure. Industry trend towards low-cobalt LIBs seems clear. Technology dynamics remain high and constrains industry investments at scale. Potential gaps in supply and demand can rise and are likely to limit EV traction as a key enabler.

Given the interrelations of the uncertainties, critical challenges could negatively impact key enablers which diminish the optimistic outlook. Regarding the expert estimations, a bias has to be noted. However, the industry is facing a strong regulatory push and future challenges are already anticipated and technological uncertainties considered. The European industry has little choice and must transit towards a CE to achieve decarbonization goals and to be competitive in the long-term. Although, high closed loop levels might not be reached before 2040, industry infrastructure needs to be created from now on. The probability of the optimistic case will strongly increase from 2030 onwards. Taking the findings into account, the likelihood of each scenario can be adopted to following probabilities: Conservative scenario (S_1): 20%, base case scenario (S_2): 35%, and optimistic scenario (S_3): 45%.

S_1 – Conservative scenario

In this scenario, the CE only occurs at a low level. EV traction is slow since consumers are still buying ICEs and lack interest in CE. Due to technological dynamics, almost no level of standardization was reached and the high uncertainty for future technologies has hampered investments. This results in insufficient recycling capacities. The business is still unattractive because of inefficient technologies, low available volume in the market, and small margins. Consequently, European recycling has no significant impact on reducing the demand for virgin materials. Regulations also lack efficacy. The dependency on Asian players is increasing since access to recycled material is needed and the European supply side cannot meet demand. Direct-to-recycling pathways are prioritized over second life applications due to the need for SRMs. The market remains immature and does not evolve.

S_2 – Base case scenario

The base case includes moderate CE levels. EV adaption has increased but not at scale while consumers undervalue recycling due to lack of education. Newly implemented directives set clear industry boundaries, have reduced uncertainties, and accelerated investments. Indeed, compared to international peers, new EU directives appear as overregulated. The underestimation of global implications led to drawbacks that diminish European independence. Recycling mainly improved on the process level as close industry partnerships between automakers, cell producers, and recycling companies enabled cost reductions. However, European recycling technologies lag behind Asian competitors. But European recyclers can, nevertheless, provide a solid number of SRMs to the domestic market. Second life applications are primarily utilized as a hedging instrument against volatile raw materials prices. Use cases in SES do not grow and remain as niche options applied only at lab scale or for intermediary purposes.

S_3 – Optimistic Scenario

Circularity reached highest possible levels. Decreasing the cost of batteries and strong consumer preferences for circular products led to faster than expected EV traction. This allows the industry to operate at scale while regulations set a level-playing field in international competition. A potential gap in supply and demand affects growth. Recycling strongly increased to secure access to CRMs. Recycling technologies became more efficient and able to keep pace with changing battery chemistries. Domestic market prices for recycled materials are driven by regulatory requirements which makes the business more attractive. High recovery rates and large market volumes allow recycling to maximize the supply of SRMs for the European market and to generate a significant effort for a closed loop. Dependency on Asian players might be reduced but still exists. Although the second life market remains small until 2030, a viable market for the long-term occurs when SRM markets are more developed. The high degree of circularity in the European value chain becomes a USP in international competition and further develops into a global role model for CE.

Stakeholder	Conservative Scenario	Base Case Scenario	Optimistic Scenario
Federal / Government	- Fails to promote national economy - High bureaucracy creates hurdles	- Reduces bureaucracy and accelerates permissions processes - Support of research activities and initiatives	- Creates incentives for investments - Strong support of domestic recycling
Regulator / Legislative	- Directives failed initial objectives - European dependency on Asian players increased - Overregulation leads to slow-down	- New directives decrease uncertainty in industry and lead to higher investments	- Adjusts directive proactively - Creates level playing field for CE products - New directives support European companies and make value chain more independent
Automakers	- Directives disrupted competitive advantages - Low collection rates due lack of control - Fails in collaboration with cell producers	- View second life applications only as hedging instrument - Require cell design purely driven by cost and performance instead of CE aspects	- Requires design for reuse and recycling - Creates innovative business models around battery ownership - Views second life as business opportunity
Cell producer	- Research fails to develop new technologies in time - European cell producers cannot close gap to Asian competitors	- Competitive dynamics lead to variety of cell compositions - Design aspects focus on cost and capacity	- New cell designs are optimized for second life and recycling - Cell performance is strongly increased and accelerates EV traction
Recycling companies	- Undersupply of recycled materials for European market - Fail to rise infrastructure significantly due to low investments	- Concentrate on minimal recycling rates from directive - Focus on most valuable materials	- Recycling capacity is strongly increased - Foster close collabo-rations with automakers and cell producers - New technologies increase recovery rates - Provides large part of recycled materials for European market
Consumer	- Low acceptance of circular products - Individual mobility increases - Favors ICEs due to potential drawbacks of EVs or low reach	- Adapts circular products but does not value them - Does assess the car sustainability by use phase emission	- Pushes car companies to offer more circular products - High acceptance of innovative solutions - Strong increase in usage of shared mobility

Table 20: Stakeholder actions in different scenarios

6. Conclusion

This thesis investigated the future of a Circular Economy in electric vehicle batteries. The work was built on two underlying research questions to 1) assess how likely second life applications will play out in the framework of a CE and 2) create a prognosis for a CE in electric vehicle batteries in 5 to 10 years from now.

For RQ1 it was found that second life applications favor CE frameworks based on environmental imperatives. The main use case can be found in the energy storage area but several technical and economic barriers have been identified. Missing designs for second life is one of the key issues of first battery generations. Interviewed experts estimated that future generations will consider second life in the design phase. In contrast to theory, industry insights revealed that second life tends to be primarily perceived as hedging instrument against volatile resource prices. Material flow analysis observed that second life would delay recycling which constrains closed loop potential. Some argue it could bridge the gap to more efficient recycling technologies. However, previous findings were inconclusive as some experts and scholars emphasized unforeseen opportunities. It can be concluded that the future of second life applications remains uncertain. There is a high likelihood that the second life market remains small – less than 20-30% of EoL batteries. The outlook for the long term seems more substantial as recycling markets become more saturated.

Addressing RQ2, the optimistic scenario was characterized by the highest possible adaption of CE levels and faster than expected EV traction in tandem with supply side gaps. Improved recycling technologies enable high recovery rates and provide significant amount of recycled material. Second life appears as viable option but needs to be further developed for the longer term.

Consumers have critical perceptions of the battery production process but see BEVs as environmentally sustainable. The acceptance of circular products seems to be a given, but consumers have to be educated about benefits. Environmental concerns, purchasing intentions driven by sustainability, and CE awareness suggest that consumers will support the transition to CE.

Limitations and further research

This thesis is subject to limitations resulting from its limited timeframe and resources. The data set of the survey was unbalanced. The high degree of uncertainty, also confirmed by the expert interviews, makes accurate prognoses difficult and speculative for this topic.

Battery Passports provides a domain for further research analyzing second life applications as it simplifies the SoH assessment which some scholars previously identified as a barrier. Maybe lithium batteries will be displaced by hydrogen fuel cells or other battery technologies since some automakers are betting on this and this should also be a line of inquiry for researchers interested in battery technology and CE. In general, as the topic evolves, there is considerable scope to become more granular about specific elements of the battery cell. For example, how will the treatment of lithium differ from cobalt, etc., with respect to recycling and CE.

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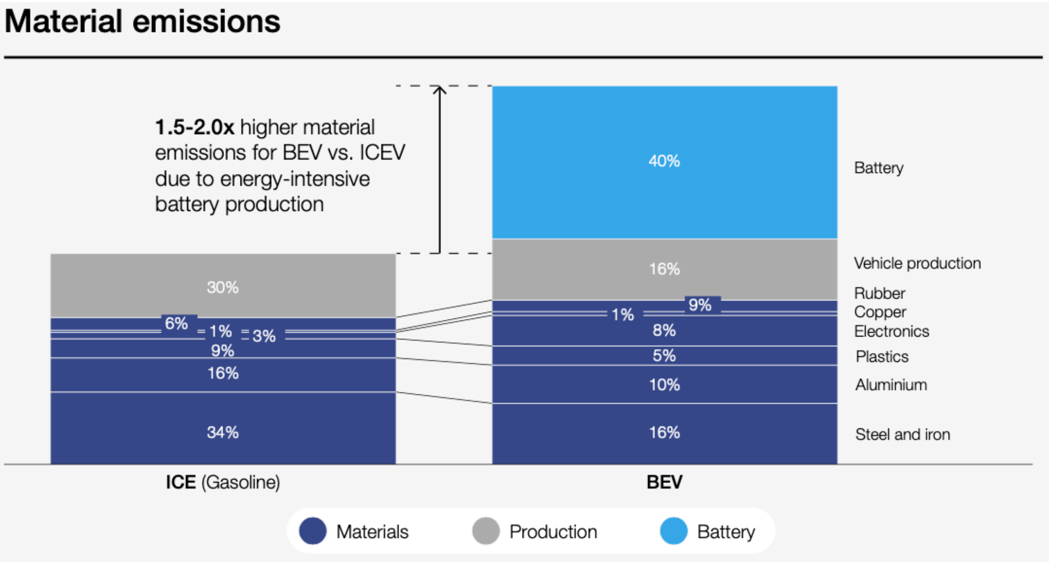
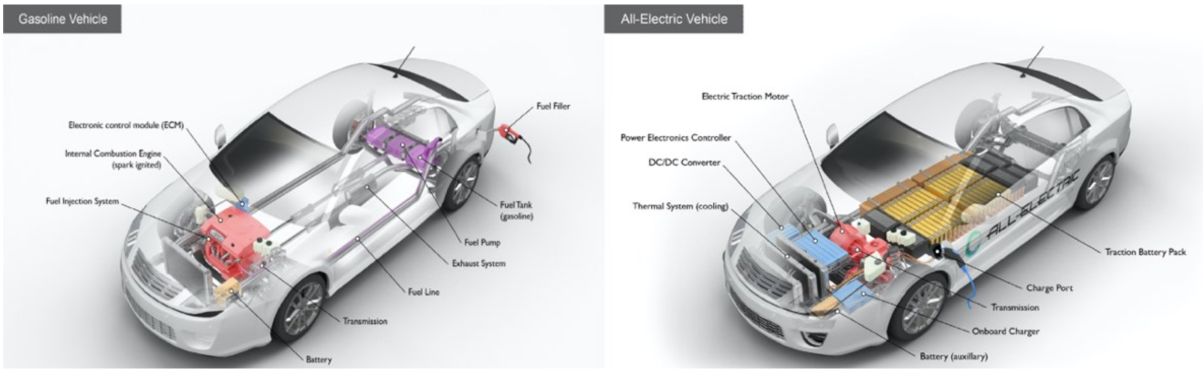
7. Appendices

7.1 Appendix A: Comparison ICE and BEV material emissions



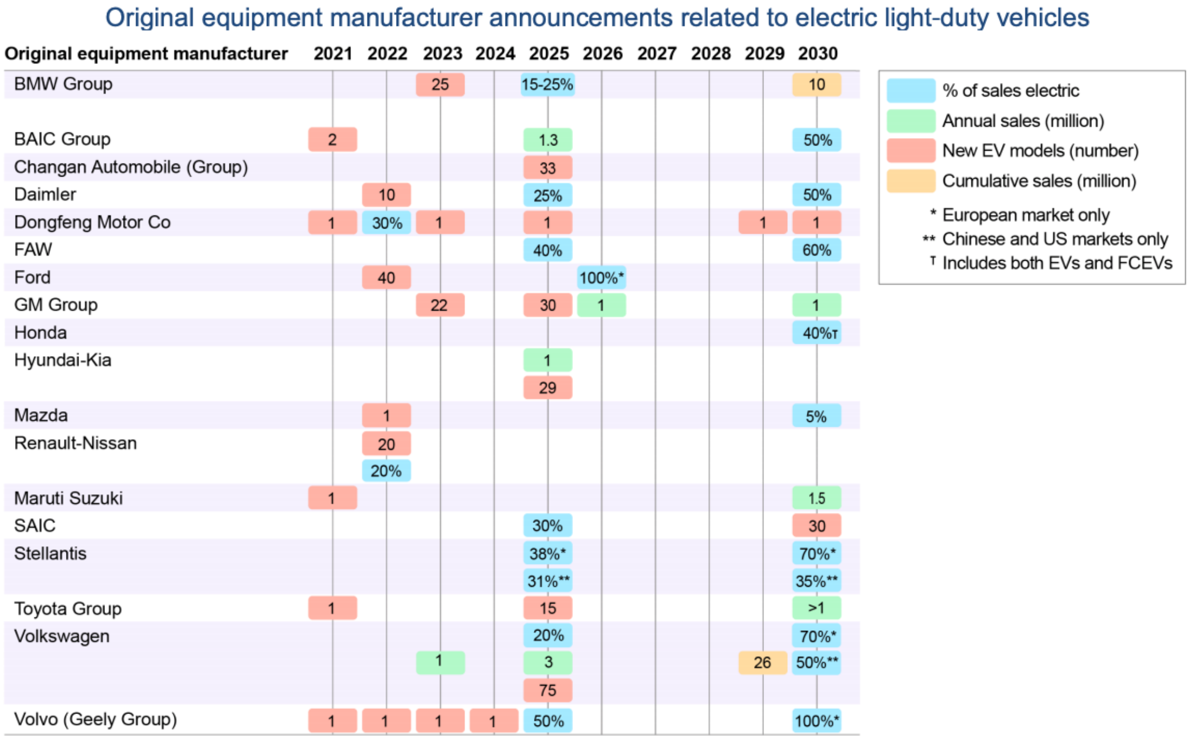
(WEF & SYSTEMIQ, 2021, p. 32)

7.2 Appendix B: Comparison of an ICE and a BEV



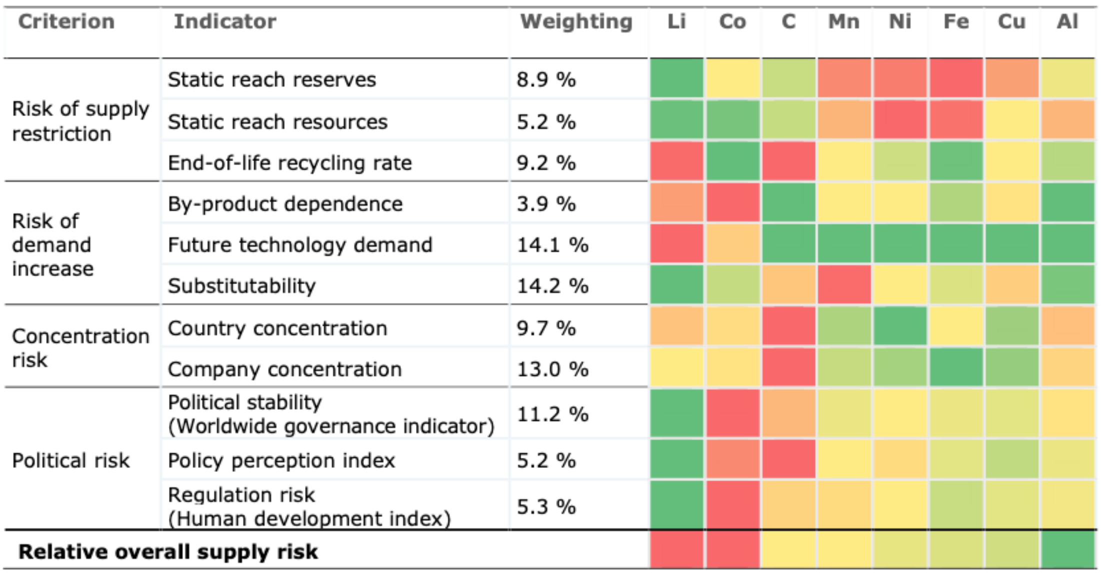
(U.S. Department of Energy, 2021)

7.3 Appendix C: Automaker announcements related to sales of EVs



(IEA, 2021a, p. 25)

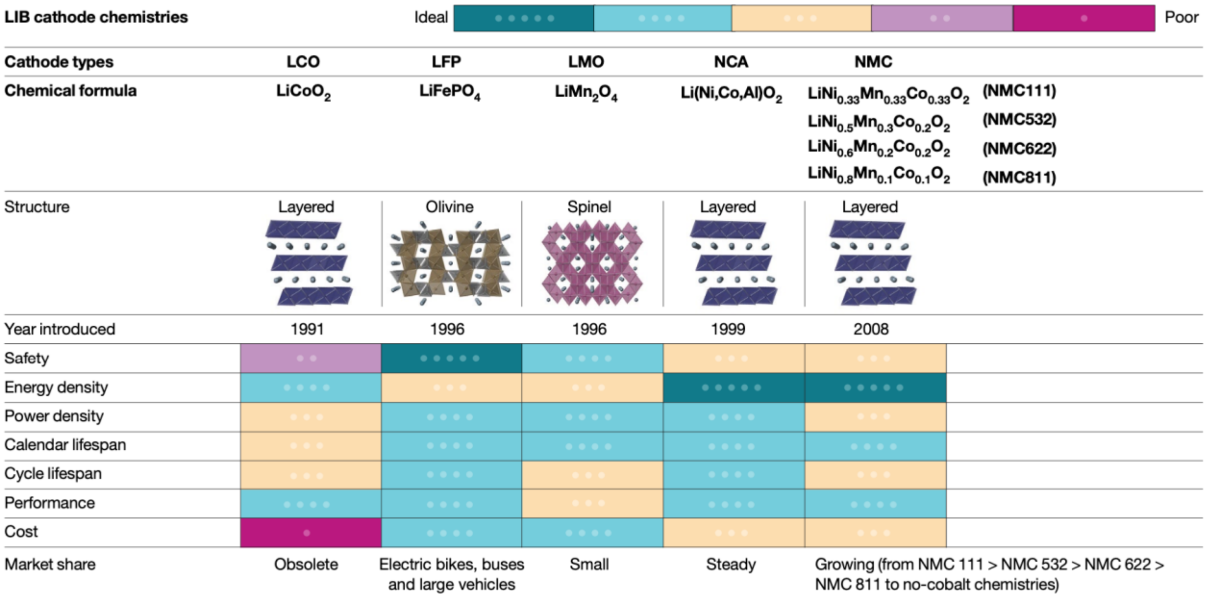
7.4 Appendix D: Supply risks of lithium-ion battery elements



Note: Comparisons are made across rows, i.e. for each indicator.

(Ellingsen & Hung, 2018, p. 37, based on Helbig et al., 2018)

7.5 Appendix E: Performance characteristics of different LIB cathodes



LIB cathode chemistries — Ideal ••••• / •••• / ••• / •• / • Poor

Cathode types	**LCO**	**LFP**	**LMO**	**NCA**	**NMC**
Chemical formula	$LiCoO_2$	$LiFePO_4$	$LiMn_2O_4$	$Li(Ni,Co,Al)O_2$	$LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ (NMC111) $LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$ (NMC532) $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ (NMC622) $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC811)
Structure	Layered	Olivine	Spinel	Layered	Layered
Year introduced	1991	1996	1996	1999	2008
Safety	••	•••••	••••	•••	•••
Energy density	••••	•••	•••	•••••	•••••
Power density	•••	••••	••••	••••	•••
Calendar lifespan	•••	••••	••••	••••	••••
Cycle lifespan	•••	••••	•••	••••	•••
Performance	••••	••••	•••	••••	••••
Cost	•	••••	••••	•••	•••
Market share	Obsolete	Electric bikes, buses and large vehicles	Small	Steady	Growing (from NMC 111 > NMC 532 > NMC 622 > NMC 811 to no-cobalt chemistries)

(Harper et al., 2019, p. 79)

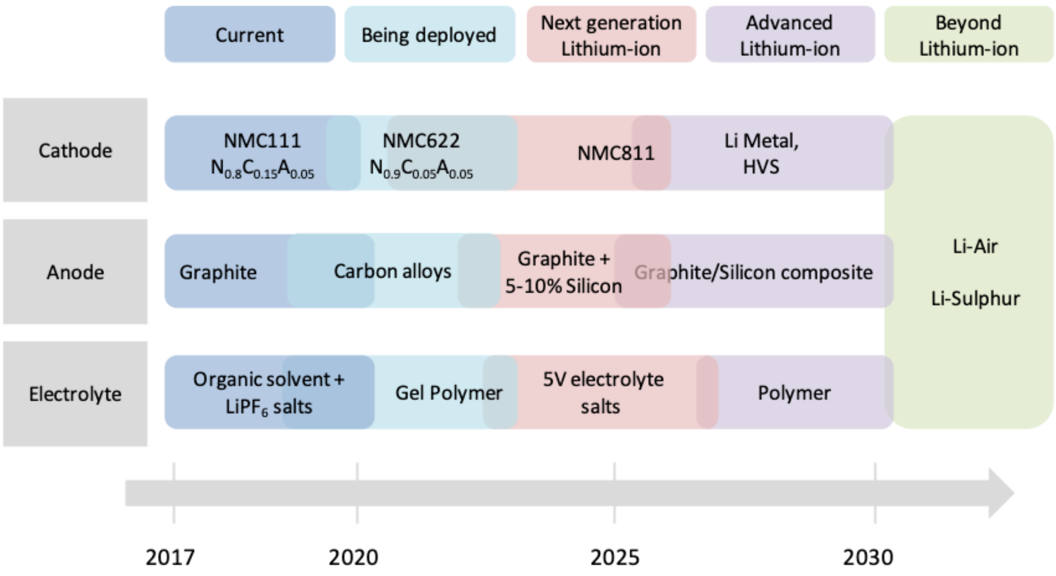
7.6 Appendix F: Lithium-Ion Battery Pack Composition by Weight (kg/kWh)

	LFP	LMO	NCA	NMC 111	NMC532	NMC 622	NMC 811
lithium	0.095	0.106	0.102	0.141	0.136	0.118	0.100
nickel	0.000	0.000	0.672	0.351	0.508	0.531	0.600
cobalt	0.000	0.000	0.127	0.352	0.204	0.178	0.075
manganese	0.000	1.396	0.000	0.328	0.285	0.166	0.070
aluminum	3.528	3.369	2.920	3.110	3.070	3.017	2.921
copper	0.946	0.863	0.564	0.677	0.661	0.605	0.549
graphite	1.085	0.911	0.978	0.978	0.981	0.960	0.961

[a]The lithium weight includes materials in both the electrolyte and the cathode; the nickel, cobalt, and manganese weight include materials in the cathode; the aluminum weight includes materials in the current collectors, cell terminals, thermal conductors, and model and battery enclosures; the copper weight includes the material in cell current collectors, terminals, thermal conductors, and the module and battery enclosures; and the graphite weight represents the material in the anode.

(Dunn et al., 2021, p. 5193)

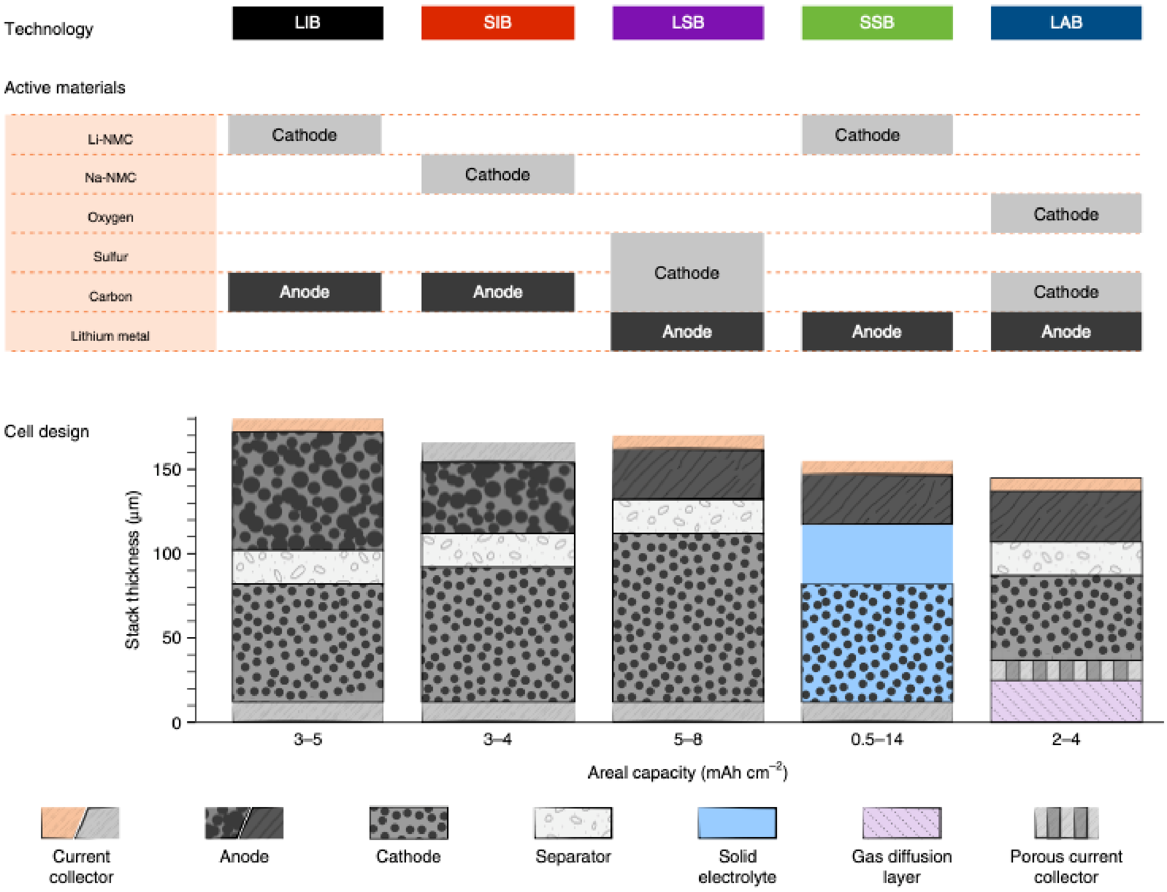
7.7 Appendix G: Overview of battery technology developments



Notes: HVS = high voltage spinel. The diagram shows the likely beginning of commercialisation of a given technology.

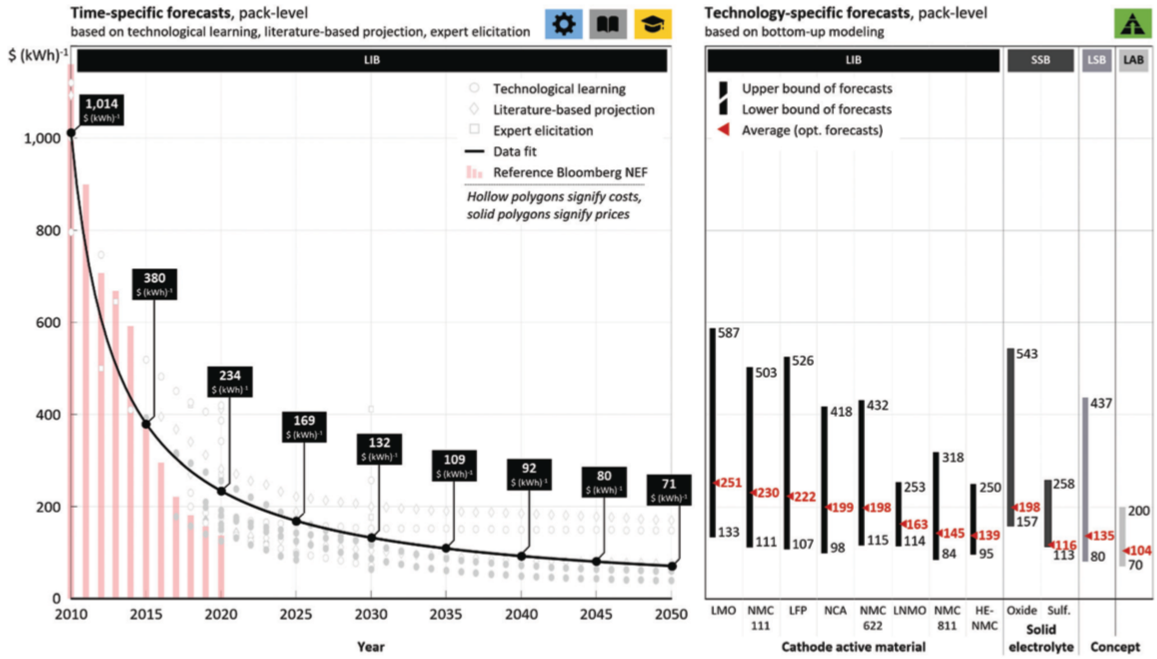
(IEA, 2018, p. 64)

7.8 Appendix H: Active materials of different battery technologies



(Duffner et al., 2021, p. 125)

7.9 Appendix I: Overview of battery cost forecast



(Mauler et al., 2021)

7.10 Appendix J: Supply & demand scenarios for lithium, cobalt, and nickel

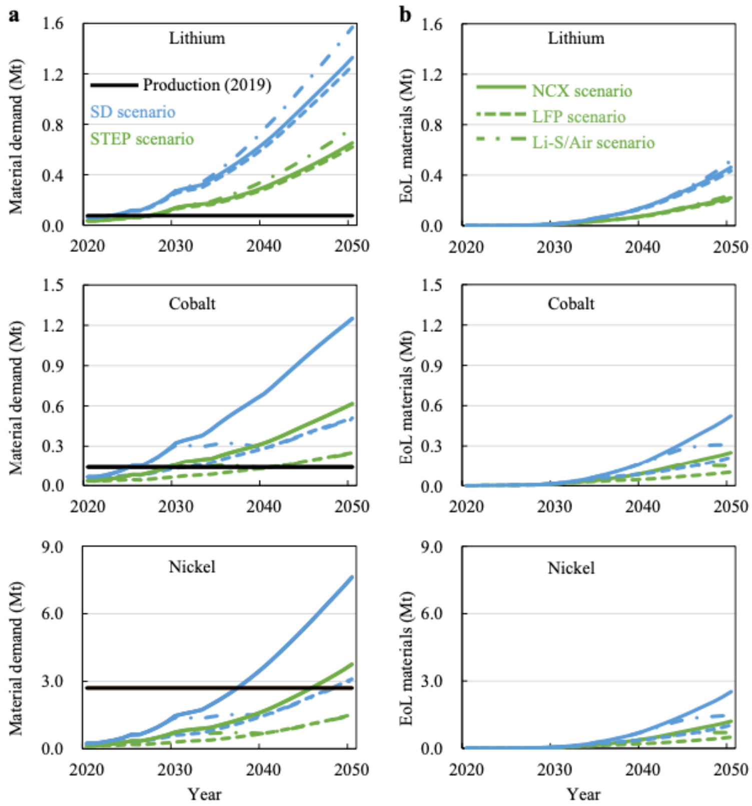


Fig. 3 Battery material flows from 2020 to 2050 for lithium, nickel, and cobalt in the NCX, LFP, and Li-S/Air battery scenarios. a Primary material demand. **b** materials in end-of-life batteries. See Supplementary Fig. 7 for other materials. STEP scenario the Stated Policies scenario, SD scenario Sustainable Development scenario, Mt million tons.

(Xu et al., 2020, p. 4)

7.11 Appendix K: Comparison of different recycling methods

Comparison of different LiB recycling methods Best • • • • • | • • • • | • • • | • • | • Worst

	Technology readiness	Complexity	Quality of recovered material	Quantity of recovered material	Waste generation	Energy usage	Capital cost	Production cost
Pyrometallurgy	• • • • •	• • • • •	•	• • •	• •	•	•	• • • • •
Hydrometallurgy	• • • •	• • •	• • •	• • • •	• • •	• • •	• • •	• • •
Direct recycling	• •	•	• •	• • • • •	• • • •	• • •	• • •	•

	Presorting of batteries required	Cathode morphology preserved	Material suitable for direct re-use	Cobalt recovered	Nickel recovered	Copper recovered	Manganese recovered	Aluminium recovered	Lithium recovered
Pyrometallurgy	• • • • •	No	No	• • • • •	• • • • •	• • • • •	• •	No	•
Hydrometallurgy	• • • •	No	No	• • • • •	• • • • •	• • • •	• • •	• • • • •	• • •
Direct recycling	•	• • • • •	• • • •	• • • • •	• • • • •	• • • • •	• • • • •	• • • • •	• • • • •

(Harper et al., 2019, p. 83)

7.12 Appendix L: Overview of EU's strategies, roadmaps, and regulations

Strategies and roadmaps		
Category	**Name**	**Description**
CE	Circular Economy Action Plan *(new plan published in 2020)*	• Outlines key value chains for circular economy, including batteries and vehicles • Includes various action points to revise certain directives, establish recycled content mandates, VAT reductions for CE products and circular procurement
Mobility	Sustainable and Smart Mobility Strategy *(published in 2020)*	• Lays the foundation for how the EU transport system can achieve its green and digital transformation
Data	European Data Strategy (published in 2020)	• Highlights the future establishment of a European Green Deal and Mobility Data Space to **enable data sharing for circular economy practices** and integrated mobility systems

Regulations		
Category	**Name**	**Description**
Vehicle Emissions	Regulation 2019/631 CO_2 emission performance standards for cars and vans *(Revision in Q2/2021)*	• Regulates the tailpipe emission performance of new cars and vans in the EU (current fleet target is 95g CO_2/km for cars)
ELV	ELV Directive 2000/53/EC *(Revision in 2021/22)*	• Targets are based on the weight of a vehicle (minimum of 95% for reuse and recovery; 85% for reuse and recycling) • European automotive manufacturers are responsible for disposal/recycling costs • Aims at the set-up of treatment facilities • Imposes provisions on vehicle design
Batteries	Directive 2006/66/EC on batteries and accumulators/ waste batteries and accumulators *Former Directive (see new proposal)*	• No explicit inclusion of lithium-ion batteries • Automotive, industrial and electric vehicle batteries are to be collected • Introduces specific reporting/labelling obligations • Prohibits marketing of batteries with specific hazardous substances • **50% recycling rate** established by battery weight
	Proposal for New Battery Regulation	• Minimum recycling efficiency rates are set to be 65% from 2025 onwards

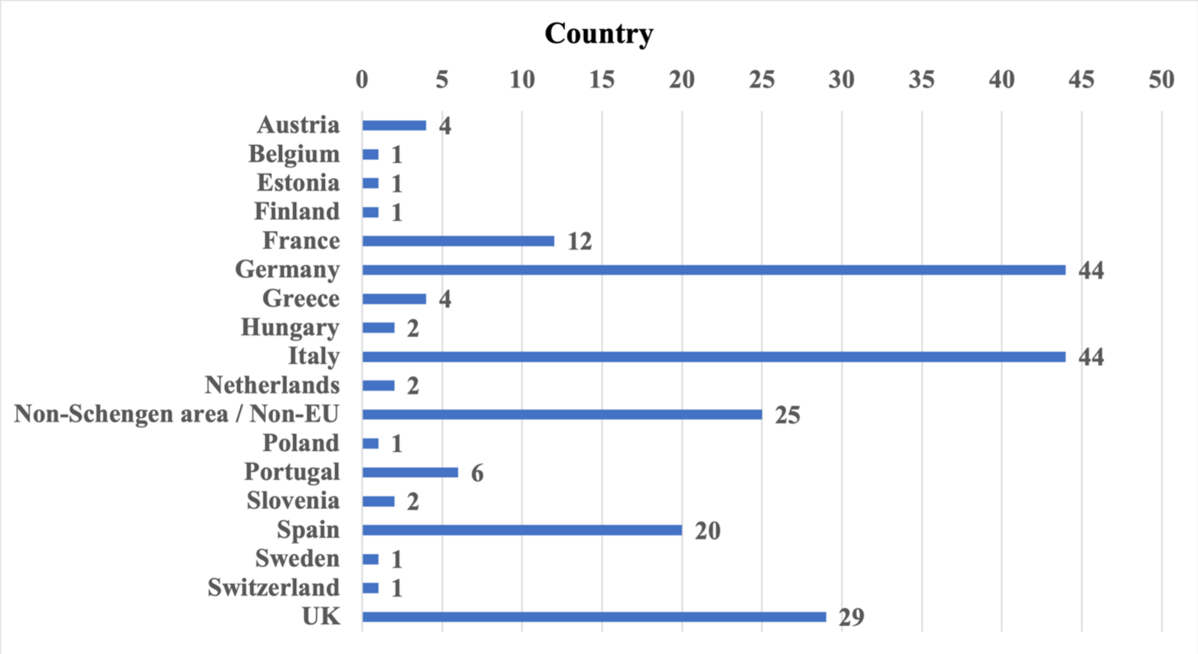
	(To be adopted in Q4/2021)	• **Recovery rates for individual materials**: cobalt 90% (95%), copper 90% (95%), nickel 90% (95%), lithium 35% (70%) – 2026 (2030) • Supported by information/labelling, carbon footprint targets, electronic exchange system and Battery Passport, Green Public Procurement

(own illustration modified from WEF & SYSTEMIQ, 2021, pp. 46–47)

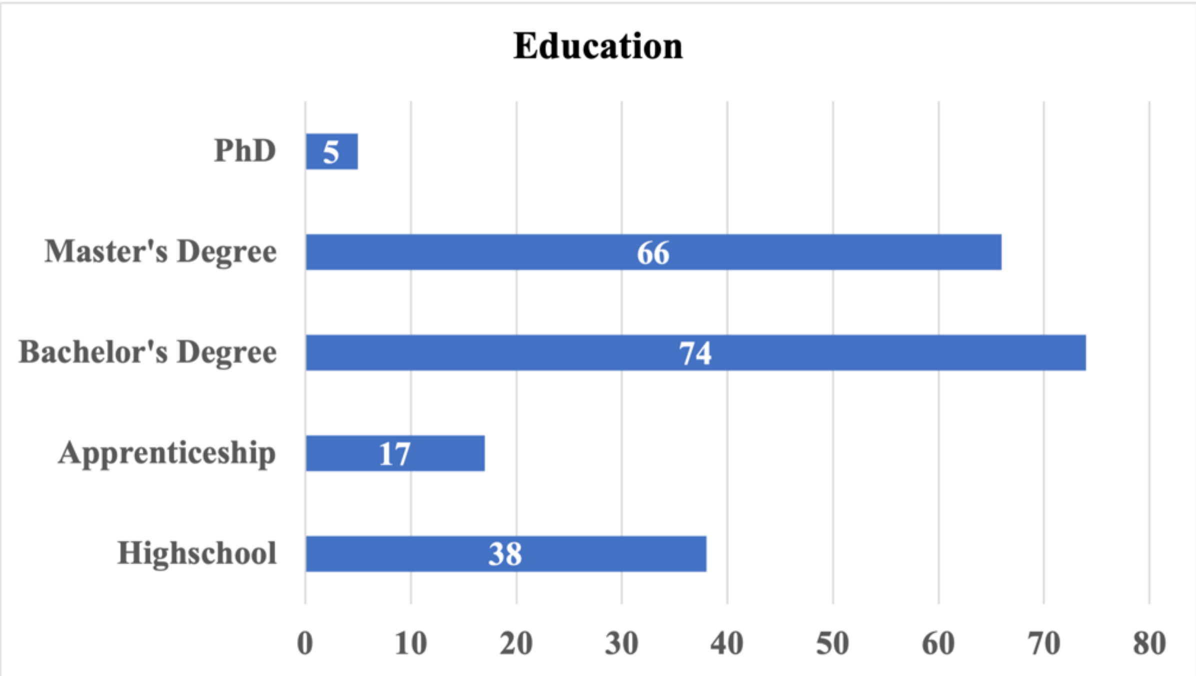
7.13 Appendix M: Interview script versions

#	**Question**
1.)	When you think about the circular economy, what are key questions that do come to your mind?
2.)	What role does a Circular Economy play in your industry and your activities?
3.)	What would be the goals for a European circular economy in electric vehicle batteries?
4.)	How will the preferred EoL treatment look in 5-10 years from now?
5.)	What will be the most prevalent use cases for second life applications?
6.)	What are the key issues regarding the success of second life applications?
7.)	Are we going to see fully integrated players in the battery value chain in Europe or specialized players for each activity?
8.)	What role do regulations play and what is expected from regulators?
9.)	What are the key barriers to create a circular economy for electric vehicles batteries in Europe?
10.)	Which factors enable or accelerate a circular economy for electric vehicle batteries in Europe?
11.)	What is your prognosis for a circular economy in electric vehicle batteries in Europe in 5-10 years from now?
12.)	Is there anything special, you would like to contribute?

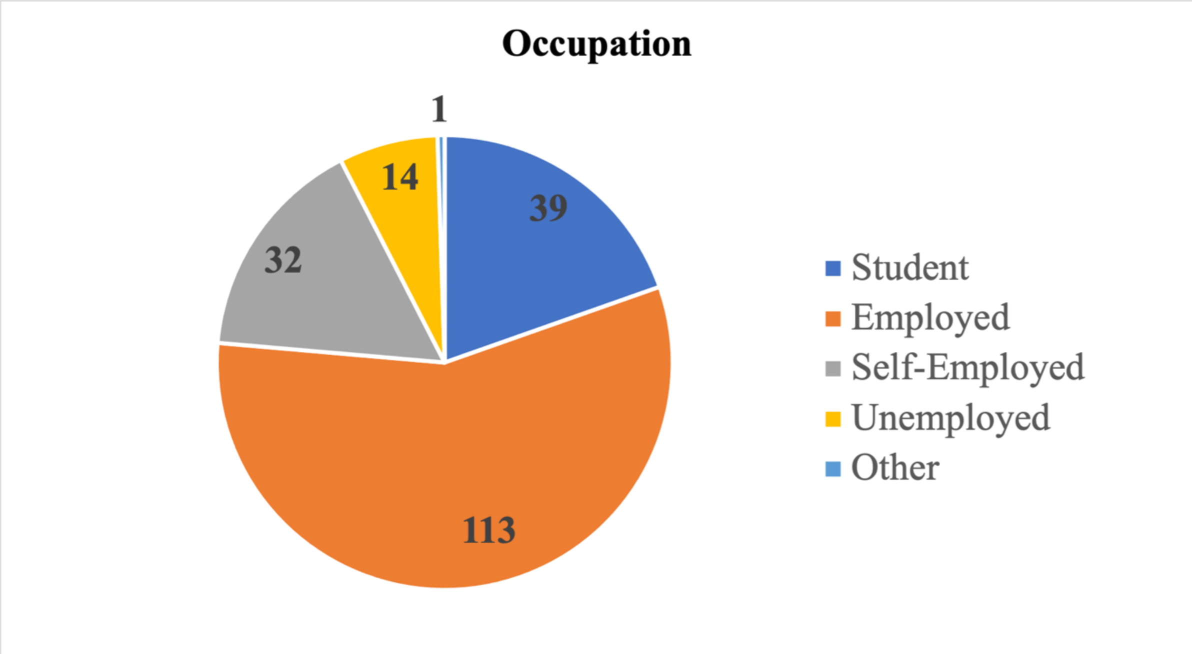
7.14 Appendix N: Survey – Country



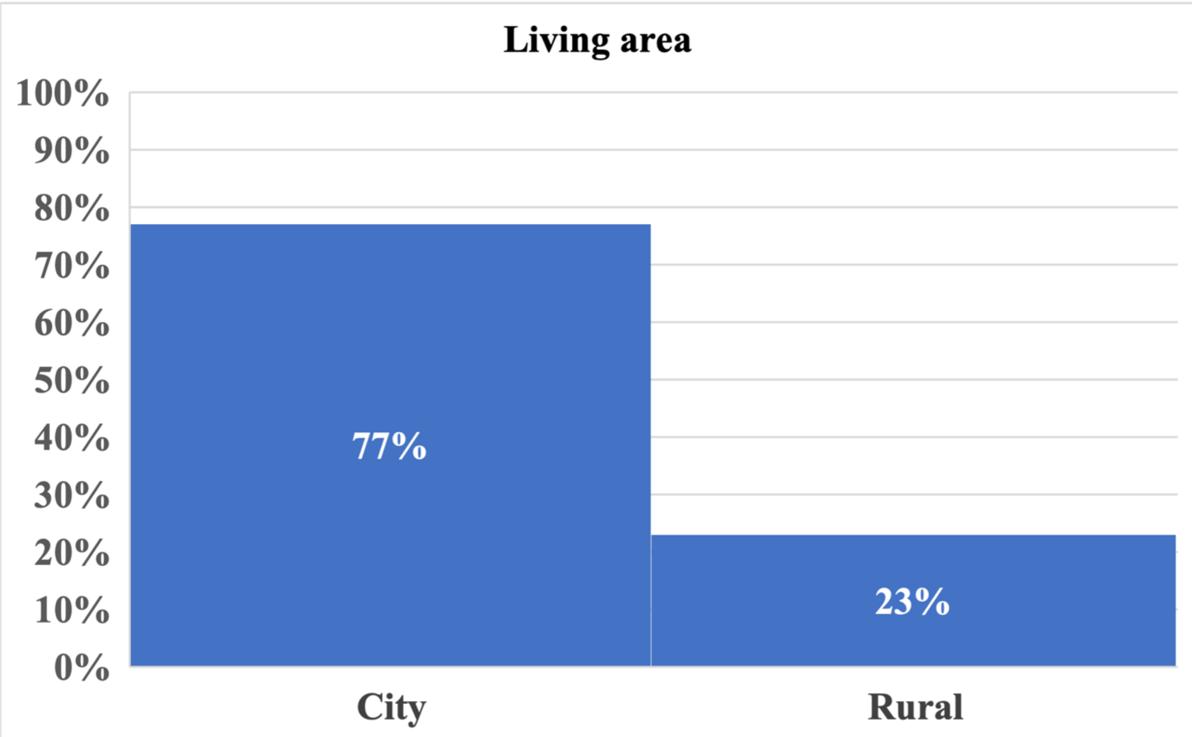
7.15 Appendix O: Survey – Education



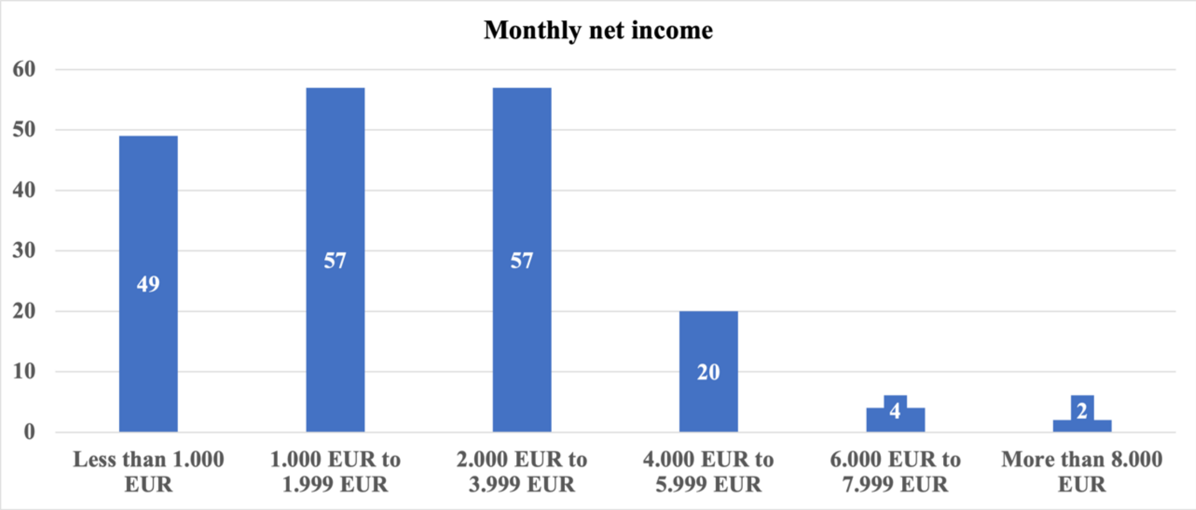
7.16 Appendix P: Survey – Education



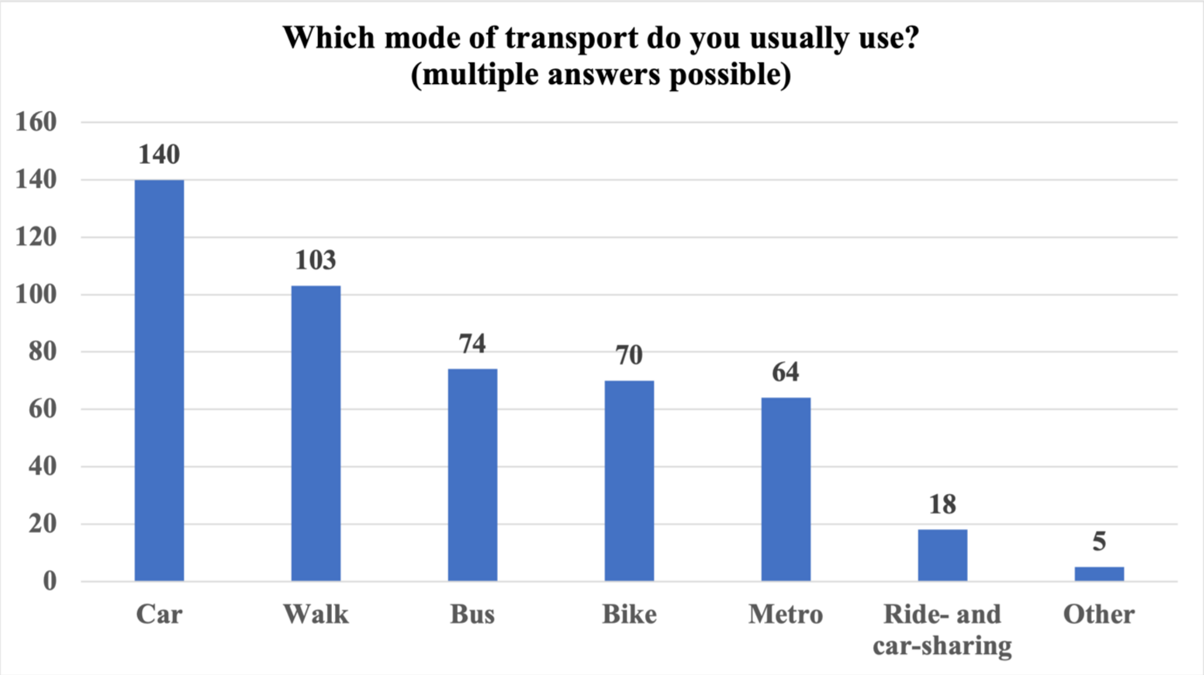
7.17 Appendix Q: Survey – Living area



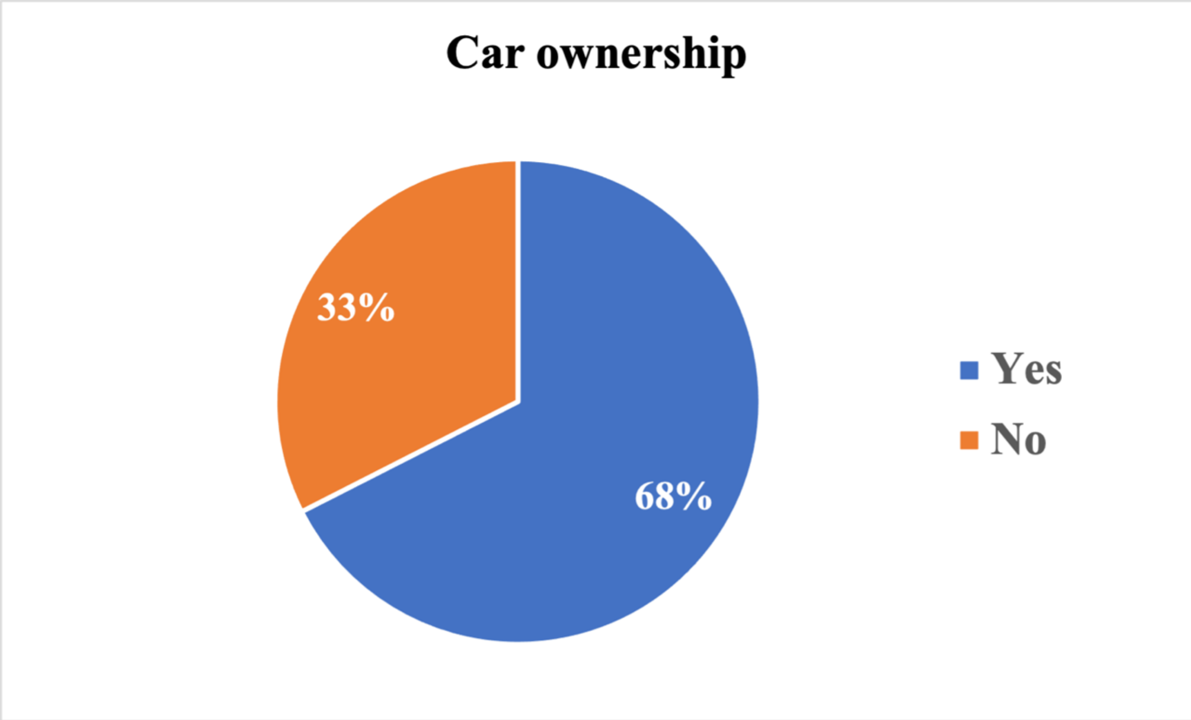
7.18 Appendix R: Survey – Net income



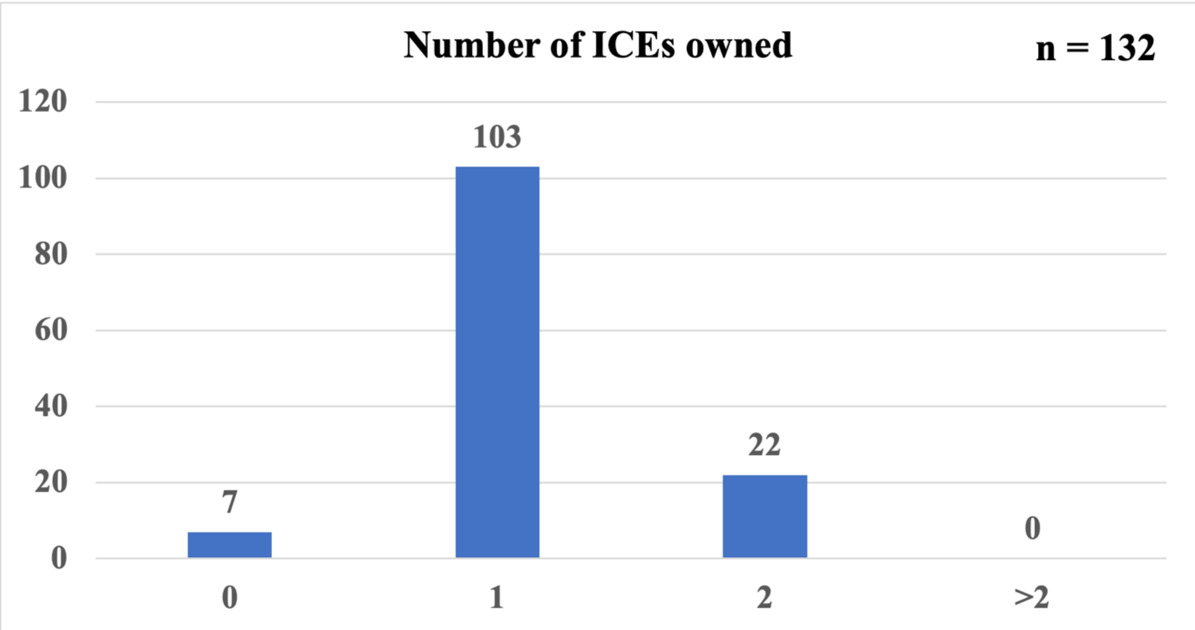
7.19 Appendix S: Survey – Mode of transport



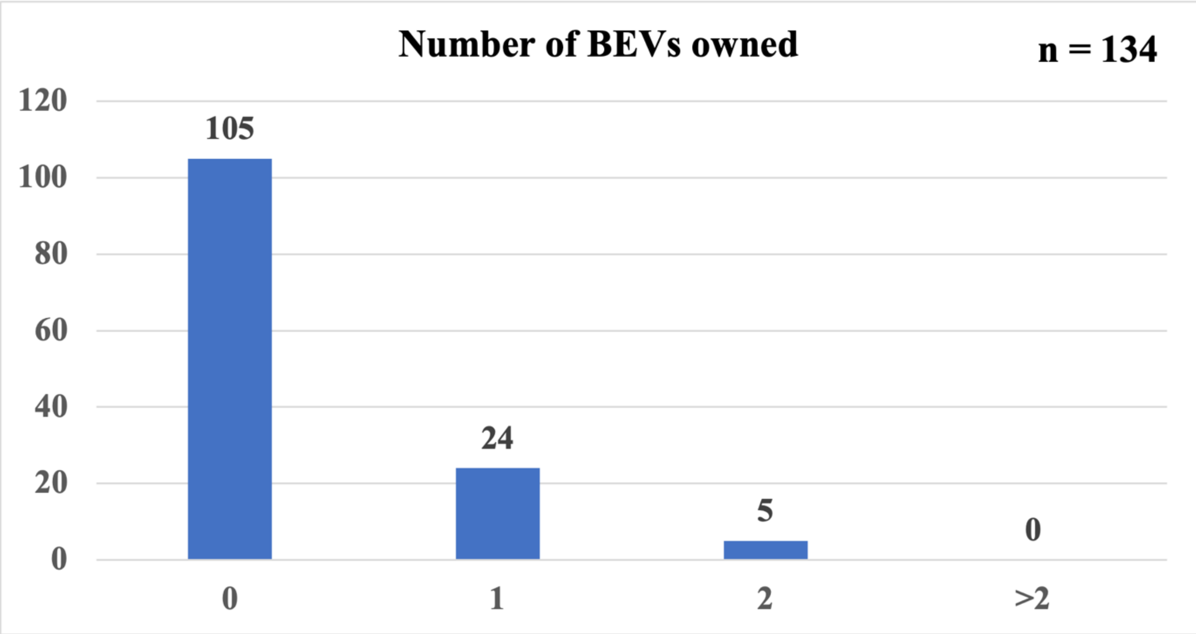
7.20 Appendix T: Survey – Car ownership



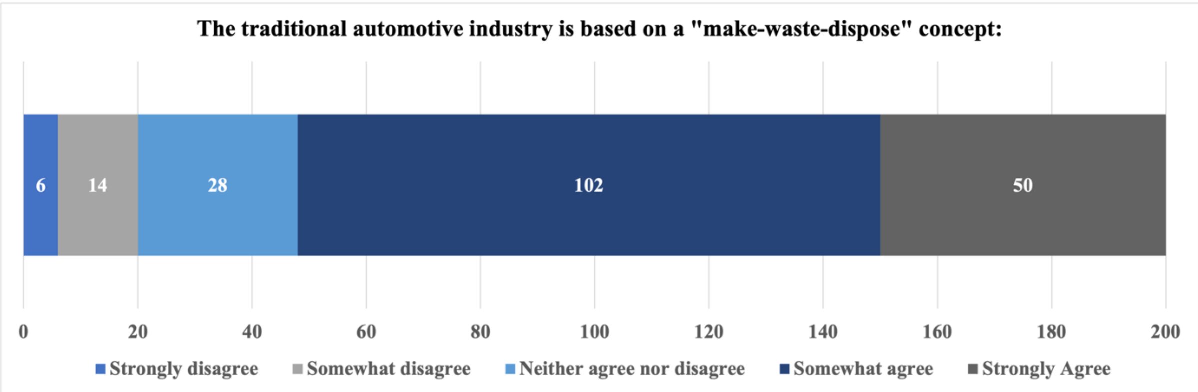
7.21 Appendix U: Survey – Number of ICEs owned



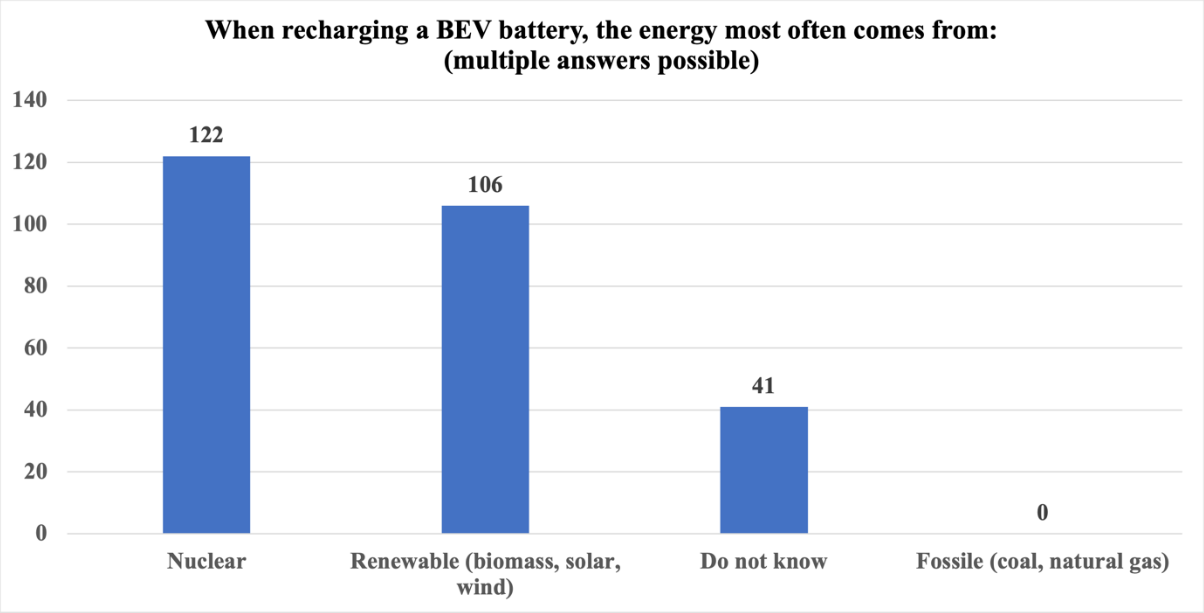
7.22 Appendix V: Survey – Number of BEVs owned



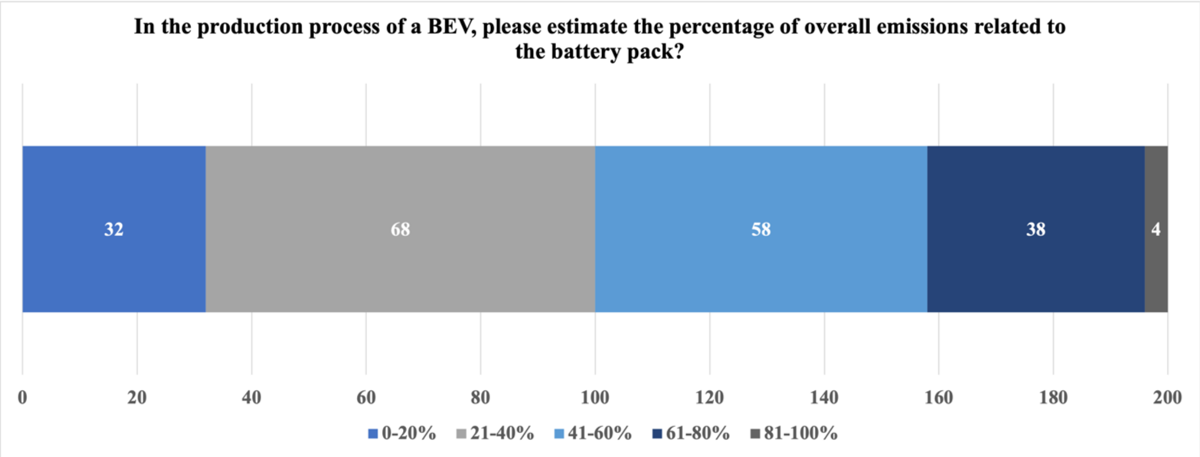
7.23 Appendix W: Survey – Environmental concern: automotive industry



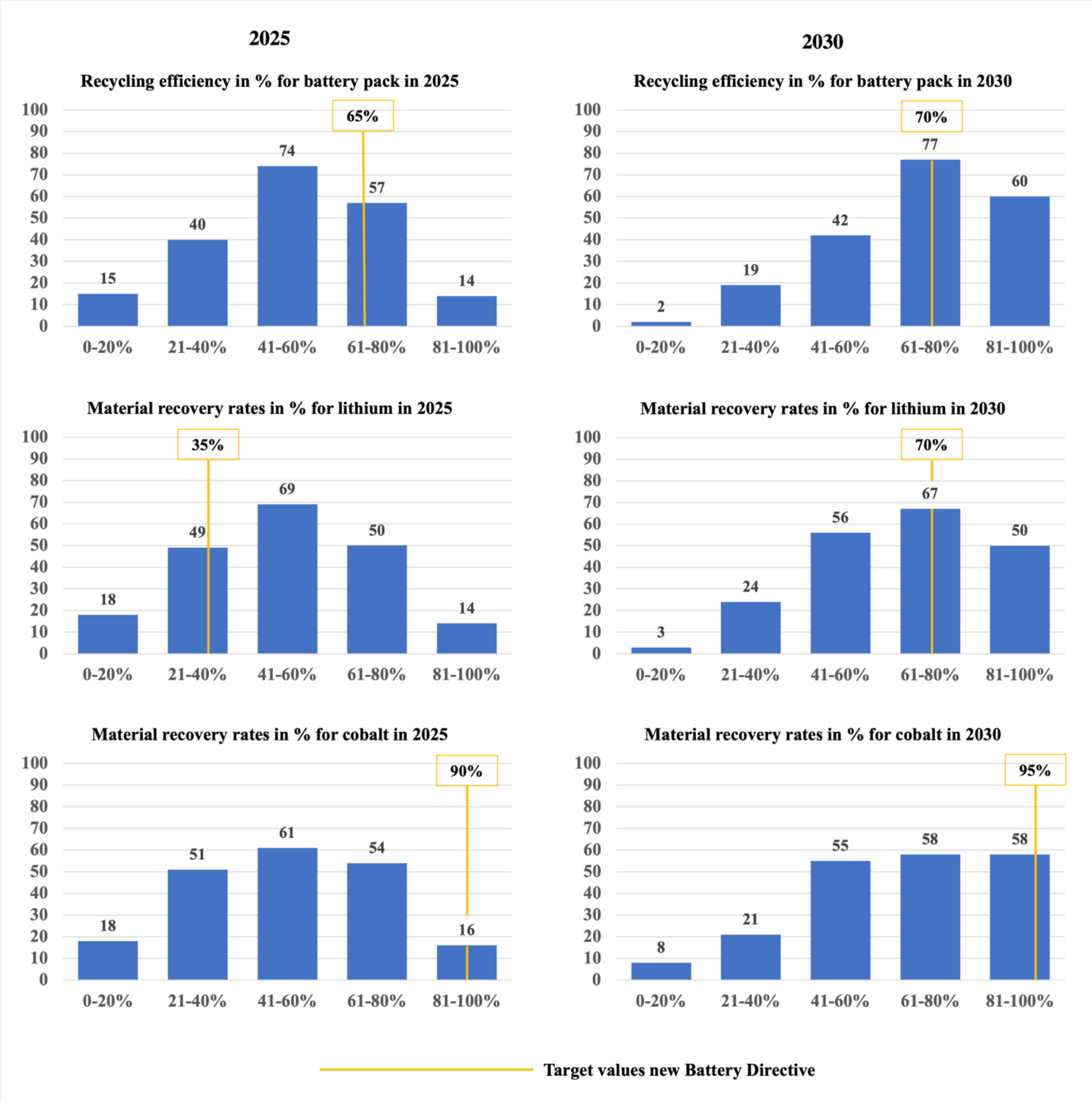
7.24 Appendix X: Survey – Recharging BEVs: energy source



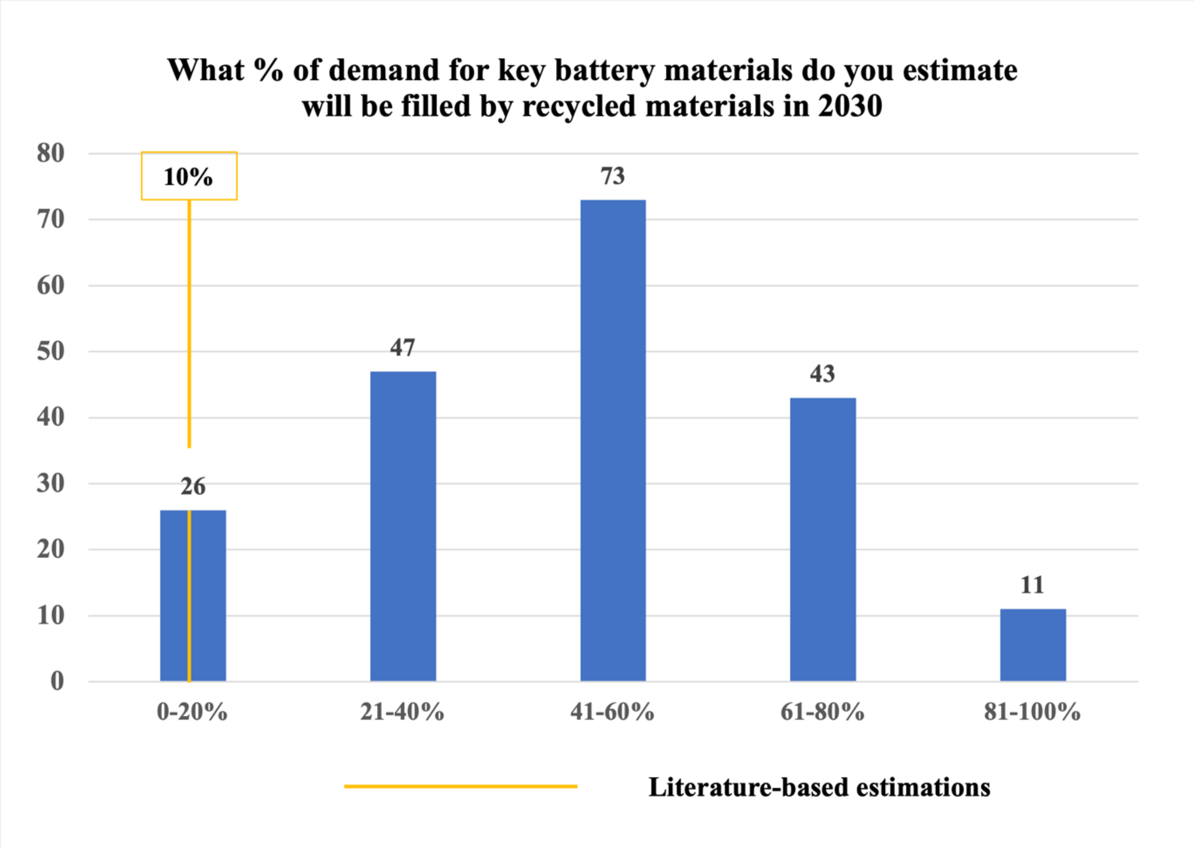
7.25 Appendix Y: Survey – Emission of battery in production phase



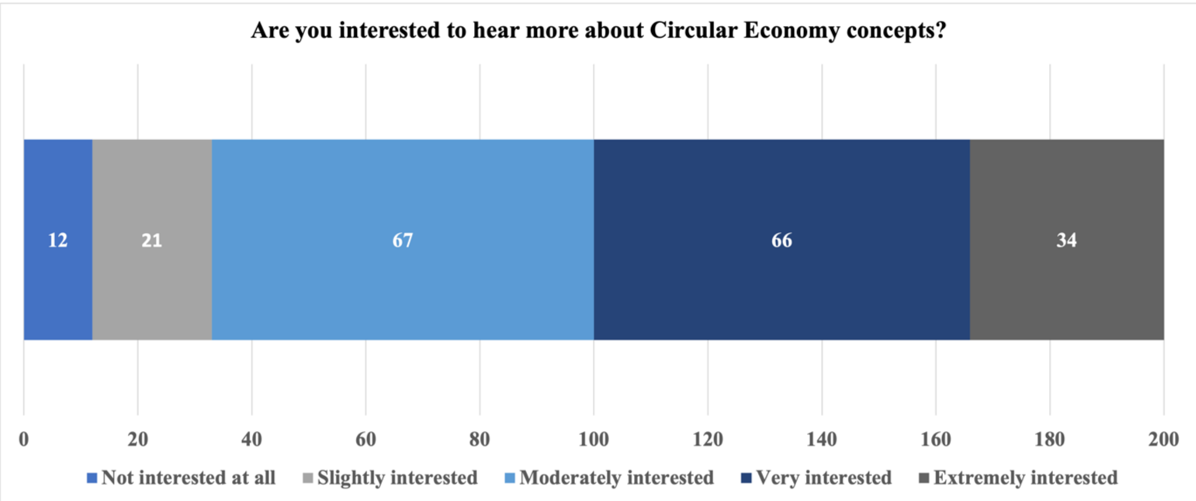
7.26 Appendix Z: Survey – Recycling knowledge



7.27 Appendix AA: Survey – Recycled materials in 2030



7.28 Appendix AB: Survey – Interest in CE concepts



7.29 Appendix AC: Survey – CE support

Likert scale 1-5	Strongly disagree (1)	Somewhat disagree	Neither nor disagree	Somewhat disagree	Strongly agree (5)	Mean
Policy						
Set aggressive Circular Economy targets for the industry and require them	4%	5%	17%	46%	29%	$\mu = 3{,}9$
Invest directly or incentivize investments in European infrastructure (e.g. production and recycling facilities)	4%	5%	14%	37%	41%	$\mu = 4{,}07$
Assess BEV CO2 performance from a life cycle perspective (use phase as well as production phase)	3%	5%	13%	42%	38%	$\mu = 4{,}09$
Require car manufacturers to share information about the battery usage and status of health with other companies	3%	5%	17%	42%	34%	$\mu = 4{,}09$
Transparency						
Having full transparency about the life cycle emissions of the BEV instead only of the use phase emissions	2%	6%	16%	40%	37%	$\mu = 4{,}04$
Having transparency in the battery production (e.g., mining, cell manufacturing) and what happens after the batteries end-of-life (e.g., collection, reuse, recycling)	3%	6%	13%	34%	45%	$\mu = 412$
Circularity and independency						
European battery production should aim to increase the % of material demand covered by recycled material	3%	4%	10%	39%	46%	$\mu = 4{,}21$
European battery industry should become less independent from Asian producers	4%	11%	27%	27%	33%	$\mu = 3{,}75$
Second life						
A battery should be reused for other applications before it goes into recycling	3%	3%	16%	33%	47%	$\mu = 4{,}18$
Reusing a battery for other applications to increase resource efficiency is more important than bringing the materials directly back into manufacturing	2%	6%	24%	37%	32%	$\mu = 3{,}91$

7.30 Appendix AD: Survey – Buy BEV if end up in a waste dump