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Sustainability and circularity metrics for EV batteries: Enabling circular economy strategy decision making and value communication

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Abstract

The increasing focus on lithium-ion batteries (LIBs) in the context of electrification of transport sector has raised concerns about their high costs, resource and energy demands, environmental impact, and social supply chain risks. To address these challenges and maximize the value of LIBs throughout their lifecycle, circular economy (CE) strategies, such as reusing and repurposing, are being explored. These strategies offer economic, environmental, and social benefits. However, managing LIBs' lifecycle from an environmental perspective involves balancing objectives related to resource depletion and climate change, alongside contextual factors and business considerations like regulatory requirements and customer acceptance. The study found a knowledge gap of sustainability and circularity metrics for life cycle management of LIBs to promote slowing the loop strategies. To track and communicate these relevant metrics for CE strategies, the development of a Digital Battery Passport (DBP) is considered essential.

This research study investigates sustainability and circularity metrics that are pertinent to the DBP and support the implementation of slowing the loop strategies. The study examines the practical, academic, and policy perspectives by conducting interviews across the value chain. The findings emphasize the significance of adopting a diverse set of metrics industry-wide, enabling data-driven decision-making and effective communication to support CE business models. Additionally, the study explores the role of servitization in operationalizing the DBP. Servitization facilitates data access, streamlines battery ownership, and enables the adoption of circular economy strategies by promoting the use of second-life products.

Keywords: Sustainability metrics, Circularity metrics, LIB CE strategies, Second life battery energy storage system, Product service system

Executive Summary

Background

As electronic vehicles (EVs) gain popularity, the demand for lithium-ion batteries (LIBs) used in these vehicles is also expected to rise significantly. However, the manufacturing and disposal of LIBs have environmental and social impacts, such as energy-intensive production, habitat destruction from raw material extraction, toxicity concerns, and social concerns of child labor, forced labor, corruption, and poverty. Circular economy (CE) strategies, including narrowing resource loops, slowing resource loops, and closing resource loops, are being explored to address these challenges and optimize the value of LIBs throughout their lifecycle. Repurposing EV batteries for energy storage systems is gaining traction as a promising approach, as it supports renewable energy integration and extends the lifespan of batteries. However, there is a lack of research on sustainability and circularity metrics that can enable informed decision-making and value communication of LIBs. The development of a Digital Battery Passport (DBP) is seen as a crucial tool for tracking and communicating these metrics. Additionally, it is hypothesized that the adoption of product service system (PSS) models in the EV industry can facilitate data sharing by fostering stakeholder cooperation, and improved product management towards a CE.

Research aims and methodology

The aim of this study is to explore sustainability and circularity metrics that can enable slowing the loop CE strategies for batteries and their sustainability value communication of batteries. To contribute to this aim, the following research questions (RQs) are examined:

RQ1: How can sustainability and circularity metrics as part of DBP can support slowing the loop strategies for batteries to create most sustainability value?

RQ2: What are the perceptions of value chain actors and potential users of second-life batteries towards sustainability and circularity metrics that can be used to support their adoption?

RQ3: How can servitization help in operationalizing the DBP?

The data collection methods employed include a literature review, analysis of publicly available documents, and semi-structured interviews. Total of 24 semi-structured interviews were conducted covering policy expert, CE experts, key actors in the battery value chain, and software as a service provider for DBP. These interviews aimed to capture practitioners' perspectives, decision-making processes, and experiences related to circularity strategies for batteries. The interviews also explored stakeholders' perceptions of sustainability and circularity metrics, data requirements for the DBP, and the facilitation of CE strategies through knowledge sharing.

Findings

RQ1: What sustainability and circularity metrics are relevant for DBP to support slowing the loop strategies?

Environmental metrics: The relevant environmental metrics for batteries to support slowing the loop strategies include carbon footprint, resource footprint, and other impact categories such as toxicity, air quality, total energy consumption, ozone depletion, and water consumption. Carbon footprint is particularly significant as it is regulated by the EU battery regulation. The use phase and repurposing/remanufacturing stages would need to be covered for realistic understanding of GHG reduction benefits from life extension and applications of second life battery energy storage system (SLBESS) covering grid stability and increases renewable energy

sources use. Renewable energy integration could be measured separately inspired from the SDG target 7.2. Resource footprint assessment is another important metric measuring critical mineral depletion implications due to CE strategies.

Social metrics: The relevant social metrics for batteries to support slowing the loop strategies include social impacts in the upstream supply chain, such as human rights, labor rights occupational health and safety and poverty. CE strategies can provide social benefits by reducing negative impacts, such as avoiding child labor associated with mining activities by reducing need for new batteries due to improved battery lifetime and material management downstream. SLBESS additionally contributes to achieving SDGs inspired metrics, in the area of affordable and clean energy access, affordable transportation and job generation with opportunities in the refurbishment, repair, and production of second-life batteries contributing to poverty reduction and promoting technical skills and decent jobs. However, in literature positive social impacts are rarely measured using systematic assessments.

Circularity metrics: To support slowing the loop strategies, relevant circularity metrics for batteries include recycled content, collection rate, and material recovery rates, which are mandated by the EU battery regulation. Developing an overall circularity score that increases transparency and enables informed purchasing decisions for products and end-users could incentivize the production of batteries designed with circularity in mind. Further aggregated steering metrics, and granular monitoring metrics are relevant for decision making and monitoring. These metrics evaluate aspects such as resource efficiency, product life extension, disassembly, recycling, renewable energy consumption, material usage reduction, product lifespan, ownership time, and recycling rates.

RQ2: What are the perceptions of value chain actors towards these sustainability and circularity metrics?

Environmental: The primary environmental metric considered important was CO_2 emissions. It is crucial to develop a methodology for measuring this. Other metrics, such as total energy consumption, water consumption, toxicity, and air pollution, were ranked in decreasing order of importance. Supporting renewable energy and addressing resource depletion were particularly important for communicating value and supporting business case of repurposed batteries.

Social: Regarding social metrics, the current focus is on transparency and traceability. Using certifications and indices related to social aspects on the DBP could provide greater assurance and transparency. However, there is a need to develop metrics similar to those developed by the Global Battery Alliance (GBA) to better quantify social impacts and understand the link between social aspects and the circular economy, which is currently weak. However, operationalizing metrics in social impact areas can be complex due to various tradeoffs.

Circularity metrics: Stakeholders along the value chain identified the ease of disassembly index as the most important for enabling circular economy (CE) strategies. Other important enablers included standardization, safety, and data accessibility. However, not all value chain stkeholders prioritize the same aspects of circularity. While metrics like the share of renewable energy and reductions in water, waste, energy, and materials per unit of production were important throughout the value chain, metrics like product life extension were more significant during product use and strategies related to reusing and repurposing. It is necessary to supplement existing metrics mandated by regulation with a comprehensive set of circularity metrics to not only measure product circularity performance and communicate the value of the product to stakeholders but also address crucial aspects of the circular economy. The link between economic aspects and metrics was observed to be crucial for adoption and integrating sustainability value into circularity metrics was highlighted as a priority.

Overall: The main drivers for using metrics were identified as legal requirements and customer demand. Some metrics aim to enable CE strategies, while others are intended to ensure industry compliance with standards. Potential use of metrics includes, procurement teams using the metrics for supplier contracts, setting targets for improvement, and using for value communication and product differentiation. To make the metrics mainstream, it is important for original equipment manufacturers (OEMs) to lead by demanding them for them to be accepted across the value chain with a common understanding.

RQ3: How can servitization help in operationalizing the DBP?

Servitization can help in operationalizing the DBP by enabling data access, ownership control, and supporting circular economy strategies. As the EU battery regulation mandates data collection, servitization models might not be a necessity to access relevant data. Also, huge investments like SLBESS as a product would also require data monitoring services. However, through servitization, providers can have full control over the product, allowing them to collect and share data, facilitate data standardization, and ensure data quality. Additionally, ownership of batteries through servitization models enables better control over the battery's secondary revenue stream and supports sustainability goals like higher recycled content and offer second life products. However, there are challenges, including customer preferences for ownership, concerns about battery performance, and short-term cost considerations. Understanding customer needs, monitoring product performance, and fostering collaborative relationships are essential for successful implementation of servitization models in the battery industry.

Recommendations

Based on the findings of this research, several recommendations for LIB value chain actors and policy makers that aim to develop a sustainable and circular life cycle management for LIBs are formulated:

1. **Use of CE metrics along with environmental and social metrics ad different levels**

There is a need to realize the benefits of circularity metrics in informing design decisions, monitoring progress, and managing complex externalities like biodiversity without the need for time consuming assessments. Prioritizing data-backed approaches and considering linkages of environmental and social value to circular economy in communications with customers. Further, these metrics need to be explored at product level and organizational level.

2. **Industry wide effort to develop a common language and methodology for metrics**

Industry stakeholders need to adopt a unified approach to measure and monitor circular performance. Establishing a common set of metrics and calculation methodologies is crucial for promoting a shared vision of a circular economy. Original equipment manufacturers (OEMs) would play a key role in driving the adoption of metrics throughout the value chain.

3. **Diversify metrics on DBP in future iterations**

Policymakers should complement the existing metrics with comprehensive sustainability and circularity metrics such that CE hierarchy can be followed while communicating the whole picture of product impacts throughout the life cycle.

4. **Consider servitization models for enabling CE**

Servitization models can be a valuable approach to operationalize the DBP, facilitating data access, streamlining battery ownership, and stakeholder cooperation. Additionally, ownership through servitization supports sustainability goals and adoption of second life products.

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Abbreviations

BESS - Battery energy storage system

BMS - Battery Management System

CBM - Circular Business Model

CE - Circular Economy

DBP - Digital battery passport

EPR - Extended Producer Responsibility

EV - Electric Vehicle

GBA - Global battery alliance

GHG - Greenhouse Gas

LCA - Lifecycle analysis

LCO - Lithium Cobalt Oxide

LFP - Lithium Iron Phosphate

LFP - Lithium Phosphate

LIB - Lithium-Ion Battery

LMO - Lithium Manganese

LNO - Lithium Nickel Oxide

LTO - Lithium Titanate

MFA - Material flow analysis

NMC - Lithium Nickel Manganese Cobalt Oxide

OEM - Original Equipment Manufacturer

PSS - Product service system

RES - Renewable energy sources

RUL - Remanining useful life

SaaS - Software as a service

SLBESS - Second life battery energy storage system

SOH - State of Health

1 Introduction

Human activity, particularly the industrial revolution, has caused global temperatures to rise by about 1°C above pre-industrial levels. It has already led to profound changes in human and natural systems, with extreme droughts, floods, acidified oceans, increased poverty, rising sea levels and loss of biodiversity. Greenhouse gas (GHG) emissions are the main cause of global temperature rise (IPCC, 2022).

Transport is responsible for about one fifth of global GHG emissions, and road transport accounts for three quarters of transport emissions, or 15% of total emissions. In the European Union (EU), passenger cars account for around 80% of GHG emissions in the transport sector (International Transport Forum, 2017). In particular, heavy-duty vehicles such as buses and trucks are responsible for around a quarter of CO_2 emissions from road transport in the EU. By 2030, two-thirds of the world's population is expected to live in cities, contributing to exponential demand for transport and infrastructure/mobility (UN, 2022, Volvo Group, 2021). For trucks, for example, the main driver of this trend is the growing demand for freight transport from booming e-commerce (Volvo Group, 2021). To contribute to the goal of a carbon-neutral EU, vehicles will increasingly be powered by electric batteries or fuel cells (IEA, 2022).

Electric vehicles are becoming increasingly popular as a way to reduce reliance on fossil fuels and decrease carbon emissions from transportation as technological developments in batteries advance. Electric car sales continued to increase in 2021 by more than 65% year-on-year to 2.3 million, after the boom of 2020 (IEA, 2022). Registrations of electric buses and heavy-duty trucks also increased in 2021. Sales of electric buses increased 40% over the previous year and global sales of electric medium- and heavy-duty trucks more than doubled over 2020 volumes (IEA, 2022). The market for electric vehicles is growing rapidly, and there is a large demand for lithium-ion batteries (LIB). Studies have predicted a growth of 600% in LIB demand by 2030 (Degen, 2023).

It is estimated that Li-ion batteries (LIBs) typically preserve 70%–80% of their initial capacity when retired from their electromobility use (Bobba, Mathieux, et al., 2018; Olsson et al., 2018). By 2030, second-life battery capacity will hit over 275GWh per year which presents huge opportunities for energy storage (*Environmental Impact of the Second Life of an Automotive Battery*, n.d.). Repurposing of EV batteries for energy storage services is gaining prominence in literature and practice due to its ability to support integration of high amounts of intermittent renewable energy sources (RES) into the electric grid. Repurposing of EV batteries for energy storage services is gaining prominence in literature and practice due to its ability to support integration high amount of intermittent RES into the electric grid being more versatile in location, size and application and with their ability to provide flexibility services for the grid (Lombardi & Schwabe, 2017). The role of renewable energy sources is vital for a smooth energy transition from fossil fuels to 100% RES within the 21st century.

In the EU Circular Economy Action Plan, sector of LIBs is included as a key product value chain, and the development of a new regulatory framework for batteries was announced with consideration of reuse, repurposing, and recycling, thus underpinning the political circular economy ambitions for LIBs in pursuit of 90% reduction in transport related GHG emissions by 2050 (European Commission, 2020b, European Commission, 2019). In January 2023, a provisional agreement was reached on the European Union's proposed battery regulation 2020, which aims to strengthen sustainability rules for batteries and waste batteries throughout their entire life-cycle - from production to reuse and recycling. It aims to increase transparency, traceability, and accountability across the battery life cycle, it requires access to battery management systems, and it mandates digital passports, carbon footprint declarations and maximum thresholds. In addition to traditional extended-producer-responsibility targets for collection and recycling, it has specific recycling rates for lithium, cobalt and nickel, while also specifying targets for the use of recycled materials in new batteries to incentivize demand (European Commission, 2020a).

1.1 Problem definition

Rechargeable batteries are proving to be key for both electromobility and clean energy transition. Demand for LIBs will be driven by the automotive sector in the coming years. Demand for energy storage systems (ESS) storage will also increase, driven by the deployment of renewables (European Commission. Joint Research Centre., 2023). However, they are not free of their own impacts on the planet. Battery manufacturing is energy intense and produces emissions that contribute to the climate crisis. The raw materials like lithium require extraction from sensitive and unique environments. Processes of brine evaporation, mining, or oil and gas extraction processes can cause habitat destruction and biodiversity loss. Toxicity is another serious concern. Mining operations and material manufacturing can expose workers to toxic chemicals and environments. Along with environmental impact, battery components can have lasting adverse social impacts. For example, cobalt, a ubiquitous Li-ion cathode component, is mined almost exclusively in the Democratic Republic of Congo (DRC), where child labor, dangerous working conditions, and exploitative practices are pervasive. Furthermore, waste electric vehicle batteries pose challenges in terms of fires and hazardous contamination, and the recovery of resources requires environmentally sound recycling practices (Sharma & Manthiram, 2020).

Hence, scholars have been calling for the development of a circular economy approach with life cycle strategy and management for LIBs with consideration of social and environmental criteria (Olsson et al., 2018, Albertsen et al., 2021, Richter, 2022). The CE has developed as an alternative economic paradigm to the linear economy aimed at preserving the embedded environmental and economic value in products over time. CE strategies can be broadly divided in three strategies: (1) narrowing resource loops by reducing overall resource consumption, resource efficiency and bio-based material in design, (2) slowing resource loops by prolonging the use cycle of raw materials and products to preserve its embedded product value, and (3) closing resource loops to retain the material value of the product (Bocken et al., 2016). Specifically, products whose environmental impact is mainly caused in the production phase have a lot of potential to benefit from CE strategies (Nußholz, 2017), which is why LIBs have been discussed as a promising product from a CE perspective and would be critical for the development of sustainable battery EV (Picatoste et al., 2022; Albertsen et al., 2021).

The extensive number of LIBs adopted across the globe will eventually enter the waste stream. According to the Circularity Gap Report 2020, the world is now only 8.6% circular. Which means of all the minerals, fossil fuels, metals, and biomass that enter it each year, just 8.6% are cycled back (CGRi, 2022). Circular economy approach for the LIBs that have entered the market and in near term would enter the market, would thus be essential to focus on repair, reuse, refurbishment, repurposing, and recycling strategies to optimize their life-cycle value. Further, LIBs being the costliest part of an EV, contributing to a major share of the total costs there is a high interest amongst business stakeholders to capitalize on the embedded value of the battery after its first use in a vehicle (IEA, 2019; Reinhardt et al., 2020).

When it comes to end of life of batteries, current challenge is to decide on whether to repurpose an EV battery or to recycle it directly. The majority of the academics agree that repurposing EV batteries for a second-life application of energy storage systems (SLBESS) aid in the preservation of raw resources, water, and power, as well as the reduction of CO_2 (Shahjalal et al., 2022). However, the environmental impacts are dependent on the energy system under investigation, as well as on the recycling processes, capacity of the LIB at end of life and varying across battery chemistries (Shahjalal et al., 2022, Schulz-Mönninghoff et al., 2021, Tao et al., 2021, Philippot et al., 2022), there is no straightforward answer to a circular economy strategy with most sustainability value for EV batteries. It is concluded that further work is needed to define what constitutes success factors of second-life batteries repurposing as a circular business model.

On the regulation front, once the battery regulation enters into force, sustainability requirements on carbon footprint, recycled content and performance and durability will be introduced gradually from 2024 onwards. A key part of the regulatory framework is higher collection targets being introduced over time. For batteries the target will be 51% in 2028 and 61% in 2031. All collected batteries have to be recycled and high levels of recovery have to be achieved, in particular of valuable materials such as copper, cobalt, lithium, nickel and lead (European Commission, 2020a).

As the literature highlights the different benefits of repurposing and delaying recycling, alongside the regulatory emphasis on recycling, it becomes crucial to make data-driven decisions regarding circular economy (CE) strategies. Value chain stakeholders would require high-quality data and practical tools to make these decisions (Berger et al., 2022). Therefore, a significant need for holistic assessments including sustainability and circularity aspects that provides understanding of sustainability potential for different scenarios for batteries coming out of their electromobility application is evident in the current body of literature (Bobba et al., 2019; Thies et al., 2019). Consequently, an emerging research area is to systematically map these metrics pertinent to different life-cycle stages of the battery as part of managerial decision-making in order to maximize sustainability value while involving stakeholders to share the knowledge (Berger et al., 2022).

Besides, the awareness and understanding of circular economy principles among customers is limited about EVs LIBs as well as interest in remanufactured, repaired products is low (Azadnia et al., 2021). Additionally, as UNCTAD's director of international trade has stated "Most consumers are only aware of the 'clean' aspects of electric vehicles,". "The dirty aspects of the production process are out of sight."[1] Thus, measurable metrics will communicate the sustainability and circularity value enabling a conscious purchasing decision by the end-user.

A concept that is gaining attention in the political agenda is the development of a Digital Product Passport (DPP). From the anchoring in high-level policy strategies, one can derive the high expectations on the DPP as an essential new tool for enabling a holistic and comprehensive recording of product information and sustainability aspects for decision making. Digital product passports are on political agendas and could be a key part of supplying better data, making supply chains more transparent and enabling collaboration between value-chain actors.

The latest EU's legislative framework for batteries calls for industrial batteries and electric-vehicle batteries to have an electronic record for each individual battery placed on the market in the form of a 'Digital Battery Passport' by 1 January 2026 (European Commission, 2020a). The battery passport should furthermore enable second life operators to take informed business decisions and allow recyclers to better plan their operations and improve their recycling efficiencies. Researchers are working on identifying sustainability and circularity metrics to be incorporated in the digital battery passport to enable decision making (Berger et al., 2022). These

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[1] https://unctad.org/news/developing-countries-pay-environmental-cost-electric-car-batteries

metrics would require numerous data streams, stakeholder cooperation for exchange of data and various tools and technologies to be deployed.

Further, product as a service is emerging as a potential new business model. Service-based business models can help to overcome some key barriers to the adoption of used products, such as lack of consumer confidence and uncertainty about performance and remaining lifetime. Given batteries having high investment cost, a service business model enables reducing the costs for customers while the producer (or service provider) can harness different recurring revenue streams while serving different customers in different business sectors and even in numerous geographical locations (Mont, 2002; Ramos et al., 2021). PSS requires close stakeholder cooperation/collaboration and knowledge and data sharing, education of customers by producers. Data on product conditions, location, use intensity, and availability, lead to improved performance of products and processes by applying big data analytics. This would provide digitally enabled functionalities of monitoring users' activities, preventive and predictive maintenance and estimation of products and components residual life. Firms can thus advance management towards CE by feeding sustainability-oriented decision-making processes with the required information and facilitate a more efficient collaboration between the manufacturer, service provider, logistician, and customer (Bressanelli et al., 2018; Hofmann, 2019). Hypothesis is that PSS can assist enabling data by changing stakeholder relationships and harnessing technologies.

Overall, there is a knowledge gap in terms of defining metrics for enabling second-life battery repurposing particularly and slowing of the loop CE strategies in general of LIBs. Additionally, the emerging role of PSS model need to be explored in leveraging technology for data access and improving collaboration among stakeholders.

1.2 Aim and research questions

In order to address the described problem, the aim of this study is to explore sustainability and circularity metrics that can enable slowing loop CE strategies for batteries and their sustainability value communication of batteries. To contribute to this aim, the following research questions (RQs) are examined:

RQ1: How can sustainability and circularity metrics as part of DBP can support slowing the loop strategies for batteries to create most sustainability value?

RQ2: What are the perceptions of value chain actors towards these sustainability and circularity metrics?

RQ3: How can servitization help in operationalizing the DBP?

1.3 Audience

The intended audience for this master's thesis includes practitioners and researchers who work in the field of circular economy and lithium-ion batteries (LIBs), as well as industries that are involved in the LIBs value chain. The thesis covers emerging academic research on circularity metrics, digital product passport, and servitization, which will be relevant to those interested in the latest developments in sustainable CE strategies for LIBs. Additionally, policymakers may find this thesis beneficial as it explores the interplay between policy and CBM initiatives for LIBs. The knowledge gained from this research may be used to improve and adapt metrics in policy to incentivize sustainable CE strategies for LIBs along the value chain. Overall, this thesis aims to provide a comprehensive understanding of various sustainability and circularity metrics for LIBs that enable slowing the loop CE strategies and potential of servitization business model to operationalize DBP.

1.4 Disposition

In Chapter One, the background of the research, problem statement, research questions, and the intended audience were introduced.

Chapter Two presents and justifies the methodology, research design, and the use of a case study approach in this thesis. It also discusses the process of data collection and analysis, along with the scope, limitations, and ethical considerations.

Chapter Three conducts a comprehensive literature review on the relevant theoretical concepts for this study and the current research status on circular economy of LIBs, challenges and potential solutions. The chapter concludes by summarizing the identified knowledge gaps.

Chapter Four presents the findings and their analysis structured according to the research questions.

Chapter Five discusses and contextualizes the findings by connecting them to the existing literature and emphasizing the contribution of this research to the current body of knowledge. Additionally, it includes recommendations for policymakers, industry actors and future research.

Finally, Chapter Six concludes the thesis by providing a summary of the findings.

2 Methodology

This chapter explains the methodology of this thesis used to produce knowledge and answer the previously established research questions. It introduces the research design in section 2.1, methods for data collection and analysis in sections 2.2 and 2.3, discusses the scope and limitations in section 2.4 and ethical considerations in section 2.5.

2.1 Research design

The research approach taken in this thesis is transdisciplinary in nature and reflects the researcher's interdisciplinary background. An interdisciplinary perspective is necessary to study circularity strategies and its requirements because they are connected to different disciplines (i.e. business, technology, environment, or political aspects). Further the research follows the pragmatic worldview, focussing on real-world problems often guided by practical implications of findings useful to that problem Creswell & Creswell, 2018). The framing of the problem was facilitated in collaboration with stakeholders from Volvo Energy and the author. The conceptual research design (see the Table below) to address the problem is guided by three research stages.

Table 2-1 Stages of research

Stages of research	**Stage 1**	**Stage 2**	**Stage 3**
RQs	RQ1: What sustainability and circularity metrics are relevant for DBP to support slowing the loop strategies?	RQ2: What are the perceptions of value chain actors towards these sustainability and circularity metrics?	RQ3: How can servitization help in operationalizing the DBP?
Aim	To understand the use of metrics at three levels: • Practical: Existing metrics in the value chain of batteries • Academic level: Metrics researchers highlight for CE decision making. • Policy level: Metrics mandated by policies	To understand: • Perspectives of value chain actors and end-users towards second-life batteries with the background of recent EU policies and literature • Practical: Future outlook for metrics given the recent EU policies and literature • Opinions on different metrics and their need/usability	To prove the hypothesis that service models can: • Change stakeholder relationships • Enable data collection • Help in deployment of technologies

2.2 Methods used to collect data

2.2.1 Literature review

The aim of the thesis is to study the metrics to enable holistic assessments of CE strategies for LIBs. Further, the development of a Digital Battery Passport (DBP) is gaining attention as a tool for recording product information and sustainability aspects mandated by the EU battery regulation. Thus, the aim was to identify relevant metrics for LIBs with respect to the DBP particularly focusing on enabling slowing the loop strategies. It is also crucial to explore data requirements, and the potential of product-as-a-service (PSS) models to facilitate stakeholder cooperation and enable data collection.

Thus to fulfill the aim of the thesis the search strings for literature review included 'Circular economy' 'sustainability' 'EV batteries', 'BESS', 'BESS Sustainability', 'Battery Energy Storage

System Sustainability', 'Battery Energy Storage System as a service', 'Second Life Battery Energy Storage System', 'Servitization Sustainability', 'Product as a service', 'Product as a service in business-to-business context', 'Sustainability value assessment and monitoring frameworks' for the introduction and problem definition. Further combination of strings was utilized to structure the findings detailed. All the literature reviewed were academic peer-reviewed literature. There was a deliberate attempt to get perspectives from different fields of engineering, management, and sustainability. The platform used was Google Scholar and Lund university libraries' resources (Canals Casals et al., 2019).

Table 2-2 Literature review methodology topic areas

<table>
<tr><th>Areas and stages</th><th>Batteries (first-life, second-life, end-of life)</th><th>General</th></tr>
<tr><td rowspan="3">Stage 1</td><td colspan="2">Environmental assessments and social impacts
(Impact categories, indicators, tools, technologies)</td></tr>
<tr><td colspan="2">Circular economy strategy and Circularity metrics/assessments
(R-strategy, C-indicators, frameworks)</td></tr>
<tr><td>Digital Battery Passports
(Metrics, stakeholder perspectives, data requirements)</td><td>Digital product passport
(Circular economy enabler, benefits, challenges)</td></tr>
<tr><td>Stage 3</td><td>Servitization and PSS
(Stakeholder relationship, digitization)</td><td>Servitization in B2B
(PSS in renewable energy sector)</td></tr>
</table>

2.2.2 Grey literature/ Public documents review

The first phase of the research method applied in this thesis would be a content analysis of publicly available documents and legal documentations relevant to EV batteries. The metrics pertinent to batteries required for RQ1 will be derived from policymaker publications (European Commission, 2020a), as well as reports from digital product and battery passport initiatives. The content analysis sought to identify the required metrics, tools and technologies, data streams.

This study also examined industry public position papers and reports, such as the EUROBAT[2], Project ALBATTS[3], Global Battery Alliance (GBA)[4], and Battery Pass Consortium[5]. Notably, the "Battery Pass" project, involving industry and academic partners across the value chain,

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[2] https://www.eurobat.org/

[3] https://www.project-albatts.eu/

[4] https://www.globalbattery.org/battery-passport/

[5] https://thebatterypass.eu/

played a significant role. Of particular relevance to this study was the publication of the battery passport's content guidelines on April 17, 2023, which were analyzed and utilized in the research.

The role of these public documents is twofold. First, they provide a stakeholder perspective with respect to batteries and what is the level of use of sustainability and circularity metrics in the currently. Secondly, the dependence and the inter-relations of the stakeholders for data and information sharing will be revealed.

2.2.3 Semi-structured interviews

Interviews as data collection method is chosen because it is an adequate qualitative method to capture the practitioner's perspectives, decision making process, experiences and opinions on the matter in a natural setting (Creswell & Creswell, 2018). The approach of semi-structured interviews further would provide a structure while leaving room for flexibility leading to adjustment to the interview questions whenever deemed necessary.

For RQ1 semi-structured interviews were conducted with researchers in the domain, policy experts following developments at European Commission around DBP and circularity strategies for batteries to understand the extent of data envisioned for DBPs along with general perceptions towards hierarchy of circularity strategies for batteries. Circular economy experts were also interviewed to understand circular metrics in current practice and the complexities of metrics, and operational aspects of these metrics. Including data streams, and technologies required for operationalization of CE strategies.

This research focuses on the role of metrics in facilitating decisions related to circularity strategies for batteries, specifically emphasizing strategies that prolong the battery life cycle. For the second research question (RQ2), interviews were conducted with key actors in the battery value chain and potential users of second-life batteries. The approach used in this study is based on the lifecycle perspective proposed by Berger et al. (2022), examining stakeholders' perceptions of sustainability and circularity metrics and how they can support circular economy strategies for batteries. Additionally, gathering insights on stakeholders' perspectives and future plans for implementing the DBP with sustainability and circularity metrics helps shed light on the prevailing discussions regarding data requirements and data sharing in the battery domain. The goal is to identify the overall focus on sustainability within the battery value chain, observe the evolving narrative following recent EU regulations, and determine which stakeholders have been most actively involved in these discussions.

In addressing RQ3, this study sought insights from Electric Vehicle Original Equipment Manufacturers (EV OEMs), second-life battery and battery storage providers regarding their relationships with stakeholders in the context of Product-Service Systems (PSS). The focus was on exploring challenges related to data requirements for repurposing, the adoption of new technological tools, and the facilitation of circular economy strategies through knowledge sharing with stakeholders. The author drew from their experience in the Sustainability Solutions in Context (SSC project, 2022), which involved investigating the product-as-a-service model for second-life Battery Energy Storage Systems (BESS). Direct interviews were conducted with potential customers and Volvo stakeholders who had experience with PSS business models. Furthermore, interviews were conducted with software-as-a-service providers involved in operationalizing the Digital Battery Passport (DBP), allowing them to share insights on the challenges associated with data collection, enablers of servitization, and the overall role of servitization in the context of DBP implementation.

For RQ3 the EV OEMs, second-life battery or battery storage providers were asked to comment on the nature of relationships with stakeholders due to PSS, challenges with respect to data requirements for repurposing, service business model enabling data collection and adoption of new technological tools. One of the key focus areas was also on how knowledge sharing with stakeholders enabled circular economy strategy related decision making. Author's experience from Sustainability Solutions in Context (SSC) 2022 project where product as a service model for second life BESS were explored by directly interviewing potential customers and Volvo stakeholders with experience in PSS business models. Additionally, software as service providers engaged in operationalizing DBP were interviewed to share their experience regarding challenges in data collection, enablers and role of servitization.

Table 2-3Interview partners for different stages of research

Stages	Stage 1	Stage 2 and 3
Interview partners	1. Policy experts 2. Circular economy experts	1. Battery manufactures (cell, module, pack) 2. Volvo stakeholders (first life use, repurposing) 3. Recyclers 4. Second-life BESS providers 5. SaaS providers working on operationalizing DBP

2.3 Methods used to process information

The interviews were recorded, transcribed, and analyzed using content analysis software NVivo. A set of codes was deductively created based on the literature review, and these codes were iteratively updated during the interviews as new relevant information was shared. The content analysis process for Research Questions 1 and 2 followed a three-step approach: (i) digital transcription of the interviews, (ii) comprehensive review of all data to establish a global understanding, and (iii) coding, following the methodology outlined by Creswell (2014).

2.4 Scope and Delimitations

The geographical scope of this master's thesis was limited to the European Union (EU). Initially, the focus was specifically on batteries for heavy-duty applications such as trucks, buses, construction equipment, and marine vessels. However, through conversations with interviewees and a review of the literature, it became evident that EV batteries for passenger cars had a more extensive presence and should be the primary focus of the investigation. The study excluded small-scale residential battery storage systems due to their size. The research prioritized sustainability and circularity metrics over battery performance and diagnostic data in the digital battery passport. The study concentrated on exploring circular economy strategies applicable to lithium-ion batteries (LIBs) expected to enter the waste stream in the near future, such as remanufacturing, refurbishing, repurposing, and recycling. Although battery design strategies like 'rethink' and 'reduce' and first-use intensification are important in the circular economy hierarchy, they were not within the scope of the study due to limited control over their development. The evaluation of metrics was conducted at the company level, and differences in perspectives and metric importance were analyzed based on individuals' positions within the company.

2.5 Ethical considerations

The research being qualitative in nature has underlying risks of personal perceptions influencing it. To avoid it my own preconceptions in data collection the author applied the methodological approach to reduce that risk.

This research was conducted with the support of Volvo Energy. That included that they provided feedback and suggestions on research direction as well as financial support. The author acknowledges that that there is a risk of bias and influence on my research. However, the risk was mitigated by constantly being reflexive about it and backing the research with duly searched literature and findings. Other than that, there are no circumstance that compromised the author's honesty and personal integrity has been identified.

All interviewees' participation were voluntary, and they were informed about the goal of the research, the collaboration between the author with Volvo Energy, and the planned use of the information obtained prior to the interview. Further, they were asked for consent before being recorded and no sensitive information was collected from the participants. Any quotations used from the interviewees was reviewed by them for accuracy. The data was securely stored on the author's laptop and protected cloud system of the university.

3 Literature review

3.1 Background on battery chemistries and technologies

LIBs are increasingly used in strategic sectors such as mobility, energy storage systems and portable devices, and this trend is expected to increase further in the next decade (BatteriesEurope, 2021a). Due to the high capacity of active materials and a higher single cell voltage than other technologies, lithium-based technologies provide the highest energy density of all rechargeable systems operating at room temperature. Depending on the technical requirements, lithium is used with different chemistries such as graphite, nickel, manganese, and cobalt oxides: Lithium Cobalt Oxide (LCO) and Lithium Nickel Oxide (LNO), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Manganese (LMO), Lithium Phosphate (LFP), Lithium Titanate (LTO) (EUROBAT, 2022).

Dunn et al., 2021 claims that the most common EV LIB cathode chemistries are NCA and NMC are the best performing battery chemistries available for EV installations today, while LCO, LMO and LFP are currently the most widely used batteries in EV applications because of their abundant resources, stable crystal structures, and low price (Houache et al., 2022). These battery chemistries can therefore be expected as the major second life battery streams available in the future. NMC meanwhile seems to be the dominant chemistry moving forward and is recommended as a focal technology for future mobility solution development (Houache et al., 2022)

The ultimate goal has always been towards higher energy density with longer driving range and higher performance, but other factors such as cell cost and supply chain diversity, concerns about supplies of key battery materials like cobalt which has historically been the most widespread LIB transition metal, but due to its high human and environmental cost, battery producers have innovative chemistries with low cobalt cathodes are expected to increase their market share in the future (Dunn et al., 2021). LIBs are expected to dominate the global and the EU battery market for the next two decades even though novel battery types are expected to arise (European Commission. Joint Research Centre., 2023).

While this paper focuses on LIBs one advance to keep an eye on are the solid-state batteries and Sodium-ion batteries. Solid-state batteries replace this liquid with ceramics or other solid materials that enable higher energy density, potentially improving the range of electric vehicles. Solid-state batteries could also move charge around faster, meaning shorter charging times. And because some solvents used in electrolytes can be flammable, proponents of solid-state batteries say they improve safety by cutting fire risk. Sodium-ion batteries have a design similar to that of lithium-ion batteries, including a liquid electrolyte, but instead of relying on lithium, they use sodium as the main chemical ingredient, which is not a critical mineral.

3.1.1 Circular economy for LIBs

Circular economy principles are perceived as a promising option to meet the world's climate targets and move towards a more efficient use and reuse of resources. A transition to a circular economy could positively impact carbon emissions, environment, and society, and help to future-proof businesses and increase business value (Velenturf & Purnell, 2021).

According to the most popular definition developed by the Ellen MacArthur Foundation (EMF), a circular economy is "an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models". It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers (Kirchherr et al., 2018).

In this context, the European Commission adopted the European Green Deal to achieve the climate neutrality target by 2050, and the New Circular Economy Action Plan as one of its main pillars. This new CE framework, built on the previous CE Action Plan, aims to ensure the use of resources for longer periods at the same time minimising the amount of waste generated. To do so, it includes measures to boost the design of sustainable products and focuses on resource intensive sectors with a high potential for circularity (electronics and Information Communications Technology (ICT), batteries and vehicles, packaging, plastics, textiles, construction and housing, and food) (Valls-Val et al., 2022).

Table 3-1The ten R-strategies according to Potting et al. (2017)

Refuse (R0)	**Make product redundant by abandoning its function or by offering the same function with a radically different product;**
Rethink (R1)	Make product use more intensive (e.g., through sharing products or putting multifunctional products on the market);
Reduce (R2)	Increase efficiency in product manufacturing or use by consuming fewer natural resources or materials;
Reuse (R3)	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function (and is not waste) for the same purpose for which it was conceived;
Repair (R4)	Repair and maintenance of defective product so it can be used with its original function;
Refurbish (R5)	Restore an old product and bring it up to date;
Remanufacture (R6)	Use parts of discarded product in a new product with the same function;
Repurpose (R7)	Use discarded product or its parts in a new product with a different function;
Recycle (R8)	Process materials to obtain the same (high grade) or lower (low grade) quality;
Recovery (R9)	Incineration of materials with energy recovery.

Circular economy for EV batteries

Researchers have emphasized the need for a comprehensive life cycle strategy and management for Lithium-Ion Batteries (LIBs) considering their high social and environmental impacts. LIBs are particularly suited for CE strategies as their impact is primarily concentrated in the production phase. Battery manufacturing is energy intense and produces emissions that contribute to the climate crisis. The raw materials like lithium require extraction from sensitive and unique environments. Processes of brine evaporation, mining, or oil and gas extraction processes can cause habitat destruction and biodiversity loss. Toxicity is another serious concern. Mining operations and material manufacturing can expose workers to toxic chemicals and environments. Along with environmental impact, battery components can have a lasting social impact. For example, cobalt, a ubiquitous Li-ion cathode component, is mined almost exclusively in the Democratic Republic of Congo (DRC), where child labor, dangerous working conditions, and exploitative practices are pervasive (Sharma & Manthiram, 2020). Downstream growing numbers of spent LIBs poses enormous threat to the natural environment and human health, as batteries contain hazardous materials. The fire and explosion incidents are currently the most common events that have been evidenced by real-life incidents. Leaching is another pollution pathway that may be released to soil, water (groundwater) and air, depending on recycling, disposal method or abuse incident. Released pollutants may pose a serious threat to wildlife and humans with often immediate effects (Mrozik et al., 2021). Thus, CE models can provide promising solutions for sustainable production of LIBs.

Additionally, CE strategies are crucial to improve the supply security of raw material of LIBs as they contain a large number of critical metals, including cobalt, nickel, copper, and manganese (Kosai et al., 2022). The EU is dependent on third countries for the supply of raw materials for the manufacture of LIBs and represents a very low share of global production. What is most striking is that supply is highly concentrated in China, which dominated global capacity in 2020. Similarly, there are dependencies and bottlenecks downstream in the supply chain for processed materials, components, and assemblies, as supply is controlled by an oligopoly in Asia (European Commission. Joint Research Centre., 2023). Given that LIBs are a source of critical metals, the implementation of CE towards the EVBs is needed to deal with the concerns of supply shortcomings and, while simultaneously reducing the negative environmental impacts (Sopha et al., 2022).

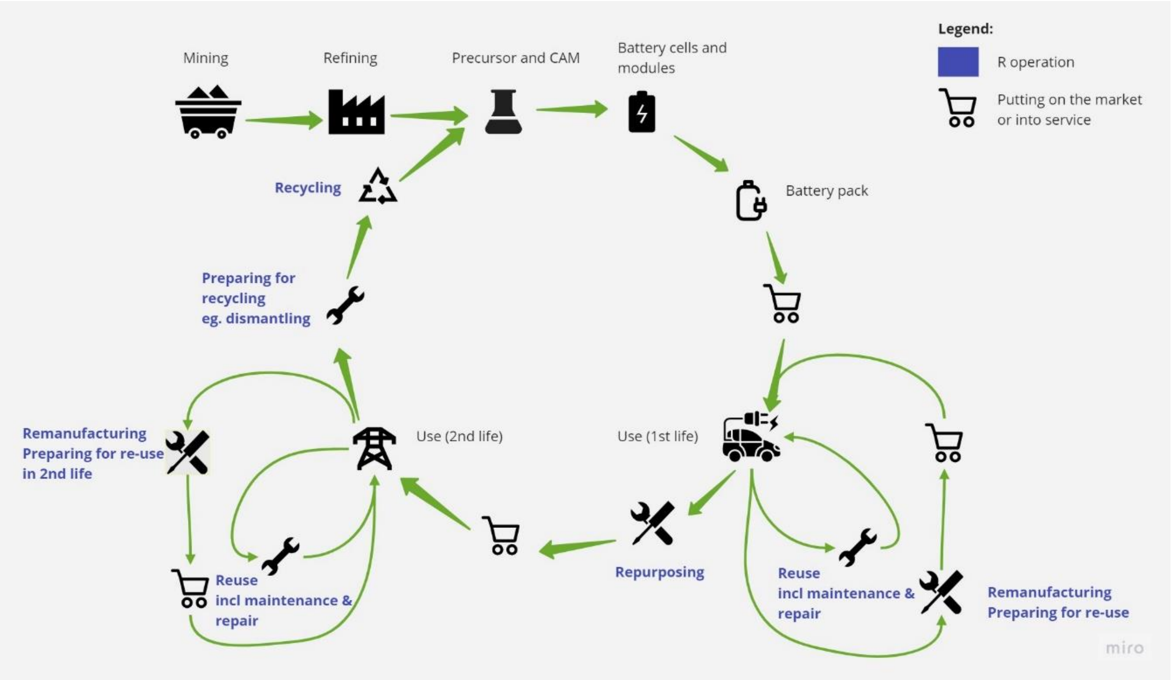

Figure 3-1Overview on battery handling operations along the value chain. Source: The Battery Pass Consortium, (2023)

Among the CE strategies for LIBs identified in literature, three main options are applicable to the case of batteries at their EoL stage: "refurbishment and remanufacturing", "repurposing & cascading", and" recycling" (Schulz-Mönninghoff & Evans, 2023). Albertsen et al., (2021) confirmed that, among 25 companies that were studies, the most adopted EoL path is repurposing, followed by, from the highest to the lowest, repairing, refurbishing, and remanufacturing. In the following sections these CE strategies are explored in detail. Figure 3-1 presents the overview of battery operations along the value chain used as a reference in this study.

Remanufacturing and reuse of batteries in EVs

Remanufacturing means any technical operation on a used battery that includes the disassembly and evaluation of all its battery modules and cells and the use of a certain amount of battery cells and modules, new, used or recovered from waste, or other battery components, to restore the battery capacity to at least 90% of the original rated battery capacity, and where the state of health of all individual battery cells is homogeneous, not differing more than 3% from one another, and results in the battery being used for the same purpose or application than the one for which the battery was originally designed. (EU Battery Regulation, Article 2,1(26a)).

The residual value of used automobile batteries remains significantly high, even when their capacity drops to just 80%. This high residual value makes it unprofitable to continue using them in cars. However, the cells and peripheral modules, such as housing, cooling, and management systems, retain enough value for a remanufacturing process (Kampker et al., 2016). Despite the potential of remanufacturing lithium-ion batteries (LIBs), it is not extensively found in practice (Albertsen et al., 2021). According to Albertsen et al., (2021), among 25 companies that were studied, the only evidence of a remanufacturing closed-loop supply chain for an EU OEM was found at Daimler for the LIBs from Smart. To address this issue, product design should incorporate modular interfaces, replaceable components, and minimize the use of glue. However, current developments in LIB design do not seem to prioritize these aspects (Michaelis et al., 2018).

Remanufacturing for original purpose has appeared to be the most applicable in Sweden because a broader scope of the second-life application of the EVBs has not yet existed, and new EVBs have not entered their first life yet (Vu et al., 2020). However, it was noted that remanufacturing is not always the best solution over time. It is suggested that reusing is a preferable option over recycling due to optimum financial gain and environmental impact reduction (Sopha et al., 2022).

Repurposing

Repurposing means any operation that results in parts or the complete battery that is not a waste battery, being used for a different purpose or application than the one that the battery was originally designed for (EU Battery Regulation, Article 2,1(26)). A lot of research has focused on the potential of repurposing LIBs after their first use in a vehicle for a second life in a different application. LIBs usually retain 70-80% of capacity after its first life in an EV, sufficient for use in a second life application. There are several possible applications that have been identified as suitable for a second life of LIBs. SLBESS has been effectively for applications like small-scale energy storages for self-optimizing renewable energy sources like solar photovoltaic systems, peak shaving, and energy arbitrage at residential or industrial level, supporting off-grid stationary application by forming micro grids, supporting national power grids through participation in frequency regulation markets, fast-charging stations etc. (Shahjalal et al., 2022; Kotak et al., 2021).

The repurposing process for the second life can includes screening, varying level of disassembly, testing for degradation and failure, packaging the batteries for second life, as well as adding electrical hardware, control, and safety systems. Sometimes batteries can be utilized as a full pack without any disassembly. But most of the time, there is a need for disassembly process. The disassembly procedure includes opening the battery pack casing, removing the electrical and mechanical connections between the cells, and removing auxiliary electronic parts. Some authors assume that dismantling down to cell level is not feasible from a technical or economic perspective. Faulty LIBs must be examined on a module level to then select and assemble modules with similar characteristics together to a new battery pack for a second life application (Shahjalal et al., 2022).

It is expected that by 2025 there will be 3.4 million discarded end of life EV batteries, amounting to 953 GWh of battery capacity (Thakur et al., 2022). IDTechEx forecasts that the second-life EV battery market will reach US$7B in value by 2033. A growing number of repurposer and battery diagnostician start-ups are starting to establish robust supply chains with automotive OEMs. US and Europe are key regions with actors making great advancements in deploying second-life BESS. These actors have generally been focused on behind-the-meter installations. However, some actors who have commercialized these second-life BESS will soon be looking to scale their technologies to be suitable for large grid-scale applications[6].

Recycling: closed-loop Recycling technologies

Recycling of batteries has extensive literature. It is considered the most commonly available approach for EOL LIB. For long-term development, battery recycling is crucial. As the battery value chain expands, it may increasingly be regarded as critical from a supply chain standpoint and is frequently cited as a major impetus toward achieving a closed-loop recycling system in the EU. For example, approximately 60% of lithium could be supplied by recovered lithium in the future (Qiao et al., 2021). However, the recovery of recycling processes depends significantly on the combination of different operations deployed. Also, by recycling batteries, a great degree of eco-toxicity impact can be avoided because it prevents leakage from landfills (Richa et al., 2017).

The recycling of LIBs is also encouraged by legislation in the EU where the Battery Directive 2006/66/EC was instituted. The directive requires each EU Member State must meet a collection rate of 45% and a recycling efficiency of at least 50 wt% for non-lead acid and non-nickel cadmium batteries. The EU Battery Directive regulations also require battery producers to take responsibility for their waste at EoL. The producers have to pay for the collection, treatment, recycling, and disposal of waste batteries in proportion to their market share.

Physical and chemical processes can be used to recycle valuable resources such as metals and cathode active materials. Recycling is a time-consuming procedure that normally requires many phases. (Shahjalal et al., 2022). In general, it can be divided into the phases of various steps of pre-treatment and metal extraction method. Pretreatment includes collecting, inspection, selection/separation, and sorting. During the pre-treatment phase, LIBs are potentially disassembled to module or cell level and discharged. Because of the lack of a standardized battery pack, the disassembly is currently done manually, which is time-consuming and uneconomic in countries with high labor costs (Harperet al., 2019)

Then, during the mechanical part of pre-treatment processes LIBs are treated with shredders, sieves, and magnetic separator. Crushing and separating stages can help enrich precious materials, and multistage methods have the ability to be used on a wide scale. The output from the mechanical pre-treatment can then be further refined through metal extraction processes. Technologies available at this stage of recycling LIBs are hydrometallurgical and pyrometallurgical (Shahjalal et al., 2022).

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[6] https://www.idtechex.com/en/research-article/the-second-life-ev-battery-market-to-reach-us-7b-by-2033/28844

The pyrometallurgical process extracts metals by heating the waste electrodes and adding flues to form alloys. Lithium can be recovered by chemical leaching of the slag, but the cost and energy requirements are not economically favorable. Pyrometallurgy requires less pretreatment of the battery scrap, therefore, it has the advantage of having the lowest cost. However, burning plastics will release a variety of highly hazardous chemicals, which leads to secondary pollution (Shahjalal et al., 2022; Zhao et al., 2021).

Hydrometallurgy on the other hand consumes less energy and can deal with the low concentration of different metals. Metals are recovered through leaching and extraction at significantly lower temperatures. The advantage of hydrometallurgy is its high recovery. Hydrometallurgy technology recovers 90% of the materials with 98% purity (Zhao et al., 2021)

Currently, the majority of the recycling companies are adopting the pyrometallurgical process, mainly because of the lower cost and scalability. However, it is becoming more favorable to use the hydrometallurgical process as higher value can be derived from a broader range of precious metals to offset the processing cost (Sopha et al., 2022).

3.1.2 Challenge of CE hierarchy from environmental point of view

Life cycle assessments (LCAs) are commonly used to evaluate the environmental impact of products or services across various categories such as energy demand, climate change, metal depletion, particulate matter, and human toxicity. Among circular business models for lithium-ion batteries (LIBs), repurposing has been found to have the highest potential for reducing greenhouse gas emissions compared to other options like remanufacturing and recycling. Postponing the end of life of LIBs by approximately 10 years can lead to additional CO_2 benefits of LIB recycling ranging from 44% to 73%, depending on the electricity grid mix (Schulz-Mönninghoff et al., 2021). The use of second-life batteries (SLBs) can contribute to the preservation of raw resources, water, power, and CO_2 reduction (Shahjalal et al., 2022). In the case of a stand-alone house with a diesel generator, even if a repurposed battery does not replace a new one, results in a 49% reduction in greenhouse gas emissions (Bobba et al., 2018).

However, implementing SLB energy storage systems for multiple applications to improve profitability can potentially compromise the environmental benefits of LIB repurposing by 10% to 22%, depending on the system size (Schulz-Mönninghoff et al., 2021). Additionally, a study found that repurposing only reduces the impact on climate change compared to recycling in countries with an electricity mix below 113 g CO_2 eq/kWh (Philippot et al., 2022). Further due to variability in methodological choices the normalized impacts of LIBs varied widely, ranging from 4,400 kg CO2eq to 55,000 kg CO_2 eq, depending on factors such as battery chemistry, impact assessment method, available inventories, and the circular economy scenario analyzed (Picatoste et al., 2022).

There are some limitations to consider in the presented studies. Some of them make assumptions regarding the performance and remaining useful life of SLBs. When comparing second-life applications, many studies use lead-acid batteries as alternatives, even though newer storage systems generally utilize LIBs. Additionally, studies comparing repurposed LIBs to new ones often assume the same technical specifications, disregarding the potentially lower environmental impact per kWh of newer LIBs using advanced technology. Nonetheless, despite these limitations, the general trend of the results can still provide valuable guidance for decision-making (Albertsen, 2020). And more importantly, while battery recycling is a dominant topic in LCA studies followed by repurposing, other circular economy strategies such as repair, maintenance, upgrades, and remanufacturing have received less attention in the LCA literature (Picatoste et al., 2022). Additionally, only a few LCA literature is based on primary data, whereas the majority utilized secondary (and not updated) LCIs (Picatoste et al., 2022).

Therefore, it is crucial to conduct a thorough analysis of each application area of battery repurposing to make informed decisions between reuse and recycling for EV battery end-of-life management. Additional methods such as energy flow modeling and material circularity assessments should be incorporated alongside LCAs to ensure sustainable deployment of repurposed SLBs (Schulz-Mönninghoff et al., 2021). Second-life use of batteries not only expands the recycling market but also helps reduce the high upfront cost of electric vehicles compared to internal combustion engine vehicles (Tang et al., 2019). Future research should focus on integrating circular economy and LCA studies, considering both product-level changes and business model/value chain considerations to better understand the potential impact of circular economy strategies (Picatoste et al., 2022).

Considering estimations of global resource use for LIBs from 2010 to 2050, extending the lifespan of batteries would have a significant impact on reducing resource consumption. Urgent action is needed to reduce resource use and ensure the reuse and repurposing of LIBs, especially until 2050. Circular practices like closed-loop recycling will be effective in the long term, beyond 2050 (Kosai et al., 2022). Another study on end-of-life management of LIBs concluded that recycling should be considered as a final option, and current recycling processes for electric vehicle batteries are still developing, driven mainly by regulation due to low volumes (Mossali et al., 2020).

In conclusion, repurposing lithium-ion batteries offers significant environmental benefits, particularly in terms of greenhouse gas emissions reduction. Extending the lifespan of batteries through repurposing and implementing circular economy strategies can contribute to resource preservation and CO_2 reduction. However, the hierarchy of CE strategies not straightforward from an environmental point of view as a careful analysis is required with integrating energy flow modeling, material circularity assessments, sensitivity analyses and most importantly a holistic circular economy approach into life cycle assessments.

3.2 Challenges of Circular economy for EV batteries

Circular economy is an emerging concept that aims to promote responsible and cyclical use of resources to contribute to a more sustainable future. However, its implementation has been hindered by various barriers. These barriers encompass technological, policy and regulatory, financial and economic, managerial, and social aspects. The challenges faced by the circular economy in general are further compounded when it comes to batteries, given their complex and globally fragmented value chain. Specifically, managing circular economy activities related to electric vehicle lithium-ion batteries (EVs-LIBs) particularly for slowing the loop that covers repair, remanufacturing, and repurposing, presents numerous barriers and obstacles that require careful analysis and targeted solutions.

3.2.1 Regulatory/policy barriers

The successful implementation of the circular economy relies on a supportive policy framework that incentivizes companies to adopt circular practices and recognizes the circular economy as a viable economic model. Unfortunately, such policies are often lacking, and the focus of existing instruments rarely targets the obstacles presented by the linear economy. Additionally, scaling up circular innovations can be challenging, and linear technologies often maintain their market dominance despite their inefficiency (Corvellec et al., 2022).

Furthermore, the second life of EV LIBs for stationary applications faces significant regulatory barriers. The absence of proper policy and regulations hinders the implementation of practices and initiatives to enable the second life of EV-LIBs for stationary purposes (Aazdnia et al., 2021). Producers registered under the Extended Producer Responsibility (EPR) scheme face liability concerns associated with the initial use of LIBs due to the lack of clear rules regarding EPR transfer (Bobba, Cusenza, et al., 2018; Olsson et al., 2018; Richa et al., 2017). Additionally, the legal status and product definition of second-life batteries remain uncertain, which diminishes the attractiveness of second-life applications (Bobba et al., 2018). Moreover, the absence of widely accepted test methodologies to assess the safety of second-life LIBs, including hazards and fire risks associated with handling Li-ion batteries, represents a significant gap in international standards (Bobba et al., 2018; Office for Product Safety and Standards, 2022). Addressing these regulatory barriers is essential for unlocking the full potential of second-life EV-LIBs in stationary applications.

It is important to note that recycled content targets often indirectly incentivize recycling rather than extending the lifespan of products. This can result in LIB value chain actors prioritizing compliance with regulatory requirements over the environmental benefits of life extension activities. Therefore, policy design should carefully consider the incentives it creates (EUROBAT, 2022).

McKinsey has identified a lack of regulation that creates uncertainties for OEMs, second-life battery companies, and potential customers. In a European Innovation Deal study involving automotive OEM Renault and other partners, retired EV batteries were still classified as dangerous goods, leading to expensive transportation challenges. The risk of perfectly functional and reusable EV batteries being prematurely classified as waste hampers their transportation across different countries to meet market demands within the European Union. The lack of a clear definition for second-life EV batteries and transportation regulations poses challenges for business-to-user (B2U) companies (Hensley et al., 2012).

In conclusion, overcoming regulatory barriers is crucial for the successful implementation of the circular economy and realizing the potential of second-life applications for EV-LIBs. It requires the development of supportive policies, clarification of legal frameworks, the establishment of safety standards, and the reassessment of incentives to encourage life extension activities.

3.2.2 Business model challenges

Implementing slowing the loop CE strategies for EV LIBs poses several barriers to the business model along with the regulatory challenge highlighted above. These barriers are economic, customer acceptance and data accessibility elaborated in the following sub-sections.

Economic barriers

The economic aspect of implementing circular economy strategies for EV batteries is characterized by uncertainty regarding economic returns, market viability, and the lack of economic incentives. The adoption of circular economy practices for batteries entails substantial costs associated with establishing infrastructure for collection, sorting, dismantling, recycling, and remanufacturing centres. Additionally, significant upfront investments are required due to the need for advanced technologies and a highly skilled workforce (Azadnia et al., 2021).

In this context, strategies that aim to slow down the loop of battery disposal face additional challenges due to the lower prices of new batteries. This can result in the cannibalization of sales revenues when offering repurposed or remanufactured products in comparison to new ones. According to a McKinsey report, the price of a complete automotive lithium-ion battery pack is expected to decrease to approximately $160 per kWh by 2025, compared to $500 to $600 per kWh in 2011 (Hensley et al., 2012). The costs associated with repurposing include facility capital costs, disassembly, testing, binning, and the production of new batteries is estimated to range from $20/kWh to $40/kWh. Additionally, there are costs involved in collecting and shipping second-life batteries to repurposing centres is approximately $40/kWh (Hensley et al., 2012). for the second life business models it is necessary to evaluate the associated operational costs of logistics, transportation, reworking, disposal. Along with that development of algorithms and standardized test procedures to assess the remaining useful life would be required (Eleftheriadis et al., 2022). Thus, identifying or combining applications that offer high value and profitability is crucial.

Customer acceptance barriers

The lack of awareness and understanding of circular economy principles among stakeholders, including customers, poses a significant hindrance to implementation of circular economy strategies. In the context of circular economy, transforming the consumer role from mere consumers to active users requires a radical shift in mindset, which may not always resonate with customers or be feasible in practice (Corvellec et al., 2022). Customers' limited awareness and interest in circular offerings also extend to EVs and LIBs. There is a lack of awareness and understanding among customers regarding the potential benefits of remanufactured and repaired products (Azadnia et al., 2021).

Moreover, consumers often have limited knowledge about the production process and the environmental impacts associated with electric vehicles. Many consumers are primarily aware of the "clean" aspects of electric vehicles while remaining unaware of the resource-intensive and potentially unsustainable aspects related to the mining of raw materials, such as lithium, which is concentrated in a few developing countries[7]. This lack of awareness leads to a skewed perception of electric batteries as sustainable, undermining the sustainability challenges of

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[7] https://unctad.org/news/developing-countries-pay-environmental-cost-electric-car-batteries

batteries production and overshadowing the advantages offered by second-life batteries and their role in slowing resource extraction loops (SSC project, 2022).

Other major challenges faced by second-life battery providers is the misconception among the general public that batteries in a circular economy should be cheap or even free. There is a lack of understanding about the extensive engineering and work involved in refurbishing second-life batteries, including the incorporation of new components like inverters and casings (Greenimpact, 2022). It is crucial to raise awareness and educate people about the benefits and value of second-life batteries, dispelling the stigma surrounding them and highlighting that they are sold as new products with the same warranties as new batteries (SSC project, 2022).

This challenge also happens at the organizational level. There is lack of wholistic understanding of CE which results in companies implementing only minimal changes in their current business model, e. g. increasing recycling, and claiming to be part of CE. Whereas CE must be understood as a fundamental systemic change instead of a minor shift to the status quo to ensure its impact (Kirchherr et al., 2018). Moreover, the economic benefits of the circular economy may not be fully understood, which can lead to uncertainty and reluctance to invest in circular practices (Corvellec et al., 2022).

Data accessibility barriers

On the technical side, it was found that since not all the cells may be eligible for a potential second life use, accurate tracking of first life battery ageing data would be crucial to select the most suitable second life batteries. Thus, proper monitoring and battery selection would be crucial to certify the technical viability of battery second life (Martinez-Laserna et al., 2018). Thus, need for access to relevant battery information such as origin, health, and previous use through the battery management system (BMS) (Shahjalal et al., 2022).

Sharing battery data poses a significant challenge for EV OEMs due to concerns related to intellectual property, consumer privacy, and the maturity of the market (Bobba et al., 2018). Additionally, difficulties in accurately forecasting end-of-life battery supply create uncertainty in second-life battery production, which necessitates a minimum batch size of the same battery type to ensure the viability of second-life battery production (Bobba et al., 2018).

3.2.3 Challenges of impact assessment

Lack of primary data for LCAs

The lack of primary data in battery life cycle assessment (LCA) poses significant challenges in EVB research (Bobba et al., 2018; Kotak et al., 2021; Picatoste et al., 2022). Only a few LCA literature is based on primary data, whereas the majority utilised secondary (and not updated) LCIs (Picatoste et al., 2022). Relying on secondary data sources results in limitations and variability, compromising standardization and reliability (Bobba et al., 2018). Primary data is crucial for evaluating EV batteries, addressing technical barriers, battery performance, degradation, and assessing state-of-health upon removal (Koroma et al., 2022). The scarcity of data on forecasted battery capacity and collection of traction LIBs further hinders research (Bobba et al., 2019). Access to OEM data and development of assessment capabilities are needed (Ahmadi et al., 2017). To improve LCA and overcome data limitations, gathering detailed primary data and conducting sensitivity analyses are recommended (Bobba et al., 2019).

Thus, it is imperative to enhance data collection efforts, particularly during the use stage, to gather more comprehensive information and primary data for evaluating battery degradation and lifetime in specific second-use applications. Improving data collection at all life cycle stages is critical to address these challenges.

Need for holistic assessment

To support the business model for second use of EV batteries, the sustainability of extending their lifetime needs to be demonstrated by assessing economic, social, and environmental aspects together (Bobba et al., 2018). Additionally, Thies et al., (2019) that conducted social life cycle assessment (S-LCA) to analyze social hotspots in the supply chain of LIBs also concluded that to enhance supply chain sustainability, the analysis of social risk should be complemented by economic and environmental considerations.

When it comes to undertaking CE in the overall assessment of products, in practice CE's link to sustainable development has been weak with focus more on economic aspects (Kirchherr et al., 2018). Particularly problematic finding was CE understanding only entailing one or two of the three dimensions of sustainable development can result in CE implementation that is not sustainable, e. g. one lacking social consideration.

Similarly, with respect to EV batteries an integrated assessment of the circularity and environmental aspects was seen lacking. While battery recycling is a dominant topic in LCA studies followed by repurposing, other circular economy strategies such as repair, maintenance, upgrades, and remanufacturing have received less attention in the LCA literature (Picatoste et al., 2022). Thus, it is recommended by Picatoste et al., (2022) that future research should develop integrated CE and LCA studies that combine circularity and life cycle impact assessment to understand the potential impact of CE strategies on product, business models, and value chains.

Overall, absence of adequate metrics and standards is seen as one of the major limitations of implementing circular economy (Shevchenko et al., 2022). There is lack of standardized evaluation criteria that pose challenges in evaluating the environmental, social, and economic impacts of circular business models and hinder the evaluation of transition towards circular economy itself. With adequate metrics at policy, organizational, and customer levels the action towards implementing the circular economy will be based on scientific evidence and quantification, able to create awareness while ensuring positive sustainability impact, otherwise CE may risk driving "circularity for circularity's sake".

In conclusion, there is a need for a metrics backed by accurate data that can provide holistic assessment that incorporates economic, social, and environmental aspects, along with circular economy aspects. This is essential to support the business model for the second life of EV batteries while creating awareness by communicating values batteries that have undergone CE operations.

3.3 Solutions

3.3.1 Measuring circularity

The European Commission recognizes the importance of circularity indicators in its action plan for the Circular Economy (EC, 2015), stating that reliable indicators are crucial for assessing progress and the effectiveness of actions at both the EU and national levels (European Commission). The need for CE performance indicators to measure organizational progress towards the CE has also been emphasized in the EEA and EU communication on A New Industrial Strategy for Europe, highlighting the necessity for structured information to inform decision-making and improve circular business investment decisions (Saidani et al., 2019).

It is now widely acknowledged by practitioners and academics that monitoring and evaluation tools, such as metrics, are essential for promoting the CE and quantifying progress (Franco et al., 2021). Consequently, there is an increasing number of efforts in the literature to develop indicators for the CE concept.

Circularity metrics have multiple potential uses, including serving as key performance indicators for benchmarking and comparing industries, as product labels to inform consumer choices, and as a basis for regulatory change. Organizations are increasingly prioritizing the implementation of actions that facilitate the transition to a CE and the communication of these efforts to stakeholders. Consequently, approaches for assessing the level of CE implementation have become necessary to determine the current state of circularity and track improvements (Valls-Val et al., 2022).

Circularity metrics can also be utilized to capture the benefits of reuse and recycling at the end-of-life of products during decision-making processes. Walker et al. (2018) further emphasize that C-indicators can inform life cycle design decisions without the need for extensive and time-consuming life cycle analysis (Saidani et al., 2019).

Given the complexity of the CE paradigm and the interrelationships among actors along the value chain, metrics provide a standardized language that simplifies information exchange and enhances understanding, thus facilitating the transition to a circular economy (Verberne, 2016). Indicators play a crucial role in taking circularity to the next level by creating a shared understanding and a common language (Bocken et al., 2017). They contribute to a deeper understanding and integration of the CE, enabling businesses that adopt CE principles to collaborate, progress together, and set targets against which circularity progress can be measured.

Types of circularity metrics can be categorized into the following according to (Saidani et al., 2019):

1. Levels: These indicators can be classified into micro, meso, and macro levels. Micro-level indicators focus on organizations, products, and consumers. Meso-level indicators consider symbiosis associations and industrial parks. Macro-level indicators encompass cities, provinces, regions, or countries.
2. Loops: Existing circularity indicators often fail to systematically consider all potential circular economy loops. The loops typically included are maintenance/prolongation, reuse/remanufacturing, and recycling, as depicted in the technosphere part of the circular economy butterfly diagram proposed by the Ellen MacArthur Foundation (EMF, 2015).
3. Performance: Circularity indicators can measure both the intrinsic circularity (e.g., resource recirculation rates) and the impacts of circular economy loops (e.g., sustainability effects). According to Potting et al. (2016), monitoring progress towards a circular economy should address the transition process as well as its effects. The European Environment Agency (EEA, 2016) emphasizes that assessing circularity performance should consider progress indicators such as resource efficiency and material consumption, as well as the effects of a circular economy transition, such as changes in energy consumption, added value of products and services, and employment levels.
4. Usages: Circularity indicators serve various purposes, including information, decision-making, communication, and learning. Information-oriented indicators help understand the current situation, track progress, benchmark performance, and identify areas for improvement. Decision-oriented indicators support decision-makers in formulating targets, strategies, and policy choices. Communication-oriented indicators facilitate internal communication of achievements to stakeholders and external communication to the public. Finally, learning-oriented indicators contribute to workforce education and consumer awareness.

Circularity metrics associated with R-strategies play a crucial role in a strategic measurement framework designed to monitor and evaluate the circularity performance of organizations within the context of transitioning to a circular economy (Franco et al., 2021).

However, there are drawbacks associated with the circularity metrics especially with metrics at micro level. Firstly, in the systematic literature review, by Saidani et al. (2019) it was found that the majority (90%) of these indicators focused on recycling loops, while 65% considered remanufacturing or reuse loops, and only 45% incorporated all major circular economy loops within the same set of indicators (Franco et al., 2021).

Secondly, while numerous circularity indicators have emerged to measure material flow or the recirculated value of a system (such as a product or a nation), only a few studies have compared these indicators with environmental performance or connected them across different societal levels. To adequately assess and track circular economy performance, it is recommended to employ assessment methods and indicators at each level, such as life cycle assessment (LCA) at the micro-level and multi-regional input-output (MRIO) analysis at the macro-level and integrate them within a suitable framework. The challenge lies in establishing connections between the micro and macro levels (Harris et al., 2021).

Finally, despite significant research dedicated to measuring circularity performance at the micro level, there are evident research gaps in terms of circularity metrics that specifically monitor and assess organizations' progress towards a circular economy based on their value propositions and circular strategic choices (Franco et al., 2021).

In conclusion, the European Commission and various researchers recognize the crucial role of circularity indicators in assessing progress and effectiveness in transitioning to a circular economy. Metrics have emerged as essential tools for promoting the circular economy and quantifying progress. They serve multiple purposes, including benchmarking, informing consumer choices, facilitating regulatory change, and assessing organizational implementation of circular strategies. By capturing the benefits of reuse and recycling, these metrics enable informed decision-making without extensive analysis. Moreover, they provide a standardized language for information exchange and enhance understanding among stakeholders, simplifying the complex nature of the circular economy paradigm. However, there are challenges in terms of incorporating all circularity loops and connecting micro and macro levels of assessment. Despite the need for further research and refinement, the benefits of using circularity metrics outweigh the challenges. By adopting these metrics, businesses, policymakers, and society as a whole can strive towards a more sustainable and circular future

3.3.2 Digital product passports

Product Passports have been proposed and advocated as a policy concept by the United Kingdom (UK) Government in its waste and resource strategy (HM Government, 2018) and explored more rigorously by the European Commission (EC) in both product-agnostic (draft) product sustainability regulations (2022) (European Commission, 2022a) and product-specific battery regulations (European Commission, 2020a). The approach of digitalizing product information is a component of the European Circular Economy Action Plan. The EU Strategy for Data states that digital product passports “will provide information on a product’s origin, durability, composition, reuse, repair and dismantling possibilities, and end-of-life handling”. And with the European Union’s requirement of a digital battery passport in the draft EU Battery regulation, the pace is picking up.

Moving towards a circular economy increases the requirements for industry in the areas of product compliance and product sustainability. An ever-growing number of regulations and continuous demand for reporting necessitates the handling of even more data and puts a strain on costs. Therefore, a key element in reaching compliance and sustainability and – ultimately – circularity is a strong focus on digitalization of circular economy data, parameters, and metrics. Digital solutions are a means to achieve the required transparency by increasing traceability and efficiency and providing real-time information on a product at all stages of its life cycle, and to all relevant stakeholders. By this increase in transparency, digital approaches can not only support the transition to a circular economy, but also enable its scaling, provided they also reflect values and business models. These aspects are brought together in the digital product passport, which acts as a nucleus to derive all kinds of information and decisions to advance circular economy. Digitalizing product data and allowing for easy access to information for all relevant stakeholders could prove a key factor for transitioning to and scaling the circular economy. the digital product passport could be a central element of the digital circular economy and as such it needs to be developed further, ideally through a multistakeholder collaboration across the entire industry value chain (Walden et al., 2021).

The concept of Product Passports has gained significant attention and support from various entities. The United Kingdom Government and the European Commission have proposed and explored the idea of Product Passports as a policy concept. The European Circular Economy Action Plan recognizes the digitalization of product information as an important approach. The EU Strategy for Data emphasizes that digital product passports should provide comprehensive information on a product's origin, durability, composition, reuse, repair, dismantling possibilities, and end-of-life handling. The draft EU Battery regulation also mandates the use of a digital battery passport.

As industries move towards a circular economy, compliance with regulations and ensuring product sustainability become increasingly important. This leads to a growing need for data handling and reporting, which can be costly and challenging. Therefore, digitalization plays a crucial role in achieving compliance, sustainability, and circularity. By leveraging digital solutions, such as digital product passports, transparency, traceability, and efficiency can be enhanced. These solutions enable real-time access to product information throughout its life cycle, benefiting all relevant stakeholders. Digital approaches not only support the transition to a circular economy but also facilitate its scalability, provided they align with values and business models. The digital product passport acts as a central hub for deriving essential information and making informed decisions to advance the circular economy. Its development should ideally involve a collaborative effort among stakeholders across the industry value chain to ensure its effectiveness. By digitalizing product data and promoting easy access to information, the digital product passport can play a crucial role in driving and scaling the circular economy (Walden et al., 2021).

The concept

The implementation of a Digital Product Passport (DPP) has the potential to revolutionize the way stakeholders interact with product information throughout its entire life cycle. By accompanying the physical product, the DPP enables various actors, including consumers and waste management companies, to access relevant information and make informed decisions that promote sustainable development. Consumers can use the DPP during the purchase and use phase to evaluate a product's sustainability credentials, while waste management companies can leverage the DPP to streamline disassembling and recycling processes. This interaction with product information at multiple levels empowers stakeholders to contribute actively to the advancement of sustainable practices (Adisorn et al., 2021).

Some actors will be able to access and read data, while others will be able to write data into the passport, thus enabling and supporting (Walden et al., 2021):

1. Traceability – from raw materials extraction/production, through to product life cycle, all the way to the product's end of useful life, enabling better efficiency and transparency,
2. Due diligence efforts (particularly in relation to the upcoming EU Battery regulation requirements)
3. Services related to circular economy – such as remanufacturing, repurposing, repair,
4. Higher rates of recycling,
5. Reliable information made available to a wide range of stakeholders, both public and private
6. Better enforcement tools and market surveillance mechanisms for authorities (enforcing tariffs, taxes, and trade rules)

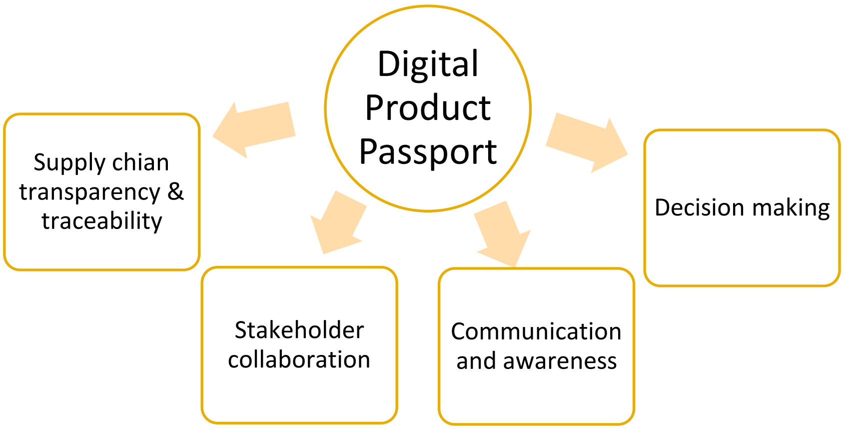

Figure 3-2 Benefits of Digital product passport (DPP)

A proposed universal definition of digital product passport (King et al., 2023)

"A Digital Product Passport Ecosystem (DPPE) is a socio-technical System of Systems, which is collaboratively owned by the producers, users, and disposers of products. A DPPE evidences sustainable business practice and product design values, encourages change in consumer and disposer behavior, and enables greater collective efforts towards a circular economy by all product stakeholders (resource, producer, user, disposers) and economic stakeholders. It does this by defining the metrics for sustainability and circularity for a given product and across product lifecycles, which requires a whole-life assessment against social and environmental impact performance metrics, then translates these into a comparable set of attributes for uniquely identifiable product designs. The DPPE provides a mechanism for uniquely identifying, describing, and exchanging product and actor data between actors. It also requires evidence to support the claims made by actors and evidence of a clear chain of custody of the product, its parts and associated events. The DPPE provides the information necessary to identify hazardous, problematic, and valuable materials, maintain the useful life of the product, and how to dispose of it optimally. The DPPE operates within acknowledged constraints (such as commercial interests, data quality and data ownership, a variety of sustainability metrics, privacy concerns, legacy systems, cost, skills, and current capacity) to achieve the sustainability values and goals of societal stakeholders."

The proposed universal definition of a Digital Product Passport Ecosystem (DPPE) highlights its role as a socio-technical system owned by multiple stakeholders, including producers, users, and disposers of products. The DPPE aims to promote sustainable business practices, encourage behavioral change, and foster collective efforts towards a circular economy. It achieves this by identifying sustainability and circularity metrics for products and through its life cycles. It would further facilitate exchange of product and actor data, and providing information for identifying hazardous materials, optimizing product lifespan, and ensuring proper disposal. Overall, the DPPE serves as a collaborative platform that enables stakeholders to assess, share, and utilize information to advance the principles of sustainability and circularity.

Challenges remain in implementing a Digital Product Passport (DPP) system. Firstly, there is a lack of unified approaches to implementing DPPs across different industries. Each industry may have unique requirements and considerations, making it difficult to establish a standardized approach. Secondly, ensuring the continuous updating of product passports throughout a product's life cycle is a significant challenge. It is crucial to determine how product information will be collected, verified, and kept up to date over time. Thirdly, issues related to confidential business information and intellectual property (IP) security need to be addressed to gain industry-wide adoption of the DPP concept. Protecting sensitive information while providing necessary transparency poses a complex task (King et al., 2023; Walden et al., 2021).

In conclusion, despite challenges such as the lack of unified approaches, data accessibility challenges, and concerns about confidential information, DPPs have gained support and recognition. DPPs can play a crucial role in achieving compliance, sustainability, and circularity by enhancing transparency and efficiency throughout the product life cycle. Collaborative efforts between regulatory and industry bodies and further development can overcome these challenges, making DPPs a valuable tool in advancing the circular economy. One example that illustrates both the potential and a roadmap for DPP is the EU Battery regulation, that is expected to come into force at the start of 2022.

3.3.3 Product-service systems (PSS) for data flows

The product as a service offering in academic literature falls under the term “product–service systems” (PSSs). It has been defined as “a marketable set of products and services capable of jointly fulfilling a user's need. The product/service ratio in this set can vary, either in terms of function fulfilment or economic value” (Mont, 2002). Servitization models can be instrumental in operationalizing the digital product passport (DBP) in several ways, such as:

Enabling data collection:

In PSS, the manufacturers can retain product ownership and thus have the incentive to pay more attention to the use phase. This in turn leads to the implementation of practices such as design for durability, upgradability, reuse and remanufacturing. This configuration turns the manufacturers into product fleet managers, providing them firsthand access to large amount of usage data throughout the operational life of a product. Exploitation of this data may help different strategies for the product along its lifecycle (Khan et al., 2018).

However, the successful implementation of circular supply chain management practices requires the development of new skills, such as designing products for remanufacturing. Unfortunately, a lack of coordination and collaboration among stakeholders can hinder the acquisition of these necessary skills (Hofman et al., 2020). To make informed decisions regarding product design, production, reuse, and recycling, it is essential to standardize data and processes, ensure transparency, and facilitate data sharing among stakeholders (Walden et al., 2021).

Through servitization models, companies can collect valuable data on how their products are used, which can be used to inform the creation of a comprehensive digital product passport. For example, a company offering battery storage as a service could collect data on battery performance and usage patterns to create a product profile that includes information on environmental impact, maintenance requirements, and expected lifespan. This information can be used to inform customers' purchasing decisions and aid regulatory agencies in enforcing sustainability standards.

Digital technologies can convert autonomous products into smart and connected ones that can generate real-time information to centrally monitor and manage them. Data on product conditions, location, use intensity, and availability, lead to improved performance of products and processes by applying big data analytics. This would provide digitally enabled functionalities of monitoring users' activities, preventive and predictive maintenance and estimation of products and components residual life. Firms can thus advance management towards CE by feeding sustainability-oriented decision-making processes with the required information and facilitate a more efficient collaboration between the manufacturer, service provider, logistician, and customer (Bressanelli et al., 2018; Hofmann, 2019).

Changing stakeholder relationships:

Servitization models can alter stakeholder relationships by shifting the focus from selling products to providing a service. This can enable a more long-term relationship with customers, thereby increasing customer loyalty. Additionally, servitization can create new stakeholder relationships by fostering partnerships with other companies that offer services, such as repair and maintenance. From customer point of view, it involves higher level of customer involvement, education by producers, resistance to change in asset ownership and risk behaviours (Hofmann, 2019).

Helping in deployment of technologies:

Servitization models can help accelerate the deployment of new technologies by offering financing options that make it easier for customers to adopt them. This can be especially beneficial for emerging technologies that may have high upfront costs. Servitization can also help in the deployment of technologies by fostering partnerships with other companies that offer complementary services. For example, a company offering solar panel installations as a service could partner with a company offering battery storage as a service to provide a comprehensive energy solution to customers.

In summary, servitization models can be a valuable tool in operationalizing the digital product passport by enabling data collection, changing stakeholder relationships, and helping in the deployment of technologies. By adopting servitization models, companies can create a more sustainable and efficient ecosystem that benefits both customers and the environment.

3.4 Conclusion of literature review

Scholars have been calling for the development of a circular economy approach with life cycle strategy and management for LIBs with consideration of social and environmental criteria. Although current experience is still very limited, once used batteries are collected, recycling is presently the most commonly used and understood end-of life (EoL) treatment for used EV batteries. Slowing of the loop strategies like reuse and particularly repurposing as a new EoL option is emerging worldwide. Recent studies and pilot projects state that extending the lifetime of EV batteries by using them in other types of application can lead to various benefits, including economic, environmental, and social.

However, the ideal life cycle management of LIBs from an environmental perspective deal with competing objectives of resource depletion vs. climate change impact along with contextual factors. The feasibility of different CE activities is further influenced by safety standards and concerns, OEMs' capacities, standards, and processes, as well as the economic business case. Meeting regulatory requirements, particularly of recycled content could likely take precedence over environmental benefits of life extension activities, which is why policy needs to be designed carefully with regards to incentives created by it (Albertsen, 2020).

Thus, because of the novelty of the topic and the limited availability of data, more investigations are needed to confirm and quantify such benefits before making decisions (Schulz-Mönninghoff & Evans, 2023). The Battery Passport would support transparency by allowing users to use, store, and search asset information on demand and make it available to other battery life cycle stakeholders. By creating a unique identity (i.e., digital twin) of an asset, users can trace its journey on a secure, unalterable, and private platform. Sustainability and circularity claims would be supported with actual shared evidence of metrics and certifications or ratings. Further, servitization is hypothesized to enable adoption of second-life batteries while also enabling stakeholder coordination in the value chain and data collection for the DBP.

4 Findings and analysis

This section presents and analyses findings for *RQ1* and *RQ2* in sections 4.1 and 4.2. Findings and analysis for *RQ3* are in section 4.3.

4.1 Metrics relevant for batteries: Sustainability metrics

A major challenge in implementing circular business models is the absence of standardized evaluation criteria and metrics to evaluate their environmental, social, and economic impacts. As a result, there is a need for metrics backed by accurate data to provide a holistic assessment of batteries, in order to support decision-making and create awareness by communicating the values of a slowed loop battery system. This section explores such metrics to first answer the RQ1 of 'What sustainability and circularity metrics are relevant for batteries to support slowing the loop strategies?'. Then analyze the opinions of various value chain actors to the answer the RQ2 of 'What are the perceptions of value chain actors and potential users of second-life batteries towards these sustainability and circularity metrics?' by presenting the figure 4-2 to the interviewees as explained in the Methodology section 2.3.

In this study the impact areas represent specific environmental or social categories of concern, the metrics quantify and characterize the impact within each area, indicators are the specific measurement units, and the tools provide the means to carry out the assessment and calculate the metrics based on data inputs and defined methodologies. Figure 4-2 is the visual representation of their relationship with an example of climate change.

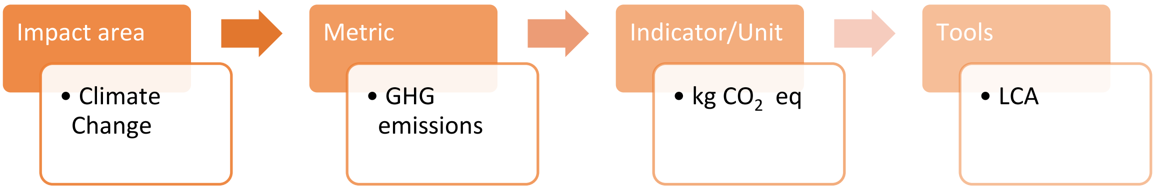

Figure 4-1Example of climate change impact area to showcase the relation between impact area, metrics, indicator and tools used in the study

4.1.1 Environmental metrics

In order to address certain aspects of both RQ1 and RQ2, which centre around the environmental metrics that can support the implementation of slowing loop circular economy (CE) strategies for batteries and their communication of value, the following sub-sections will provide a detailed exploration of this subject. Firstly, the discussion will revolve around the relevance of the environmental metric derived from relevant literature sources and existing regulations/legislation, as part of the metric library of Figure 4-2. Sustainable Development Goals (SDGs) covered in Figure 4-2 are being used for discussion purposes, and the metrics would not align precisely with the specific SDG targets. Instead, they are being used as a source of inspiration. This will be followed by an analysis of the viewpoints expressed by various value chain actors who were interviewed, aiming to gain insights into their perspectives regarding these metrics.

Carbon footprint

The initial environmental metric of significant importance is the carbon footprint, primarily due to its strong political relevance within the electric vehicle (EV) and energy sectors. At the

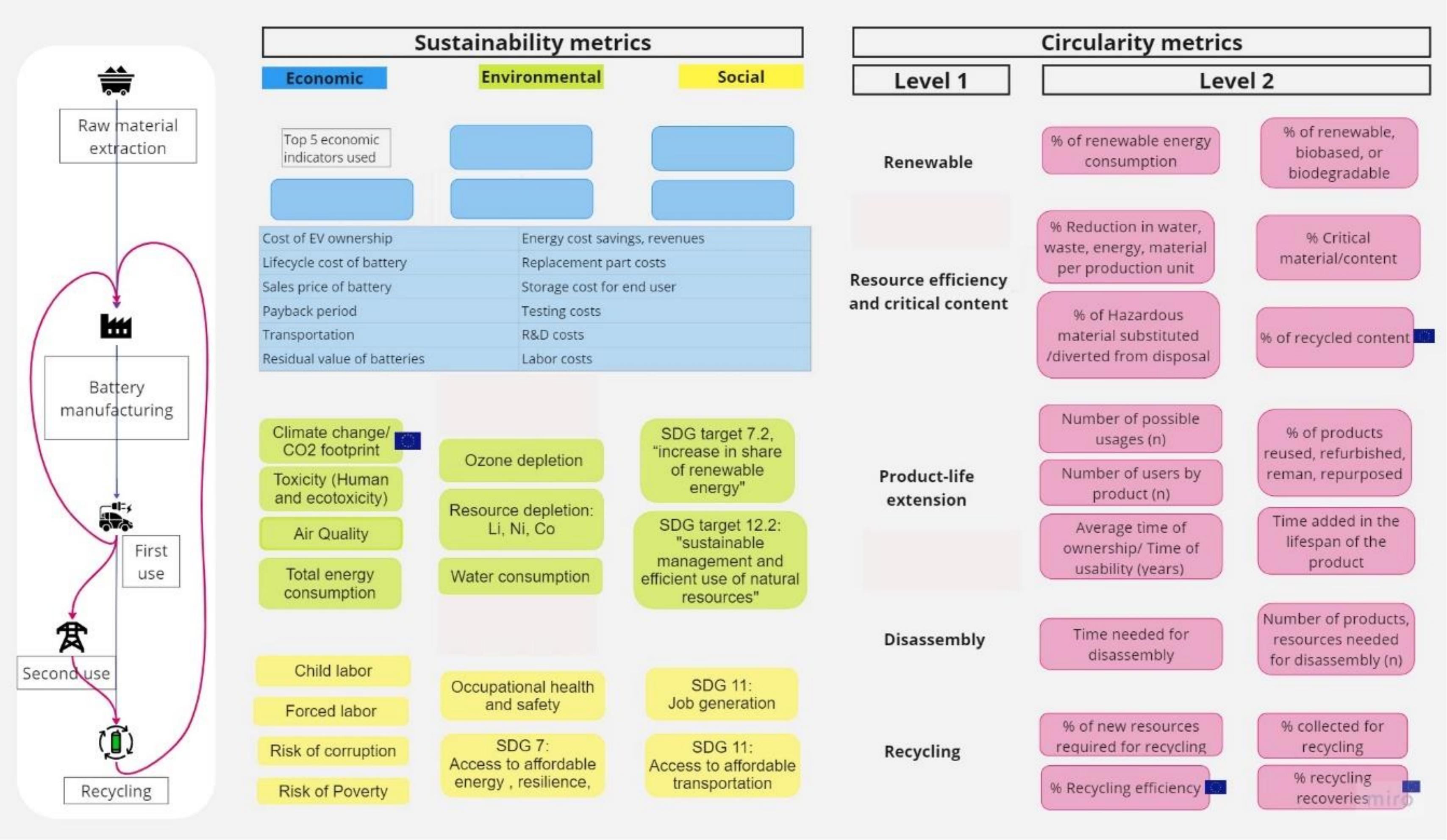

Figure 4-2Metric library relevant to batteries compiled from literature (EU flag marks the mandatory metrics part of the EU battery regulation). On the left is a simple battery value chain. Followed by sustainability metrics covering three pillars of sustainability metrics covering three pillars of sustainability Economic (in blue), Environmental (in green) and Social (in yellow). On the rightmost end are the two levels of circularity metrics. Level 1 are aggregated metrics and Level 2 are the granular metrics.

regulatory level, the EU battery regulation, (2023) mandates the inclusion of mandatory carbon footprint performance classes and maximum carbon thresholds for batteries, ensuring their compliance for market placement. This requirement also extends to the Digital Battery Passport (DBP). However, it should be noted that the use phase, which falls outside the direct control of the manufacturer, is excluded from the scope of assessment. Additionally, it is important to highlight that the regulation does not currently encompass steps that involve further use cycles, such as repurposing or remanufacturing of batteries. This omission is connected to Article 7(3a) of the battery regulation, which states that the carbon footprint requirements do not apply to second-life batteries that have previously entered the market (The Battery Pass consortium, 2023).

By excluding the use phase, as well as the reuse and repurposing phases, there is a risk of underestimating the carbon footprint associated with batteries. This can result in a limited understanding of the true environmental impact of battery production and usage. The amount of CO_2 emissions during the use phase varies depending on factors such as the battery type, capacity, and the energy source used for charging (Philippot et al., 2022). There are potential opportunities for carbon footprint reduction through repurposing and remanufacturing.

Firstly, extending the battery's lifespan through these processes can decrease the carbon footprint per functional unit, as the battery continues to deliver energy over a longer period. This approach helps avoid the need for additional batteries, leading to overall impact reductions (Philippot et al., 2022). According to the EUROBAT, (2022) position paper also emphasizes the value of reusing, remanufacturing, or repurposing batteries as an interesting option for reducing the total carbon footprint of certain battery types throughout their lifetime. In addition to environmental benefits, these approaches can also yield economic advantages in specific cases.

Secondly, repurposed batteries can be utilized in applications such as on-site renewable energy optimization and integration, contributing to grid stability support and reducing reliance on natural gas peak power energy (Shahjalal et al., 2022; Schulz-Mönninghoff et al., 2021). Repurposed batteries thus have the potential to directly reduce carbon emissions by increasing renewable energy sources on the grid, leading to increased efficiency and reduced reliance on traditional fossil fuel-based energy generation.

Through the interviews it was found that CO_2 emerged as the predominant and extensively used metric for batteries, serving communication purposes, informing business decisions, and meeting customer demands. However, accounting the CO_2 footprint is faced with methodological and data challenges. Respondents 11 and 12 emphasized the significance of CO_2 as the most advanced battery metric, with substantial industry efforts dedicated to its calculation. It was found that recyclers conducted LCAs to compare recycling and mining scenarios, aiding decision-making and highlighting the value of recycling operations (#1 and #2a). Cathode material producers focused on carbon reduction in response to customer demand, with LCAs performed accordingly (#2a). According to respondent #21 from an OEM acknowledged the importance of carbon footprint but highlighted data availability as a major challenge. They also stated that carbon footprint was used to support the business case of remanufacturing and not used as sole basis for decision-making. Notably, the author observed ongoing projects at Volvo that involve calculating carbon footprint reduction resulting from circular economy operations such as repurposing.

When addressing the reduction of carbon footprint through second life applications, respondents expressed two different perspectives. Some respondents (#12, #21, #25) emphasized the importance of establishing standard methodologies and highlighted the challenges in developing such methodologies for repurposing due to variety of applications. They noted that the ongoing development of a cradle-to-gate approach by the European Union holds promise (#1, #2, #11, #12, #20). Hence, the development of an appropriate methodology is crucial to accurately account for the carbon footprint reduction achieved through repurposing. On the other hand, other respondents (#2b, #4, #5, #10) focused on the necessity of a viable business case for repurposed batteries and safety concerns with respect to Second life battery energy storage system (SLBESS). One respondent summarized the perspective on second life batteries by stating:

"From a circular economy point of view, you cannot be reasonably against second use or second life. If there is a functional value, it is better to use the functional value instead of destroying it. The question however is if there is an economic model for it?" (Respondent #2b)

In conclusion, the carbon footprint metric is crucial for LIBs due to the regulatory mandate but excluding the use phase and repurposing underestimates its environmental impacts. Repurposing extends battery life and reduces carbon footprint per unit, and by on-site renewable energy optimization decreases reliance on fossil fuels. However, challenges exist in terms of standard methodologies needed for repurposing, and a viable business case is crucial.

Resource depletion

Another environmental metric is the resource footprint, which is of particular relevance in the field of CE for batteries. Due to the expected increase of e-mobility in the next decades, more efforts are needed to understand the potential consequences of batteries from a resource perspective. The existence of different EoL patterns for batteries, i.e., recycling/reuse/second use, may have consequences that require a comprehensive assessment of the resource value-chain of LIBs. Resource assessment can be carried out by mass-based resource accounting, in which material throughputs between natural and anthropogenic systems are measured. Examples of specific accounting methods include material flow analysis (MFA) or life cycle inventories (LCI) in the life cycle assessment framework, as well as impact-based resource accounting, using life cycle impact assessment (LCIA) methodologies where inventoried resources are multiplied by factors representing specific resource-related impacts (Mancini et al., 2015). Both MFA and LCA based approaches with resource depletion as an impact category have been documented in the literature for batteries (Bobba et al., 2019; Picatoste et al., 2022).

Resource depletion is seen as a relevant impact category by many respondents (respondent #9, #10, #11, and #14) and is available when building LCI (Respondent #2a). MFA is used to determine mass balance flows evaluated by MFA linked with a need for a visual to convince industry that slow the loop strategies will not reduce the availability of recycled materials and increase new material demand (Respondent #22). However, it was also noted that this is a less well-known metric, but also that it is not as intuitive to be understood as a metric.

A key discussion that followed around material flows for batteries is the role of second life in delaying recycling thus giving it time to become economically and environmentally efficient i.e. improve the processes and increase the overall recycling industry capacity (Kotak et al., 2021). Majority of the recyclers (#2b, #3, #4, #23) interviewed disagreed with the statement. Mechanical recycling is a mature process as long as disassembly and sorting is carried out for high quality black mass. Chemical recycling on the other hand has pyrometallurgy, which is considered mature now and even getting energy efficient. And even though hydrometallurgy is a newer chemical recycling technology that is not fully mature, but according to respondent #23 stated that it is improving as more investments are getting made, and various industry actors already running pilots. Additionally, the technology will mature in 5-10 years as the volume rises.

Manufacturing scrap is a significant feedstock for recycling now according to respondent #5. According to respondent #2b a lot of funds have been devoted to developing battery recycling flowsheet so there is no need to think about delaying recycling. Recycling needs economies of scale, thus a more centralized model for chemical recycling would make it a viable option.

Additionally, sending a battery into a second life application postpones its journey into the recycling value chain. One of the points of view was that need to prioritize recycling because for value chain risk reduction and greater ownership of materials, reducing dependence on China (Respondent #13). Several interviewees highlight the importance of keeping materials in Europe in order to safeguard the value chain and reduce risks. The EU is dependent on third countries for the supply of raw materials for the manufacture of LIBs and represents a very low share of global production. What is most striking is that supply is highly concentrated in China, dominating global capacity. Similarly, there are dependencies and bottlenecks downstream in the supply chain for processed materials, components and assemblies, as supply is controlled by an oligopoly in Asia.

Other environmental metrics

A set of other environmental metrics were compiled in the review study by Picatoste et al. (2022), involving a comprehensive evaluation of 39 LIB LCA papers. According to this study, after carbon footprint (global warming potential impact category), toxicity (human and ecotoxicity), air quality, total energy consumption, ozone depletion and water consumption were the most utilised impact categories.

During the interviews, respondent #12 highlighted that the need to assess various environmental metrics should consider factors such as the availability of calculation methods, external pressures, stakeholder expectations, and company communication strategies. Among the remaining environmental metrics, total energy consumption emerged as the next most important metric, as indicated by multiple interviewees (#1, #2a, #2b, #3, #12, #11, #21). The importance of water consumption received mixed responses, with respondents #9, #10, and #11 emphasizing its significance, particularly in the lithium supply chain and wastewater management at companies, while some recycling respondents did not express concern about water consumption. Toxicity (#1, #2a, #2b) and air quality (#4) were mentioned less frequently during the interviews.

Renewable energy integration

Another environmental metric relevant to second life of batteries is “increase in share of renewable energy”. It is also a key part of Sustainable Development Goal 7.2, making it politically significant. There is strong evidence that Battery Energy Storage Systems (BESS) have helped to increase the integration of renewable energy into the global energy mix and can contribute to achieving target 7.2 (Hannan et al., 2021). Therefore, it is crucial to consider the displaced grid mix and its development over time in the LCA methodology when applying Second Life Battery Energy Storage Systems (SLBESS) for local renewable energy integration, as noted by Schulz-Mönninghoff et al. (2021). However, the literature has not yet explored the role of SLBESS in renewable energy grid integration through participation in frequency regulation application.

The importance of increasing the proportion of renewable energy as a crucial factor for Second Life (SL) providers in supporting the energy transition was acknowledged by respondents #1, #7, and #22. However, it has not been quantified yet. Respondent #18 suggested that renewable energy does not need to be considered as a separate metric since it is indirectly covered by CO2 emissions. Respondent #2b proposed that the SDG target 7.2, which focuses on increasing the share of renewable energy, could be reported based on Energy Attribute certificates. On the other hand, a circular economy expert in the automotive industry (Respondent #17) highlighted that the production impact i.e. activities in scope 3 (upstream and downstream) of new energy storage, similar to new grid lines, is often overlooked in the industry.

Ultimately, the decision to use batteries for second life storage is primarily driven by their performance, with little consideration given to their production impact. However, for OEMs aiming to pursue sustainability goals, SDG 7.2 serves as a relevant inspiration for a metric to assess the extent to which second life storage supports the energy transition. Additionally, application-specific metrics such as the contribution of storage to renewable energy integration or its ability to provide frequency control are important to consider for SLBESS.

Another SDG closely related to CE is SDG 12 *Sustainable Consumption and Production*. Specific targets of SDG 12 are target 12.2 (by 2030, achieve the sustainable management and efficient use of natural resources) and target 12.5 (by 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse). Circularity metrics can be used to align with these SDG targets. These are further discussed in section 5.3. It is argued that CE practices and principles are transversal, and the adoption of CE practices will be necessary to achieve many targets outlined under not only SDG 12, but also several of the SDGs that will be discussed in the social sustainability metrics section 5.2 (Schroeder et al., 2019). Overall, metrics derived from SDGs have the potential to be a viable quantifiable metric, monitored at the corporate level.

In conclusion, based on the frequency of relevance expressed by the interviewees, the most important environmental metrics for supporting slowing the loop strategies were CO_2 emissions, renewable energy support, and resource depletion. The importance of other metrics such as total energy consumption, water consumption, toxicity, and air pollution were ranked in decreasing order. However, there was comparatively less emphasis on these metrics in demonstrating the impact reduction achieved through the prolongation of battery use, compared to CO_2 reduction.

4.1.2 Social impact metrics

The next relevant areas of metrics for LIBs are social as batteries have high social impacts, both upstream and downstream. Social impact of batteries in the upstream supply chain is addressed by the EU Battery Regulation in the form of “battery due diligence”. It refers to obligations aiming at “identifying, preventing and addressing actual and potential social and environmental risks linked to the sourcing, processing and trading of the raw materials and secondary raw materials required for battery manufacturing” (Article 2(36)). Areas under consideration are human rights, labour rights and industrial relations, including but not limited to (Annex X) (i) occupational health and safety, (ii) child labour, (iii) forced labour, (iv) discrimination and (v) trade union freedoms.

The examination of social impact areas specified in the EU battery regulation involved a review of relevant literature. Grey literature revealed that GBA (Global Battery Alliance) has developed the Child Labour and Human Rights Indices as metrics for assessing social impact. In academic literature, a few social impact assessments were identified (Koese et al., 2023; Thies et al., 2019). Thies et al. (2019) utilized Social-LCA methodology to identify social hotspots within the supply chain of lithium-ion batteries. The frequently associated risk categories were child labour, corruption, occupational toxins and hazards, and poverty. Koese et al. (2023) corroborated these issues in the LIB (lithium-ion battery) supply chain while identifying additional indicators such as fair salary, trafficking in persons, right of association, and pollution levels in a country as significant hotspots.

It is assumed that CE strategies can provide social benefits similar to environmental benefits by reducing negative impacts that result from avoiding the production of new batteries. For instance, if batteries are used for a longer period, mining activities, which are linked to child labour, would be reduced. Koese et al. (2023) suggests that battery lifetime or efficiency could be improved to minimize social risks associated with the battery life cycle. By ensuring longer life cycles or achieving higher efficiency, the relative contribution of various life cycle stages can be reduced, as the effects are distributed across more kWh of energy delivered. If these improvements can be made, the energy output in kWh per kg battery will increase, and consequently, the relative social risks per kWh will decrease (Koese et al., 2023).

The study by Hannan et al. (2021) that assessed the impact of Battery Energy Storage Systems (BESS) on achieving Sustainable Development Goals (SDGs) was consulted to identify direct positive societal effects of batteries. Their analysis of societal impacts was utilized to establish relevant metrics for second-life BESS. In particular, when examining the social benefits associated with circular economy (CE) strategies, the fulfillment of targets 7.1 (ensuring universal access to affordable, reliable, and modern energy services) and 7.2 (substantially increasing the share of renewable energy in the global energy mix) under SDG 7 (Affordable and Clean Energy) were taken into consideration.

In addition to SDG 7, which focuses on providing affordable energy access, second-life Battery Energy Storage Systems (BESS) can also contribute to affordable transportation. The process of repurposing batteries for a second life is seen as advantageous in lowering the initial expenses associated with Electric Vehicles (EVs) when compared to Internal Combustion Engine Vehicles (ICEVs) (Tang et al., 2019). This, in turn, supports the achievement of SDG Sustainable Cities and Communities target 11.2, which aims to provide safe, affordable, accessible, and sustainable transport systems for everyone by 2030.

Job creation is another important aspect of batteries' social impact. While the negative effects of job creation in the upstream sector have already been recognized, strategies related to the CE for batteries can also result in job opportunities in downstream sectors. In developing countries, the refurbishment and repair of discarded products from Western markets, specifically in the automotive and electronics industries like mobile phones and household goods, indirectly contribute to reducing poverty (Schroeder et al., 2019). The production of second-life batteries also requires a significant amount of manual labor. Various blue-collar skills are needed, including battery dismantling and repair, safety training for transportation (such as IATA certification and UN38.3 compliance), handling of forklifts and other equipment, training in industry norms and standards (such as IEC and UL standards), as well as knowledge of power electronics according to a Project albatts webinar[8] (2023). Therefore, CE approaches such as remanufacturing, repair, and repurposing of batteries are crucial for achieving the targets outlined in Sustainable Development Goal 4, particularly in terms of promoting technical skills and creating decent jobs (Target 4.4).

Looking at opinions of industry actors towards these various social metrics, it was observed that they are largely seen as due diligence effort as already found in literature (Berger et al., 2022) and not expressed quantitatively. Among the social metrics while all the respondents knew the importance of child labour, forced labour, poverty upstream and was observed that it is being

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[8] https://www.project-albatts.eu/Media/NewsEvents/24/NewsEvents_24_SLIDES_20230201_17432.pdf

worked out with suppliers. One of the respondents from the battery platform (Respondent #9) highlighted that it will be important to track child labour, forced labour, as mining at scale does need to happen, for the number of batteries to be made. This is in line with arguments from the literature that point out that even with recycling the dependence on primary materials in the short term will not reduce (reference). And responsibility-wise it was seen as more of purchasing responsibility's task to manage this area (Respondents #10 and #21).

When considering the opinions of industry actors regarding various social metrics, it was observed that these metrics are primarily viewed as a necessary effort for due diligence, as documented in existing literature (Berger et al., 2022). However, they are not expressed in quantitative terms. Among the social metrics, all respondents acknowledged the importance of addressing child labor, forced labor, and upstream poverty. It was noted that efforts are being made to address these issues with suppliers. One respondent from the battery platform (Respondent #9) emphasized the need to monitor child labor and forced labor, especially considering the scale of mining required to meet the demand for batteries. This aligns with arguments made in the literature, which highlight that even with recycling, the reliance on primary materials will not decrease significantly in the short term (Kotak et al., 2019). In terms of responsibility, it was perceived that managing this aspect primarily falls under the purchasing department's purview (as mentioned by Respondents #10 and #21). When it comes to social impact areas that are being tracked with quantifiable metrics, the implementation was considered problematic. Inspecting and verifying compliance would be a significant challenge due to the lack of visibility in the supply chain.

The occupational health and safety metric received more quantitative tracking both upstream and downstream, particularly during the recycling stage. Respondents #10 and #15 also highlighted its connection to reporting requirements. However, it was noted that these areas may become quantifiable metrics in the future. The development of the Global Battery Alliance's (GBA) child labor index and forced labor index, which builds upon existing UN frameworks, was viewed as an interesting advancement. However, respondents #1 and #9 expressed skepticism about its widespread adoption. The increasing reputational risks faced by companies were acknowledged. OEMs are striving for greater self-reliance in resources to mitigate supply chain risks and maintain better control over their supply chains. In addition to EU regulations, pressure from stakeholders is driving large companies to prioritize traceability, understand the chain of custody, and exercise due diligence (according to Respondents #11, #12, and #13).

Respondent #11 highlights that the Corporate Sustainability Reporting Directive (CSRD) and the interconnected European Sustainability Reporting Standards (ESRS) introduce significant changes that establish a fresh approach to sustainability reporting. Under the CSRD, all companies falling within its scope are obligated to adhere to the ESRS and include the reporting in their management report. These standards also emphasize the importance of traceability and transparency in the reporting process, as they now entail a limited assurance requirement.

Respondents who are working on operationalising the digital battery passport and traceability (Respondents #11, #12, #13) have highlighted that while environmental metrics receive significant attention, the social aspect of sustainability is often overlooked. Companies lack extensive knowledge about their supply chains and struggle with transparency due to the complex, dynamic, and international nature of these chains. This issue is still in its early stages, but progress is being made in terms of using assurances and certifications like IRMA. However, it is challenging to gauge the strictness and coverage of such schemes comprehensively. Only a few companies have obtained certification so far, but the process has begun (Respondent #11).

The digital battery passport has the potential to serve as a means of communicating these certifications to end consumers.

In general, it was observed that the positive social advantages of circular economy (CE) strategies, such as accessible energy and transportation, are crucial for effectively communicating the value of SLBESS. However, these benefits are not anticipated to be utilized as quantifiable metrics that are universally accepted throughout the value chain. Even in existing literature, limited attention is given to the positive socio-economic impacts in general. Social Life Cycle Assessment (S-LCA) primarily focuses on identifying the negative social risks associated with a product's life cycle. Nevertheless, some authors have already advocated for a greater emphasis on capturing and assessing the positive social effects within the S-LCA methodology (Koese et al., 2023).

To summarize, the primary drivers for incorporating social impact metrics are currently supply chain due diligence, transparency, and traceability mandated by the regulation and customer demand. While quantification is important, it is considered a future focus. The major drivers identified for using metrics are ensuring legal compliance and addressing supply chain risks (Berger et al., 2023). However, there is an awareness of significant social impact areas. There were recognized trade-offs related to job generation as an impact area (Respondent #11). For example, if circular economy operations in Europe lead to job creation, it may have an impact on job generation upstream, particularly in economies dependent on mining activities. Additionally, challenges arise as negative impacts occur in countries with a low socio-economic status, while the positive impacts during the use phase benefit wealthier nations (Sovacool et al., 2020).

4.2 Metrics relevant for batteries: Circularity metrics

In addition to sustainability measures, the literature emphasizes the importance of indicators and metrics related to the circular economy (CE) to effectively measure progress and support circularity goals. At regulatory level, the EU battery regulation mandates some circularity metrics in the form of recycled content, collection rate, and material recovery rates. In grey literature, the Battery Pass consortium suggested defining circularity indicators that make the removability, replaceability, and recyclability measurable and comparable as part of the battery passport. By compiling measurable indicators that provide an overall score, it would be possible to increase transparency and enable informed purchasing decisions, for products and for end-users. The introduction of such a score could serve as an incentive for the production of batteries designed with circularity in mind (The Battery Pass Consortium, 2023).

This study aimed to create a comprehensive set of circularity metrics that can be used by all stakeholders in the battery industry. These metrics are intended to support decision-making processes, communicate the value of products, and establish a common language for measuring progress towards circularity (Shevchenko et al., 2022). The study developed a framework based on the contributions of various circular strategies, using a three-level framework proposed by Saidani et al. in 2017 (Table 4-1). Additionally, circularity metrics from Franco et al. in 2021 and Pollard et al. in 2022 were adapted to suit the context of batteries (Table 4-2). This compilation of metrics provides a framework for evaluating the circularity performance of battery products.

Table 4-1 Three levels of circularity indices can be envisioned from all the available micro indicators. Adapted from Saidani et al., 2017

Indicators	**Type**	**Intelligibility**	**Purpose**	**Users**

Singular circularity score	Key metric	High, intuitive	Communication and overall progress	Administration, top managers
Aggregated	Steering metrics	Medium	Steering, control, decision	Administration, managers
Granular metrics	Monitoring metrics	Low	Analysis, monitoring, research imporvement	Experts, specialists, engineers, researchers

Table 4-2 Circularity metrics adapted from Franco et al., 2021and Pollard et al., 2022

Indicators					
Singular circularity score	Circularity score: A strategic metric used to measure the degree of circularity of a product or system, which reflects how effectively materials, energy and waste are managed throughout its lifecycle.				
Aggregated	**Renewable**	**Resource efficiency**	**Product life extension**	**Disassembly**	**Recycling**
Granular metrics	Share of renewable energy consumption Share of renewable, biobased, or biodegradable materials	Share of critical material/content Share of renewable energy consumption Share of reduction in water, waste, energy, material per production unit	Number of users by product (n) Products collected, remanufacturing, refurbished, repurposed, access to repair Number of possible usages Time added in the lifespan of the product (time unit) Average time of ownership(years)	Time (time unit) needed for disassembly Number of products, resources needed for disassembly (n)	Share of new materials required for recycling Share of material diverted from disposal Overall recycling rate Collection rate

Renewable metrics

The share of renewable energy consumption was found to be important by almost all the interviewees. Conversely, the share of renewable, biobased, or biodegradable materials was seen as not relevant for batteries

Resource efficiency metrics:

The resource efficiency metrics considered in this study include the proportion of recycled content, reductions in water, waste, energy, and materials per unit of production, as well as the share of hazardous and critical materials. The share of recycled content is highly important due to regulations, but respondents acknowledged that it could create a divide. One of the respondents (#2b) who participated in the battery regulation consultation expressed the belief that recycled content is not the most suitable indicator for assessing the circularity of metals. Instead, they emphasized the relevance of factors such as collectability and recyclability. Occasionally, customers request recycled content beyond the legal requirement, but there is a challenge in balancing the supply and demand of secondary materials. In the position paper, Eurobat recommended that the total amount of secondary materials (lead, lithium, cobalt, and nickel) used by each company annually should be considered as an aggregate, rather than examining each individual battery separately (EUROBAT, 2022).

In the 2022 provisional agreements, the most significant provision aimed at incentivizing recycling is the requirement for recycled content. Article 8, for example, states that batteries with a capacity greater than 2 kWh must contain a minimum of 12% recycled cobalt, 4% recycled lithium, and 4% recycled nickel. Majority of the interviewees agreed that setting of recycled content targets would skew the industry towards recycling. This provision represents a major change compared to previous legislations (Respondent #1).

According to a policy expert (respondent #16), by demanding recycled content, existing industries that have been engaged in recycling would gain visibility and create a market for their products. It is crucial to consider the availability of existing recycled materials in society when trying to understand the implications of such a provision. If there is an insufficient supply in the market, conflicts may arise. The EUROBAT, (2022) position paper on battery regulation highlighted the uncertainty surrounding the prediction of the quantity of secondary raw materials that will be available in 2030 and beyond to meet the targets. Additionally, even when resources are available, the industry faces challenges in finding them and ensuring their quality, which adds to transaction costs (respondent #16). Thus, respondent #16 emphasized the need for an organization or body to facilitate matchmaking between the recycling and production industries, suggesting the creation of an information portal for this purpose.

The reduction in water, waste, energy, and materials per production unit was deemed important by most interviewees involved in production (Respondent #2a, #2b, #10, #15). They also acknowledged that these factors are cost drivers and thus should be minimized to remain competitive in the market (respondent #2b).

The share of hazardous and critical content was considered important by recyclers (respondents #1, #2b and #4) who require knowledge of these elements for effective recycling. The reduction of resources and the avoidance of materials that are difficult to source or hazardous were deemed important as they come with additional costs.

Product life extension metrics:

The relevance of certain metrics, such as time added and average time of ownership, is primarily seen in the context of first life and second-life providers in the battery industry, according to respondents #1, #7, #10, and #15. Original Equipment Manufacturers (OEMs) often have dedicated teams, like remanufacturing teams, with specific targets related to the percentage of products remanufactured (respondent #21). While these metrics are undoubtedly important, one respondent (#9) highlighted the need for broader market adoption and demand for these metrics to drive significant change. They emphasized that buyers basing their decisions on these metrics would provide the biggest boost. Therefore, there is a need for these metrics to be recognized and demanded by the market.

The lifespan of batteries is influenced by various factors, and different actors in the industry have their own business models that depend on ownership dynamics. The willingness of the market to pay for product longevity is a key consideration, which also correlates with economic aspects. Metrics such as the number of possible cycles can help users make informed decisions about batteries.

In terms of calculating product life extension, it was observed that average time of batteries is already approximated by the second life providers as 8-10 years of life added. Many pointed out that number of cycles would be a better measure of product life extension. Even though it would be difficult to standardize as different applications would have different frequency of life cycle. For product life extension, respondent #10 and #15 also added that their focus is also on designing the batteries for a long lifetime.

When calculating the extension of a product's lifespan, it was noted that the average battery lifespan is already approximately being calculated by the second life providers. Some suggested that instead of using time as a metric the number of cycles would be a more appropriate measure for product life extension (Respondent #9, #15, #21). However, according to respondent #14, standardizing this measurement would be challenging due to variations in the frequency of life cycles across different applications. Additionally, respondents #10 and #15 emphasized that their focus is also on designing batteries with a longer lifetime as part of product life extension efforts.

Disassembly metrics

There was a widespread acknowledgment of the need for a disassembly metric. All the respondents showed support to such a metric with different uses. While one respondent (Respondent #2b) suggested that disassembly could be factored into the treatment charges for remanufacturing or recycling, another respondent (Respondent #14) pointed out that it could be commercially advantageous for service providers to charge more for products that are difficult to disassemble. Respondent #2b also highlighted that the practice of dismantling has not been fully developed yet and should be explored further. The mainstream adoption and acceptance of a disassembly metric by the industry could facilitate this development. It was also emphasized that this metric should not only be accepted across the value chain but also be demanded by OEMs in order for it to have impact on battery design.

When calculating such a metric, it was emphasized that factors beyond just the time required for disassembly are important. Respondents #1, #14, and #21 highlighted the significance of the possibility of disassembly without causing damage and the ease of accessing components, especially avoiding the use of glue or silicon that can make disassembly challenging. Another issue raised by respondent #21 was the interdependence between various steps involved in reaching essential parts, such as fuses, for basic operations. Respondent #21 suggested that this granular metric should thus be referred to as "ease of disassembly." Additionally, it was mentioned by Respondent #2b that this metric could also encompass labor costs.

According to the Respondent #8, an adhesive provider, the company is currently developing adhesives that can be used to separate batteries, enabling a circular economy[9]. However, there are various reasons for pursuing this goal, such as repair, second life applications, and recycling. Additionally, different companies have varying levels of willingness to modify battery designs to accommodate these adhesives. It was observed that disassembling the battery is important, but if the price of the adhesive increases due to certain innovations, there is a lack of interest, and cheaper alternatives are sought. Unfortunately, battery design considerations for other

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[9] https://www.mouser.com/pdfDocs/henkel-solutions-enabling-sustainable-ev-batteries.pdf

factors take precedence, and since the adhesive is a small component, the provider has limited bargaining power.

One notable development to pay attention to is the emergence of cell-to-pack technology, which has significant implications for battery servicing, maintenance, second-life usage, and recycling. Respondent #3 mentioned that battery manufacturers are now adopting cell-to-pack approaches, bypassing the module stage where cells are welded to a pack, resulting in batteries with higher energy density. So according to the respondent, this shift may discourage second-life applications. Respondent #8 explained that transitioning to a cell-to-pack design would require more structural adhesive. Further, in terms of crash safety, cells would assume the structural role previously held by modules. While modules are practical due to their size being adequate for various operations, moving towards cell-to-pack from a manufacturing, cost, and performance perspective is considered a logical step. This change would emphasize the importance of debonding. Cell-to-pack batteries can be repaired, reused, and repurposed once debonding is achieved. Without easily removable modules, if a single or few cells fail, the entire pack may need to be replaced, which poses greater challenges if the pack is a structural component of the vehicle. Tesla has already implemented a structural battery in their Model Y EV[10], but it's not expected that traditional OEMs will adopt such battery design changes in the near future according to IDTechX[11], although a reduction in inter-cell/module materials is highly probable for the sake of simpler energy density improvements. Joint ventures between battery manufacturers and automotive OEMs may facilitate the production of such batteries in the long run.

Recycling metrics

The EU battery regulation has played a critical role in promoting recycling efforts by enforcing recycling metrics. As a result, it was observed that the recyclers interviewed have embraced these metrics and actively track their progress. However, there is a current emphasis on "recycling efficiency" as a metric, only takes into account the output of battery materials. This approach overlooks the efficient utilization of chemicals and energy during the recycling process. Recognizing the need for a more comprehensive indicator, the percentage of new resources required for recycling has emerged as an intriguing measure (respondent #1, #2b, #4, and #14). This metric, particularly focusing on the energy consumption part has potential to foster competition, was mentioned by respondent #2b.

In Sweden, battery recycling processes are supported by renewable energy. Respondent #4 additionally pointed out that the use of battery discharge instead of the calcification pre-step has proven effective in securing raw materials while also powering facilities. Remarkably, the current recycling rate stands at 85% by weight, surpassing the requirements set by the EU battery regulation. Ensuring price discovery of recycled content through the London Metal Exchange was said to be crucial for facilitating circularity by respondent #9. Regulation plays a pivotal role in this aspect, promoting transparency and accountability.

Despite the regulations addressing battery collection and recycling rates, there is limited emphasis on collecting batteries for reuse. This has led to concerns that the EU Commission prioritizes collection for recycling over the repurposing of retired EV batteries. While there has been historical conflict between reuse and recycling, the current legislation focuses on recycling

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[10] https://electrek.co/2020/10/07/elon-musk-tesla-structural-battery-cells-model-y-giga-berlin/

[11] https://www.idtechex.com/en/research-article/ev-material-and-component-opportunities-outside-the-battery-cell/25117

rates based on collected batteries rather than those placed on the market, which may not effectively drive recycling forward according to the policy expert (respondent #16).

Implementing a battery collection rate exclusively for repurposing would present challenges, limiting flexibility for companies managing end-of-life batteries. NMC batteries, for instance, are typically recycled to extract valuable materials like cobalt and nickel (Ilyas et al., 2023; Chen & Ho, 2018). Introducing collection rates solely for repurposing could result in controversy and potentially bypass the recycling of valuable NMC batteries. Furthermore, any collection rate for repurposing would need to consider minimum battery state of health (SOH) and/or remaining useful life (RUL) requirements, influencing the allocation of batteries to recycling or repurposing and impacting both markets. As a result, the likelihood of a battery collection target being introduced exclusively for repurposing purposes is low.

Apart from the metrics compiled by the author in Figure X, key enablers for CE strategies of batteries that came to light were safety and standardization.

Safety concerns and Reputational concerns

OEMs (Original Equipment Manufacturers) are currently hesitant to allow batteries to be used in third-party second life applications due to concerns about liability. However, the upcoming EU Battery Regulation may bring provisions that could change this situation. It should be noted, as mentioned by respondent #5, that even if legal liability is no longer an issue due to the regulation, there remains a significant concern about reputational risk associated with second life applications. Additionally, it was highlighted that second life applications are still in the pilot stage, and there are concerns about their safety, profitability, and reliability. Respondent #9, who has experience in repurposing batteries for various applications after their initial use, agreed that for the second life battery market to be successful, the transfer of liability must be a key feature of the trade.

Additionally, respondents #1, #7 and #22 stated that there is a lack of safety standards for second life applications, as highlighted in the literature. However, there is also a perspective that the energy sector is already burdened with excessive regulations (respondents #3 and #14), particularly regarding logistics, storage, and transportation, where EOL batteries are seen as challenging and potentially hazardous, leading to increased compliance costs. In order to encourage the repurposing of batteries, it will be necessary for them to meet technical requirements and receive incentives.

Thus, the reputation risk associated with second life applications and the lack of safety standards pose challenges for the viability of the market. Liability transfer and incentives will be crucial for successful battery repurposing.

Standardization

Currently, the existence of a wide range of battery pack designs, chemistries, and cell formats makes it challenging to collect the required modules for second life batteries. Therefore, battery standardization is considered crucial for facilitating CE strategies. Respondent #22 emphasized the significance of standardized batteries in ensuring the availability of spare parts and modules for repurposing. However, it is worth noting, as respondent #15, a Nordic battery manufacturer, pointed out, that while standardization is welcomed, it should not hinder innovation efforts towards the development of more sustainable battery designs.

Battery technologies are rapidly evolving, with changes occurring in cathode and anode chemistries. Respondent #2b also noted the emergence of battery chemistry combinations. Currently, the recycling process is labor-intensive, prompting discussions about implementing automation in the near future. Respondent #15 highlighted the need for automation in the Nordics due to high labor costs. The industry currently deals with small volumes but as volumes are expected to significantly increase, there is a pressing need for automation. To optimize processes, a larger quantity of the same type of battery would be beneficial.

However, second-life batteries present a challenge to automation as their variety would be a deterrent according to respondent #2b. Nevertheless, respondents #14 and #24 stated that if screening is conducted adequately, automation will not be affected by second-life batteries. Given the evolving battery technologies and the labor-intensive nature of recycling, automation is being considered to accommodate the growing volumes. While the variety of second-life batteries poses challenges, proper screening can help mitigate the impact on automation.

In conclusion, the development of circularity metrics and indicators is crucial for supporting the circular economy and measuring progress towards circular aspirations. The EU battery regulation mandates some circularity metrics, such as recycled content, collection rate, and material recovery rates. However, there is a need to complement the existing metrics with a comprehensive set of circularity metrics to not only measure product circularity performance and communicate the value of the product to stakeholders but also ensure crucial aspects of CE are addressed. The framework of three levels of circularity indices can be used as a guiding framework for measuring product circularity performance. The circularity metrics adapted from Franco et al. (2021) and Pollard et al. (2022) provide a useful set of granular metrics, aggregated metrics, and a singular circularity score for measuring the degree of circularity of a product or system.

4.3 Metrics for batteries: overall conclusion

Based on the preceding discussion, it can be concluded that the industry remains divided regarding the decision to repurpose batteries prior to recycling, and there is a widespread recognition of the challenges associated with slowing the loop strategies. To address these challenges and improve decision-making, the use of metrics is recommended, which can enhance awareness among the value chain and customers.

In supporting the business model for circular economy strategies, it is crucial to emphasize the sustainability and circularity value of R-operations (repurposing operations). To strengthen the case for repurposing before recycling, the metrics of carbon footprint with renewable energy impact category and resource depletion, evaluated through the Life cycle analysis (LCA) material flow analysis (MFA) method respectively, can be employed.

For the carbon footprint cradle to grave methodology will need to be developed to include the use phase and R strategies so that even the positive environmental impacts are considered. Repurposing extends battery life and reduces carbon footprint per unit, additionally by on-site renewable energy optimization decreases reliance on fossil fuels.

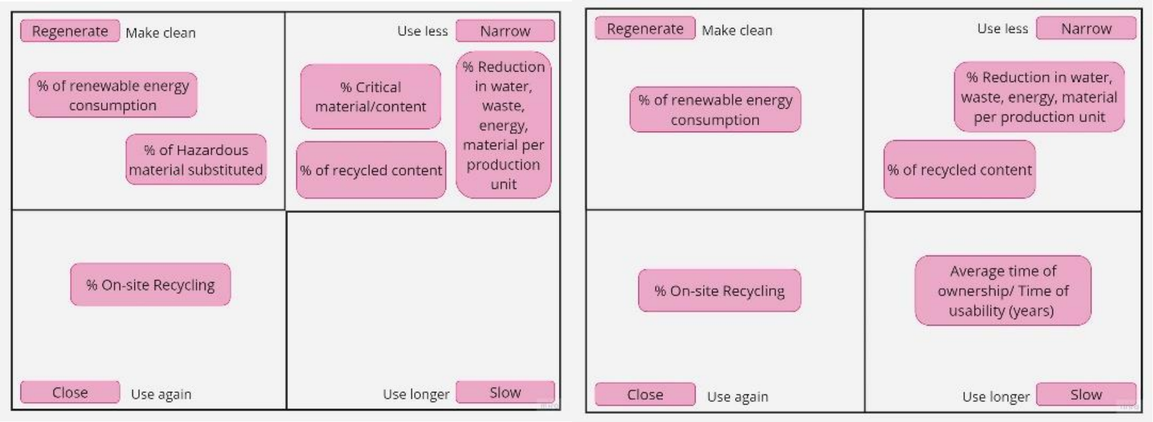
The "increase in share of renewable energy" is a significant environmental metric for the second life of batteries, aligned with Sustainable Development Goal 7.2. When implementing Second Life Battery Energy Storage Systems (SLBESS) for local renewable energy integration, considering the displaced grid mix and its evolution over time in the life cycle assessment (LCA) methodology is crucial. While the role of SLBESS in renewable energy grid integration through frequency regulation is yet to be explored in the literature, SL providers acknowledge the importance of increasing the proportion of renewable energy in supporting the energy transition.

MFA on the other hand enables a comprehensive understanding of the flow of resources throughout a product or process, encompassing raw material extraction, production, product use, and disposal. By utilizing MFA, a detailed assessment of resource inputs and outputs can be obtained, aiding in the evaluation of resource depletion.

Overall, the adoption of the environmental metrics, supports decision-making, raises awareness, and highlights the sustainability and circularity benefits of repurposing activities in the circular economy. The two key drivers of using sustainability metrics were seen to be legal and customer demand. The aim of these metrics is to get industry to follow standards, procurement and sales teams use it for contracts, companies set targets for higher and use that for communication and differentiation of products.

Regarding circularity metrics, an important observation is the necessity for them to have an economic perspective. For example, the time required for disassembly adds to the overall cost, and the metal recovery rates in recycling processes associated with metal prices are considered important (Respondent #2b and #9). Respondent #18 and #24 also emphasized the importance of environmental benefits associated with circular strategies, highlighting the need to integrate sustainability value into the circularity metric itself. In practice, it was found that metrics and strategies focusing on recycling are more well-developed in the context of circular economy (Corona et al., 2019).

Determining circular metrics for batteries is a complex task due to the global value chain and the diverse chemistries involved, with each actor in the value chain having a different role in achieving battery circularity. Furthermore, not all value chain actors prioritize the same aspects of circularity. Respondent #17 also noted that different stakeholders will be responsible for different metrics. To address this, it is suggested to divide the metrics based on each actors involvement. A framework proposed by Konietzko et al. (2020) was used, which categorizes circularity into four quadrants: narrow, clean, slow, and close the loop. This framework offers simplicity and clarity in understanding the different flows and visualizing the contributions to circular strategies. The aim is to provide a more accurate representation of product circularity and a better understanding of its integrated contribution to parallel circular strategies, rather than focusing on singular strategies from one perspective only.



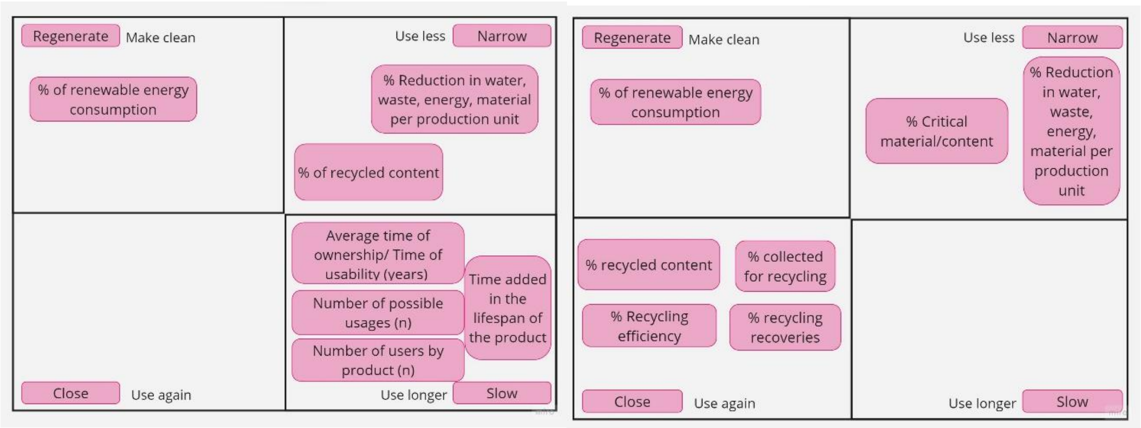


Figure 4-3 Metrics important for cathode material producers (top left), battery cell, module, pack manufacturers (top right), remanufacture and repurposing operation (bottom left), recycler (bottom right)

This study did not specifically explore the distinction between metrics that are generally important for all value chain actors and those specifically relevant to the digital battery passport (DBP). Respondent #18 emphasized that not all metrics depicted in Figure 4-3 are suitable for a DBP. Respondent #17 also highlighted the differentiation between strategic and operational metrics. One key circularity metric that needs consideration is the reduction of primary material demand and the decoupling of growth from primary resources within the battery/energy value chain. It is crucial to determine how. If the primary metric is primary material demand, it will incentivize business models focused on mobility as a service. The aim is to provide increased mobility while reducing the overall usage of materials like lithium. According to the interviewee, this is the key circularity metric that drives action, rather than solely relying on recycling.

The operational decision-making process for batteries at the product level, pertaining to their day-to-day use, relies on various factors such as battery chemistry, condition, state of health (SOH), safety, data accessibility, spare parts availability, and logistics, as identified by respondents #1, #7, #10, #21, #22, and #24. Recycling becomes more attractive for older batteries due to their higher concentration of metals and greater raw material intensity, making extension of their use in second life less favourable (as noted by respondent #2b). Respondent #17 stated that there is a reduction in the use of cobalt in new cathode chemistries, with the automotive industry favouring cobalt-free LFP chemistry, which has improved cycle life and safety performance compared to NMC. Respondent #7, a provider of second-life battery energy storage systems (SLBESS), mentioned that older modules (10 years old) have lower power density and complex internal electromechanical design, making data integration challenging. Newer batteries, such as the smart cube, are better suited for data collection. Therefore, while operational decisions at the battery level are influenced by various factors, metrics such as ease of disassembly can serve as enablers to support these decisions.

In conclusion, the adoption of sustainability and circularity metrics in the battery industry is driven by both legal requirements and customer demand. Metrics related to carbon footprint, resource depletion and renewable energy integration are important for value communication and decision-making in second-life batteries. Determining circularity metrics for batteries on the other hand is complex due to the global value chain and varying chemistries, necessitating actor-specific metrics. The "narrow, clean, slow, and close the loop" framework offers a simplified approach to visualize simultaneous circular contributions. Operational decisions at the product level involve factors such as battery chemistry, condition, safety, and data accessibility. With enabler metrics like ease of disassembly, CE operations would be incentivized from early stages of battery design. While the study acknowledges limitations in exploring metrics specifically for the digital battery passport, it underscores the need for primary material reduction and decoupling growth from primary resources in the battery/energy value chain as crucial strategic circularity metric.

4.4 Data needs, challenges, and potential use of servitization model for batteries

In the world of battery recycling and repurposing, access to accurate data is vital for optimizing operations and enabling the business model. However, there are challenges to data accessibility. The DBP shows promise as a solution, along with IoT and blockchain technology. Various Software as a Service (SaaS) companies are also playing a role in enabling DBP. As demands for transparency increase, DBP is seen as an important enabler. However, establishing connectivity, standardization, and economic incentives for data exchange remain crucial.

Recyclers need data about composition, chemistry of the battery to optimize their operations of processes in mechanical treatment (Respondent #1). Data on dismantling, voltage level, material information (more information the better) will also help them reduce the risk of incidents (Respondent #2b). Data will be required to increase safety of recycling operations and make the recycling operations efficient and optimized. Battery technologies are evolving fast. Cathode, anode chemistries changing up. Combining of battery chemistry has started to happen. We as recyclers need to know what has happened to the battery when it is repurposed. The battery repurposer (respondent #1 and #7) stated that deep knowledge of the history and performance of the modules and cells are needed from the battery management system (BMS).

There are several challenges to data accessibility, as highlighted by respondents #3 and #11. One of the primary challenges is the lack of data standardization. Currently, there is no uniform protocol for data collection, particularly regarding CO_2 emissions, resulting in different methods being used. However, the upcoming battery regulation aims to address this issue by establishing standards and ensuring uniform data collection from various suppliers and stages in the supply chain. The main hurdle faced in achieving data standardization lies in establishing connectivity among all supply chain actors and promoting consistent data communication. Each supplier tends to maintain and communicate data in their own unique way, making standardization a complex task. Moreover, suppliers outside of the EU may not be aware of the policies in place, requiring efforts to bring them onboard and align with the standardization initiatives.

Another challenge to data accessibility is related to data sovereignty. Different countries have varying laws concerning data protection and critical data pertaining to a country's infrastructure may be restricted from leaving the country. This often results in legal battles and complexities in data sharing. Furthermore, mid-stream suppliers often consider their data to be trade secrets and may be hesitant to share it easily, further impeding data accessibility in the industry.

Data privacy also poses a significant issue. The General Data Protection Regulation (GDPR) prohibits the storage of certain types of data and restricts the connection of battery passport data to vehicle identification numbers due to privacy concerns. The intersection of battery regulation and GDPR regulations may bring these data privacy issues to the forefront once again.

Data quality is another major challenge that affects data accessibility. Cleaning and ensuring the accuracy of data can be a daunting task. Even within a company, data may not be captured and maintained in a standardized manner. To overcome this challenge, proper data governance is required to establish standardized data practices, processing methods, and storage protocols.

DBP will enable us to access the relevant data. It could potentially provide data down to cell-level, but details on the granularity of data that the passport will provide are not yet clear. Thus, key stakeholders, such as remanufacturers, may still need to perform certain battery performance tests, using data available from the BMS (as detailed in Article 59), to make end-of-life management decisions, such as assessing depth-of-disassembly optimizations, or high-level recycling/re-use decisions. Key battery components, such as modules and cells will be Internet-of-Things (IoT) enabled, such that data can be shared between qualified stakeholders on a distributed ledger or blockchain. Any particular stakeholder will have access to this permissioned data in real time and is immutable (i.e., cannot be changed). Thus, while DBP has the potential to provide relevant data, additional battery performance tests may still be necessary for end-of-life management decisions. By leveraging IoT-enabled components and blockchain technology, stakeholders can securely access real-time, immutable data for informed decision making.

Various upcoming Software as a service companies (SaaS) have increasingly started playing a role in enabling DBP through their existing services of traceability and transparency. An automotive OEM would incur greater manufacturing and operating costs to implement such IoT and blockchain features into their batteries. Software companies have already started providing traceability and visibility of battery performance metrics to automotive OEMs and 2LB energy storage integrators alike, as part of their full repurposing service offering. Respondents #20 agreed that SaaS would provide connectivity and standardization. And that Blockchain will make things reputable. According to the SaaS companies (respondent #6 and #11) changes in the past few years, with covid and Ukraine war, a lot of companies want to know more about the supply chain. There are increasing investor pressures for supply chain transparency along with legal requirements of EU battery regulation and ESPR directive. DBP is again seen as an enabler. Respondent #9 from the platform for batteries view themselves as passport control. According to the interviewee there is a need for gateway for passport to actually work and that economic case for exchange of data will be the true enabler.

When asked 'How can servitization help in operationalizing the DBP?', some respondents said that servitization will not be necessary as the EU battery regulation will mandate data collection (#13 and #14). Article 59 details that OEMs must provide repurposers access to the BMS "for the purpose of assessing and determining the state of health and remaining lifetime of batteries, according to the parameters laid down in Annex VII." This means that repurposers will not have trouble in acquiring the necessary data to perform battery performance and health tests.

While other agreed that since the provider has full control over the product through servitization, data collection will be operationalized by such models (Respondent #11, #12. and #15). Additionally, as ownership of the batteries was found to be essential for understanding the second-life repurposing or recycling decision-making process, servitization models could help in adoption of CE strategies. As respondent #4 said strategy after first life is not easy due to complex ownership, there are several owners before the recycling comes in. Transfer of warranties is another area of issue. Battery manufacturer would like to have control over the batteries. Respondent #9 from the trading platform for second-life batteries said that the key thing for the OEM is questions on transfer of ownership or responsibility of the battery. That cling takes on the responsibility and transfers it on to the buyer. Additionally, McKinsey notes that when second-life markets stabilize, battery residual value will make battery ownership more attractive, leading to a rise in EV-battery leasing enabling automakers or battery makers to control the battery's second revenue stream (Hensley et al., 2012). Respondent #10, on the other hand, maintaining ownership of batteries is a priority by the having first right to getting the batteries back, as once they are recycled black mass is obtained for our new battery cells. To meet the goal of having 50% recycled content in new cells of their batteries. Thus, servitization models could play a crucial role in streamlining battery ownership. Battery ownership then would further CE strategies by allowing control over the battery's secondary revenue stream and facilitating sustainability goals like higher recycled content.

When it comes to service business models for batteries, one of the respondents (#2b) pointed out, that this model has been tried out by Renault (you buy the car, but lease the battery), however believed to have stopped because of lack of success. "Apparently, consumers prefer to put once 10,000 € extra on the table, the[a]n 100 every month." Similar point was highlighted by respondent #19 with years of experience in servitization of solar projects. Total investments is the top considerations for customers after ensuring the products functionality. This coupled with overall lack of awareness related to some of the key theoretical benefits of an as-a-service model, such as the reduced financial risk for the end-user or the increased flexibility (SSC project, 2022).

When a survey was conducted by the respondent #19 with the hypothesis that small player in the market like interesting for households or companies that have some cash flow problems might prefer service business models to avoid huge capital investment, it was found that the main reason why most customers choose the renting formula is because they don't want to have issues. "They just say to us, 'Just do it'. I don't want to invest time or money or whatever in it. Just do it and we will pay monthly our fee."

Ownership of asset was observed as the preference due to cultural reasons both by the respondent #19 and during the SSC project. However, when opinions on using second-life batteries as part of a BaaS application, as opposed to first-life batteries was tested in the SSC project, it elicited concerns from some potential end-users. The first concern related to the batteries' performance. End-users were skeptical that a battery used in a moving application such as an electric motor would be able to deliver the same performance as a first-life battery. And some end-users feared a higher prices for second-life batteries than for first-life ones, notably related to maintenance costs.

When discussing the 'green' argument or the 'sustainability' aspect of use of second life, both respondents #19 and #26 confirmed that it is not a main motivation for customers right now. There is less awareness on how servitization helps with sustainability. Their concerns are more short-term and have to do more with costs as customers voiced that price benefits would change their view on second-life batteries (SSC project, 2022). Additionally respondent #19 stated that service business model was the only way second-life PV cells could be utilized as part of an installation because then the responsibility lies on provider due to the service level agreement already made.

Another key learning was that from the interviewee #19, projects like solar panels and battery systems are already huge investment projects, so the monitoring of product is irrespective of the servitization model. This is because customers now for such big investments expect detailed diagnostic reports even if it was a direct sale business model. Respondent #26 stated that for service business model new capabilities are needed to monitor the customers and see what is working, what is not working. Again, this means taking a much more active role in the customer's daily operations as service business model is more collaborative in nature. One has to sit down with the customer after the sale and talk about their operations to optimize utilization, more than one would when compared with a 'regular' product offering.

In conclusion, the debate on the role of servitization in operationalizing the DBP highlights the different viewpoints within the industry. While some argue that the EU battery regulation's data collection requirements are sufficient, others see servitization models as key enablers for data access, ownership control, and achieving circular economy goals. The preferences of customers, concerns about battery performance, and short-term cost considerations further influence the adoption of servitization models. Ultimately, understanding customer needs, monitoring product performance, and fostering collaborative relationships are crucial for successful implementation of service business models in the battery industry.

5 Discussions

This thesis aimed to study the need for metrics in circular economy (CE) strategies of LIBs. Measurable indicators and metrics are required to communicate sustainability and circularity value while supporting managerial decision making. Further, the development of a Digital Battery Passport (DBP) is gaining attention as a tool for recording product information and sustainability aspects mandated by the EU battery regulation. Thus, the aim was to identify relevant metrics for LIBs with respect to the DBP particularly focusing on enabling slowing the loop strategies. This thesis further explored data requirements, and the potential of product-as-a-service (PSS) models to facilitate stakeholder cooperation and enable data collection.

5.1 Overview of the findings and their significance

5.1.1 Metrics for DBP

Environmental metrics play a crucial role in evaluating sustainability, and it is unsurprising that CO_2 emissions are considered the most important metric within the Digital Battery Passport (DBP). Specifically, CO_2 reduction when the passport is updated after a R-operation holds significant importance. However, the current lack of a developed methodology for the use phase poses a challenge. It would be crucial for ensuring comparability among different products and applications. In addition to CO_2 reduction, other environmental metrics such as total energy demand (TED), water usage, toxicity, and air pollution are also considered important, albeit in a decreasing order of significance. Notably, there is less emphasis on these metrics to demonstrate the reduction of impact resulting from prolonged battery use compared to CO_2 reduction. Additionally, perception and integration of these metrics within the DBP remain uncertain.

The calculation of resource depletion using Material Flow Analysis (MFA) is speculated to be more suitable for strategic decisions regarding circular economy (CE) strategies rather than at the product level as it entails understanding of material flows in a system. Consequently, it is unlikely to be incorporated into the DBP. Similarly, renewable energy support is also observed to be crucial for supporting slowing the loop strategies. However, since renewable energy support is already considered in the calculation of CO_2 emissions, it may not be necessary or appropriate to include it as a separate metric within the DBP.

With respect to social metrics, the current focus is on transparency and traceability. There is potential of using certifications related to social aspects on the DBP to provide greater assurance and transparency. However, going ahead there would be a need to develop metrics like the ones developed by the Global Battery Alliance (GBA). These could then be used to showcase reduction on social impacts due to deployment of CE strategies and the link between social aspects and the circular economy is not straightforward, primarily due to the long, global, and complex supply chains involved. Additionally, there is lack of awareness about benefits in social areas due to CE strategies.

Regarding circularity metrics for the DBP, the ease of disassembly index is given the most importance by various stakeholders along the value chain as it enables various CE strategies. Other enablers reiterated include standardization, safety, and data accessibility. Therefore, in the context of the DBP, incorporating the ease of disassembly metric along with standardization and safety labelling or ratings could further enable R strategies that slow the loop. Battery standardization could be a degree to which battery is standard Another circularity metric with potential of being on the DBP is a product life extension metric.

Table 5-1 summarizes the recommendations of additional metrics for DBP for its future iterations as discussed above. In the figure, distinction is made between enabler metric and standardization metric. Enabler metrics, as the name suggests enable CE strategies by making data accessible like technical metrics of SOH and metrics that enable overcoming hurdles of CE strategies like disassembly, safety concerns, and battery standardization. Standardization metrics on the other hand aim to set standards by creating classes or setting limits or requiring certain standards. This would be updated whenever the batteries undergo R operation and are put on market again. Unlike enabler metrics these metrics can be used to measure and monitor progress. The proposed metrics are however just a guidance and would need further exploration and clarification in areas of methodology and acceptability within the battery industry.

Table 5-1Potential metrics for DBP

Aim	**Enablers and enabler metrics**	**Standardisation Metrics**
EU Battery Regulation	Technical metrics, State of health, State of Charge, charge cycles etc. Information on battery chemistry, disassembly instructions, safety measures, accidents, etc.	1. CO_2 (cradle to gate by GBA and Gate-to-grave by Battery Pass) 2. Social due diligence (indices by GBA or certifications) 3. Recycled content
Additional recommendations	1. Ease of disassembly index 2. Safety rating 3. Battery standardization labelling or rating	1. CO_2 reduction when passport updated after R operation 2. Longevity/product life extension when passport updated after R operation More suitable metrics to be determined

Organizational level

In addition to the metrics for the Digital Battery Passport (DBP), metrics for organizational use have also emerged as important considerations. Operational metrics specific to circularity vary among different actors in the industry. Even within an organization, different departments or responsible authorities may own and be accountable for different metrics. This presents an opportunity for conducting organization-level studies to gain deeper insights into circularity practices. Further research is required to determine whether a battery-specific circularity metric, incorporating weighted action areas, is necessary or if existing widely accepted metrics like the World Business Council for Sustainable Development's Material Circularity Index (MCI) can be utilized.

At the company level, circular economy metrics will eventually be necessary to track progress and drive circularity initiatives effectively. The Circular Transition Indicators (CTI) have been identified as a prominent metric, supported by recent research that suggests CTI is a comprehensive and transparent method for assessing the level of circularity at the organizational level. While it is acknowledged that multiple indicators are needed to capture the full scope of circularity, the CTI stands out as an intuitive and understandable metric. It provides a clear visual representation of inflows and outflows, allowing employees throughout the company to understand and contribute to circularity efforts (Schulz-Mönninghoff et al., 2023).

Alternatively, metrics such as the Material Circularity Index (MCI) by the Ellen MacArthur Foundation, while providing a single number, may be challenging to comprehend and identify individual contributions. In contrast, the CTI's visual approach enables employees to easily grasp how their actions contribute to the overall circularity goals. The goal is to foster a comprehensive understanding of individual contributions to circularity throughout the organization.

The link between circular economy metrics and overall sustainability impact is an area that warrants further exploration. It is essential to integrate circular economy metrics as intrinsic components of sustainability assessments, considering their relevance to various stages, including recycling (R) operations. The incorporation of hierarchy into the metric framework is another challenge that needs to be addressed. Since every battery may not follow a predetermined path of circular economy hierarchy, flexible approaches are required to accommodate different scenarios.

A systematic case-by-case assessments of CE strategy options is recommended in the literature as part of decision-making in order to ensure maximum environmental and social impact reduction benefits. This study contributes towards definition of what constitutes success factors of LIB repurposing as a CBM from environmental, social and circular economy perspective. For strategic decision making there is a need for engaging with different methods in combination, such as energy flow modelling and LCA, to implement a CE for LIB in the future. Coupling LCA with material circularity assessments seems to be a promising avenue in research in order to ensure a sustainable deployment of LIB repurposing in the future. MFA serves as a valuable tool in assessing resource consumption and identifying opportunities for circularity improvements. However, ensuring the accuracy and comprehensiveness of the data used in MFA remains a challenge that requires attention. Meanwhile, Material Flow Analysis (MFA) needs to be based on accurate and comprehensive data to inform circularity strategies more effectively.

Use of metrics

The utilization of metrics in the context of circularity is crucial for creating a common language and facilitating cross-sector collaboration within the industry. It is essential for companies of all sizes, industries, and positions in the value chain to adopt a unified approach to measuring and monitoring circular performance. This collective effort will enable value chains to transform into value cycles, thereby progressing towards a shared vision of a circular economy.

In the future iterations of the battery passport, circularity metrics could play a vital role. These metrics would enable a comparative evaluation of batteries, allowing for differentiation of products based on their circularity performance. Such metrics would empower end-users to make conscious purchasing decisions, considering the circularity aspect of the batteries. The introduction of these metrics could serve as an incentive for the production of batteries designed with circular principles in mind and encourage the implementation of circular economy strategies, thereby minimizing premature recycling of batteries whenever possible.

During the interviews, environmental metrics and social metrics were found to have various uses. They can be utilized to support the business case by communicating the value of sustainability internally and externally to customers and stakeholders. Additionally, these metrics can serve as criteria for procurement decisions, enabling organizations to prioritize suppliers with strong environmental and social performance. Furthermore, metrics can be used as a basis for charging different prices for services, such as recycling operations. For instance, if a battery has a high ease of disassembly metric, it could be charged at a higher rate for recycling services.

Overall, the effective use of metrics in the context of circularity can drive positive change, foster sustainability-oriented decision-making, and promote the adoption of circular economy practices across the battery industry and its value chains. There is need for a larger industry, value chain and cross-sector effort so companies can speak the same language, regardless of size, industry, or value chain position. Having a common approach to measuring and monitoring circular performance is essential. This will allow value chains to adopt the metrics and progress towards a shared vision.

Benefits of CE metrics

CE metrics offer several benefits in the context of circular economy practices. Firstly, they provide valuable insights and inform life cycle design decisions without requiring a full and time-consuming life cycle analysis. This allows for more efficient and streamlined decision-making processes (Saidani et al., 2019). One important observation was the complexity associated with carbon footprint calculations, which can be overcome by adopting circularity metrics. These metrics can offer simpler calculations that facilitate frequent monitoring of progress towards circularity. Moreover, they enable effective comparisons between different strategies and products, especially when a standardized language is adopted for batteries. By focusing on circularity metrics, organizations can prioritize and drive the transition towards circular practices with greater ease.

Secondly, CE metrics can help management of several other externalities that are more difficult to calculate. For example, CO_2 emissions are easier to calculate and connect to the business model compared to biodiversity. As the use of resources accounts for more than 90 percent of the loss of biodiversity. By using resources efficiently and keeping them in use for as long as possible, we can reduce the need for extracting new resources and preserve our ecosystems. Thus, ensuring circular economy ensures conservation of biodiversity by decoupling growth from primary resource use and promoting the use of sustainable materials.

Adoption of metrics

The available literature on the practical adoption of metrics is limited. Certain individuals argue that making metrics mandatory through regulations is the sole means of mainstream acceptance. On the other hand, others believe that if prominent industry actors within the value chain demand these metrics, they will be adopted throughout the entire chain. It has been suggested that original equipment manufacturers (OEMs) will need to assume a leadership role in navigating the power dynamics surrounding metric implementation.

5.1.2 Battery business models

The circular economy strategy decision of recycling vs repurposing was found to be influenced by the level of vertical integration of the organization, meaning whether the company controls multiple stages of a product or service's supply chain, from raw materials to final distribution and extent of partnerships in the value chain. Having a viable circular business model (CBM) for various R operations is crucial for their adoption. Apart from the economics, especially important for a CBM of LIBs is customer perspective of the product. Thus, value proposition of the product plays an important role in the business model. Here the sustainability and circularity metrics can thus play a crucial role in increasing awareness and enabling conscious decision making for customers.

As the literature suggests, it was confirmed that the industry is still divided with respect to priority of repurposing vs recycling of batteries. Organizational metrics discussed in the above section thus would be crucial for data-backed decision making. At organization level distinction is again made of strategic metric, steering metrics, and monitoring metrics. Strategic metric would be used to communicate and oversee the progress towards circular economy. Steering metrics like carbon emissions or resource depletion would help in decision making of CE strategy. It is important to note the importance of primary, accurate data for LCA and MFA for more better decision making.

In the realm of battery recycling and repurposing, accurate data access is crucial for optimizing operations and facilitating the business model. Luoma et al. (2021) identified four types of data essential for circular economy (CE) requirements: customer behavior, product/service lifespan, system performance, and material flows data. However, there has been limited focus on harnessing data for enhancing circularity at a systemic level. Specifically for batteries, data accessibility poses significant challenges. Addressing these challenges necessitates cooperation and partnerships across the value chain to enable data flow, along with the implementation of technologies such as IoT and blockchain.

Research literature indicates that the industry is still divided regarding the priority of repurposing versus recycling batteries as part of circular economy strategies. The decision between recycling and repurposing is influenced by factors such as the level of vertical integration within an organization, which refers to the extent of control the company has over multiple stages of the supply chain, from raw materials to distribution. Additionally, the extent of partnerships in the value chain can also impact this decision.

To overcome these data challenges, one business model that has the potential is service business model. Servitization models has the potential to not only be a key enabler for data access, but also streamline LIBs' ownership complexities, and enable acceptance of second-life batteries as product responsibility stays with the provider. However, this business model comes with its own challenges. The preferences of customers, concerns about battery performance, and short-term cost considerations further influence the adoption of servitization models. Ultimately, understanding customer needs, monitoring product performance, and fostering collaborative relationships are crucial for successful implementation of service business models in the battery industry.

5.1.3 Recommendation for Policy makers

The initial building block of a circular economy (CE) is product design, which has a significant impact on the entire life cycle of a product. Decisions made during product design not only involve material and manufacturing choices but also influence aspects such as product lifespan, material efficiency, repairability, upgradability, modularity, remanufacturing, component reuse, and end-of-life recycling (Hass et al., 2015). This is particularly crucial for batteries, which often have complex structures. A circular product design allows for easy access, removal, and replacement of battery components, enabling the implementation of various circular strategies.

However, the EU Battery Regulation falls short in addressing the importance of product design for circular battery value chains. While it does not provide specific design suggestions for batteries, the regulation does require reporting on parameters related to product design, such as disassembly information and battery health status through the battery passport. Additionally, the ESPR proposal aims to define and specify design aspects for circularity. Nevertheless, the industry's progress towards a circular economy would greatly benefit from the development of metrics that can effectively measure and guide the implementation of circular design principles.

The emphasis on recycling, driven by regulatory requirements for recycled content, is strong and widely understood in the context of circular economy as closing the loop. The political goal of reducing Europe's dependence on critical minerals from outside the continent further supports recycling efforts. To fully embrace circular economy strategies for LIBs, it is essential to complement existing metrics with a comprehensive set of circularity metrics that specifically address slowing the loop. Enabler metrics such as ease of disassembly and standardization metrics like product life extension should be considered. Nonetheless, additional research is necessary to develop calculation methodologies and explore the suitability of other circular economy metrics for the battery passport.

5.1.4 Recommendation for Industry

In order to drive progress towards a circular economy, it is crucial for companies of all sizes and positions in the value chain to adopt a unified approach in measuring and monitoring circular performance. This requires a collective effort within industry value chains to establish a common set of metrics and calculation methodologies, promoting a shared vision of a circular economy. The awareness of the benefits of these CE metrics is essential. They provide valuable insights, inform design decisions, facilitate progress monitoring, and enable comparisons. Moreover, they help organizations manage challenging externalities, such as biodiversity, by promoting resource efficiency, sustainable materials, and the preservation of ecosystems.

To make informed and holistic decisions at the organizational level, there is a need to prioritize data-backed approaches. This involves use of sustainability covering environment and social considerations along with circularity value in communications with customers. Further, OEMs would play a key role in driving the adoption of the metrics. Their involvement is crucial in promoting the use of these metrics throughout the value chain.

Data accessibility serves as a critical enabler for implementing circular economy strategies. Therefore, the industry must work towards enabling data sharing within the value chain. This will facilitate the effective implementation of circular strategies and support informed decision-making.

5.2 Future research suggestions

Suggestions for further research in the field can greatly contribute to advancing our understanding of metric adoption and circularity strategies. The following recommendations can serve as potential avenues for future research:

Examining the Utilization of Circularity Metrics: While identifying circularity metrics is essential, it is equally important to investigate how these metrics are practically utilized in decision-making processes. Research should explore how stakeholders across the value chain use and interpret circularity metrics, and how these metrics inform their strategic choices and actions. Understanding the practical applications and implications of circularity metrics can help identify areas for improvement and optimize their effectiveness in promoting circular economy strategies.

Exploring the Interplay of Servitization and Second Life Challenges: As the concept of servitization gains traction, it is crucial to examine its interplay with the challenges and opportunities associated with the second life of products, particularly in the context of batteries. Research should investigate how servitization models can be effectively integrated with circular economy strategies for batteries and identify potential barriers and enablers for successful implementation. Understanding the interdependencies between servitization and second life challenges can lead to the development of innovative business models and strategies.

Organizational Culture, Strategic Thinking, and Strategy Formulation: The role of organizational culture, strategic thinking, and strategy formulation in relation to circular economy strategies for batteries warrants further investigation. Research can delve into the organizational dynamics and processes that facilitate or hinder the adoption and implementation of circularity strategies within battery-related industries. Drawing on frameworks such as Korhonen et al., (2018) work, researchers can analyze how organizational culture, strategic thinking, and strategy formulation practices influence the integration of circular economy principles within organizations.

By addressing these research suggestions, scholars can deepen their understanding of metric adoption and circularity strategies. This, in turn, can inform the development of more effective and context-specific approaches to promote sustainability and circularity within the battery industry and other relevant sectors.

5.3 Limitations of the study

The study at hand has certain limitations that should be acknowledged to provide a comprehensive understanding of its scope and potential biases. Firstly, one significant limitation is the absence of perspectives from original equipment manufacturers (OEMs) other than Volvo Group. This gap in the study can be attributed to the competitive nature of the electric vehicle (EV) industry, where OEMs may be hesitant to openly share their insights with researcher working with their competitor. The lack of OEM perspectives hinders a holistic understanding of the challenges and opportunities associated with metric adoption and circularity strategies.

Furthermore, the study's findings may be influenced by the limited perspectives of value chain actors. Each stakeholder within the value chain has a unique role and perspective, which can shape their insights and priorities. For instance, suppliers may prioritize metrics that showcase the sustainability of their components, while recyclers may focus on end-of-life management metrics. This limitation suggests that a more comprehensive examination involving a wider range of stakeholders would provide a more robust analysis of metric adoption and circularity strategies.

Additionally, the study lacks direct insights from customers regarding the identified metrics. Understanding customer perspectives is crucial in assessing the effectiveness and acceptance of sustainability metrics. However, due to time constraints or other factors, the study was unable to directly incorporate the opinions and preferences of customers. Future research should consider including customer perspectives to gain a better understanding of their influence on

By recognizing these limitations, it becomes evident that while the study provides valuable insights within its specific scope, further research is necessary to fill the gaps and develop a more complete understanding of the complexities surrounding metric adoption and circularity strategies in the EV industry.

6 Conclusion

As the sales of electric vehicles (EVs) increase, so does the number of LIBs being used. However, the high costs, resource and energy demands, environmental concerns, and supply risks associated with LIB production have led stakeholders to explore and adopt circular economy (CE) strategies for LIBs. Slowing the loop strategies, however, have several barriers to the business model, regulatory and customer acceptance. Since recycling, i.e., closing the loop is easily understood and implemented, the aim was to identify relevant metrics for LIBs with respect to the DBP focusing on enabling slowing the loop strategies. This thesis further explored data requirements, and the potential of product-as-a-service (PSS) models to facilitate stakeholder cooperation and enable data collection.

RQ1: What sustainability and circularity metrics are relevant for DBP to support slowing the loop strategies?

Environmental metrics: The relevant environmental metrics for batteries to support slowing the loop strategies include carbon footprint, resource footprint, and other impact categories such as toxicity, air quality, total energy consumption, ozone depletion, and water consumption. Carbon footprint is particularly significant as it is regulated by the EU battery regulation. The use phase and repurposing/remanufacturing stages would need to be covered to for realistic understanding of GHG reduction benefits from life extension and applications of SLBESS covering grid stability and increase renewable energy sources, reducing carbon emissions and reliance on fossil fuels. Renewable energy integration could be measured separately inspired from the SDG target 7.2. Resource footprint assessment involves methods like material flow analysis and life cycle inventory, considering resource depletion impacts.

Social metrics: The relevant social metrics for batteries to support slowing the loop strategies include social impacts in the upstream supply chain, such as human rights, labor rights occupational health and safety and poverty. CE strategies can provide social benefits by reducing negative impacts, such as avoiding child labor associated with mining activities by reducing need for new batteries due to improved battery lifetime and material management downstream. SLBESS additionally contributes to achieving SDGs inspires metrics, in the area of affordable and clean energy access, affordable transportation and job generation with opportunities in the refurbishment, repair, and production of second-life batteries contributing to poverty reduction and promoting technical skills and decent jobs. However, in literature positive social impacts are rarely measured using systematic assessments.

Circularity metrics: To support slowing the loop strategies, relevant circularity metrics for batteries include recycled content, collection rate, and material recovery rates, which are mandated by the EU battery regulation. Developing an overall circularity score that increases transparency and enables informed purchasing decisions for products and end-users could incentivize the production of batteries designed with circularity in mind. Further aggregated steering metrics, and granular monitoring metrics are relevant for monitoring and decision making. These metrics evaluate aspects such as resource efficiency, product life extension, disassembly, recycling, renewable energy consumption, material usage reduction, product lifespan, ownership time, and recycling rates.

RQ2: What are the perceptions of value chain actors towards these sustainability and circularity metrics?

Environmental: The primary environmental metric considered important was CO_2 emissions. It is crucial to develop a methodology for measuring this. Other metrics, such as total energy consumption, water consumption, toxicity, and air pollution, were ranked in decreasing order of importance. Supporting renewable energy and addressing resource depletion were particularly important for communicating value and supporting business case of repurposed batteries.

Social: Regarding social metrics, the current focus is on transparency and traceability. Using certifications and indices related to social aspects on the DBP could provide greater assurance and transparency. However, there is a need to develop metrics similar to those developed by the Global Battery Alliance (GBA) to better quantify social impacts and understand the link between social aspects and the circular economy, which is currently weak. However, operationalizing metrics in social impact areas can be complex due to various tradeoffs.

Circularity metrics: Stakeholders along the value chain identified the ease of disassembly index as the most important for enabling circular economy (CE) strategies. Other important enablers included standardization, safety, and data accessibility. However, not all value chain actors prioritize the same aspects of circularity. While metrics like the share of renewable energy and reductions in water, waste, energy, and materials per unit of production were important throughout the value chain, metrics like product life extension were more significant during product use and strategies related to reusing and repurposing. It is necessary to supplement existing metrics mandated by regulation with a comprehensive set of circularity metrics to not only measure product circularity performance and communicate the value of the product to stakeholders but also address crucial aspects of the circular economy. The link between economic aspects and metrics was observed to be crucial for adoption and integrating sustainability value into circularity metrics was highlighted as a priority.

Overall: The main drivers for using metrics were identified as legal requirements and customer demand. Some metrics aim to enable CE strategies, while others are intended to ensure industry compliance with standards. Potential use of metrics includes, procurement teams using the metrics for supplier contracts, setting targets for improvement and using for value communication and product differentiation. To make the metrics mainstream, it is important for original equipment manufacturers (OEMs) to lead by demanding them for them to be accepted across the value chain with a common understanding.

RQ3: How can servitization help in operationalizing the DBP?

Servitization can help in operationalizing the Digital Battery Passport (DBP) by enabling data access, ownership control, and supporting circular economy strategies. While the EU battery regulation mandates data collection, servitization models might not be a necessity to access relevant data. Though through servitization, providers have full control over the product, allowing them to collect and share data, facilitate data standardization, and ensure data quality. Additionally, ownership of batteries through servitization models enables better control over the battery's secondary revenue stream and supports sustainability goals like higher recycled content. However, there are challenges, including customer preferences for ownership, concerns about battery performance, and short-term cost considerations. Understanding customer needs, monitoring product performance, and fostering collaborative relationships are essential for successful implementation of servitization models in the battery industry.

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Appendix (if required)

7.1 Interview guide for Battery manufacturers

Topic	**Questions**	**Probes**
CE strategy	According to my desktop research I found that industry is quite divided when it comes to what to do with batteries after their first life: repurpose or recycle? What is your company's startegy?	Does the strategy depend on contract with OEMs? What are they doing now? What is the medium- and long-term strategy? What about other strategies like reuse, remanufacturing, refurbishing?
Decision making	How are these CE strategy decisions made? What factors are the basis for making these decisions?	Current and future
Metrics use and importance	According to my desktop research I found that there is a lot of value in employing different sustainability and circularity metrics to make decisions and communicate value of repaired, refurbished, remanufactured, repurposed and recycled batteries. I would here like to share my screen to walk you through these different metrics and get your priorities for them.	Current and future
Data flow DBP	The EU battery regulation will require CO_2 footprint calculation, due diligence, sharing battery information on digital battery passport. Literature called for need of primary data which would be part of the digital battery passport. You, as a battery manufacturer will be required to provide it. In terms of feasibility, what are your opinions and how are you planning to implement them? What challenges do you foresee in implementing it?	How do you plan to collect data from your suppliers? Are you planning on using any third party for this? Which digital tools would you be deploying?
EU battery regulation: opinion and implementation	The EU battery regulation says that, 1. battery is designed for high durability and easy removal by qualified professionals 2. Access to the battery management system should be provided to the person that has purchased the battery or any third party acting on its behalf at any time for evaluating the residual value of the battery, facilitating the reuse, repurposing or remanufacturing of the battery. 3. Minimum share of, respectively, cobalt, lithium or nickel recovered	What is X's approach towards operationalizing them? What challenges do you foresee in implementing it?

7.2 Interview guide for EV OEMs

Topic	**Questions**	**Probes**

CE strategy	According to my desktop research I found that industry is quite divided when it comes to what to do with batteries after their first life: repurpose or recycle? What is your company's startegy?	What about other strategies like reuse, remanufacturing, refurbishing?
Decision making	How are these CE strategy decisions made? What factors are crucial to make these decisions (business opportunity, long-term customer relationship, revenue source, reduce EV ownership cost)? Are there any metrics that you use currently for batteries?	
Metrics use and importance	According to my desktop research I found that there is a lot of value in employing different sustainability and circularity metrics to make decisions and communicate value of repaired, refurbished, remanufactured, repurposed and recycled batteries. I would here like to share my screen to walk you through these different metrics and get your priorities for them.	
Data flow DBP (need and sharing)	The metrics I showed you earlier, highly depend on availability of accurate data, which would be part of the digital battery passport. You, as OEM will be required to provide and update data. Also need data to take decisions and communicate value. What challenges do you forsee in implementing it?	How do you plan to collect data from your suppliers? Are you planning on using any third party for this? Which digital tools would you be deploying?
Service business model	Literature says that service business models can assist in collection of data needed for decision making, while maintaining relationship with customers and revenue streams. What is your view on that?	What business opportunities do you see with service business models?
EU battery regulation: opinion and implementation	The EU battery regulation will require CO_2 footprint calculation, due diligence, sharing battery information on digital battery passport. In terms of feasibility, what are your opinions and how are you planning to implement them?	

7.3 Interview guide for SL-BESS actors (manufacturers, providers)

Topic	Questions	Probes
CE strategy	According to my desktop research I found that industry is quite divided when it comes to what to do with batteries after their first life: repurpose or recycle? Eu battery regulation has recycling targets but wants to encourage battery repurpose as well. What is your opinion on it?	What are they doing now? What is the medium and long term strategy? What about other startegies like reuse, remanufacturing, refurbishing?
Decision making	How are these CE strategy decisions made? Are there any metrics that you use currently for batteries?	
	While communicating the value of SL BESS, what is the main challenge that you face?	

Data flow DBP (need and sharing)	EU regulation calls for BMS access and reset to promote reuse, repurposing... Do you foresee any challenges in implementation of that? How is the new DBP for SLBESS foreseen?	How do you get data for batteries currently? Do you have contracts with OEMs? What other actors are involved in this? How do you think this can be improved?
Metrics importance	According to my desktop research I found that there is a lot of value in employing different sustainability and circularity metrics to make decisions and communicate value of repaired, refurbished, remanufactured, repurposed and recycled batteries. I would here like to share my screen to walk you through these different metrics and get your priorities for them.	
Service business model	Literature says that service business models can assist in collection of data needed for decision making, while maintaining relationship with customers and revenue streams. What is your view on that?	What business opportunities do you see with service business models?
EU battery regulation: opinion and implementation	Which requirement of EU battery regulation do you think would be the most difficult to implement?	What challenges do you foresee in implementing it? How do you work with battery manufacturers to enable design?

7.4 Interview guide for Battery recyclers

Topic	Questions	Probes
CE strategy	According to my desktop research I found that industry is quite divided when it comes to what to do with batteries after their first life: repurpose or recycle? The latest EU battery regulation also has provisions to promote repair, remanufacturing, repurposing etc. while setting recycling targets, which creates tension between choice of circular economy strategy for batteries. One of the arguments made for repurposing batteries is that battery recycling technology is highly evolving, and the delay in battery end of life will enable these technologies to evolve and become efficient (economically and environmentally)	• What is your opinion on it? • What factors does this strategy decision depend on? • What are they does X aims to support now? What is the medium- and long-term strategy?
Decision making	How are these CE strategy decisions made? Are there any metrics that you use currently for batteries?	Sustainability: Circularity:
Metrics importance	According to my desktop research I found that there is a lot of value in employing different sustainability and circularity metrics to make decisions and communicate value of repaired, refurbished, remanufactured, repurposed and recycled batteries. I would here like to share my screen to walk you through these different metrics and get your priorities for them.	
Data flow DBP	Literature says that battery recyclers need to know what is happening to the batteries upstream (if life is being extended), to estimate battery-flow and prepare for recycling.	• How do you currently understand the battery flow? • Do you have contracts with OEMs for this? • What other actors are involved in this? • How do you think this can be improved?"

EU battery regulation: opinion and implementation	"The EU battery regulation requires that, 1. Battery is to be designed for ease in recycling by qualified professionals 2. Ensure that each waste battery is treated in an environmentally sound manner 3. Minimum recycling efficiencies and recovery targets are set	What is X's approach towards operationalizing them? What challenges do you foresee in implementing it? How do you work with battery manufacturers to enable battery design for recycling?

7.5 Interview guide for SaaS providers

Specific to service offering

1. CE strategy opinion on battery
2. Plan to operationalize DBP
3. How do they obtain data from suppliers?
    a. Primary data?
    b. Suppliers outside EU
4. Digital tools utilized to operationalize it
5. Data
    a. Due diligence data
    b. CO_2 calculation methodology
6. Opinion on circularity and sustainability metric

7.6 List of interviewees

No.	Respondent No.	Metric input	Position	Type of company	Date
1	Respondent #1	Yes	Project Manager	Mechanical recycler (+ SLBESS provider)	01/03/23 03/03/23
2	Respondent #2a Respondent #2b	Yes Yes	Sustainability manager Director Government affairs	Cathode material manufactuer	01/03/23 08/03/23 13/03/23
3	Respondent #3	No	Consulting project lead	eMobility SaaS and consultancy	02/03/23
4	Respondent #4	Yes	Manager product area batteries	Battery Recycler	03/03/23
5	Respondent #5	Yes	Director of government relations	Battery Recycler	03/03/23
6	Respondent #6	No	Consultant	Traceability SaaS	03/03/23
7	Respondent #7	Yes	Production and testing engineer	SL provider (part of collection and SL manufacturing)	08/03/23
8	Respondent #8	Yes	Battery recycling expert	Adhesive manufacturing	09/03/23
9	Respondent #9	Yes	Head of marketing	Battery platform	10/03/23
10	Respondent #10	Yes	Sustainability analyst	Battery cell manufaturer (+Recycler)	10/03/23
11	Respondent #11	Yes	Director of business development	Traceability SaaS	20/03/23 21/03/23
12	Respondent #12	Yes	Associate	CE thinktank	21/03/23
13	Respondent #13	Yes	Head of circular economy team and GBA member	Trade body	24/03/23
14	Respondent #14	Yes	Head of battery test and diagnostics	Battery recycler	24/03/23
15	Respondent #15	Yes, Partial	Sustainability director	Battery Cell Manufactuere	12/04/23
16	Respondent #16	No	Policy expert	-	02/03/23
17	Respondent #17	Yes	CE expert with automotive experience	-	08/03/23
18	Respondent #18	Yes		CE thinktank	08/03/23
19	Respondent #19	No	Marketing engineer	Renewable energy provider	08/03/23
Volvo Stakeholders					
20	Respondents #20	No	Digital product owner, Head of battery I&L, Policy consultant		24/02/23 02/03/23
21	Respondent #21	Yes	Remanufacturing engineer		29/03/23
22	Respondent #22	Yes	Head of indirect sales		30/03/23
23	Respondent #23	Yes	Head of battery recycling		28/03/23
24	Respondent #24	Yes, Partial	Head of battery industrialization		29/03/23