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What is the contribution of different business processes to material circularity at company-level? A case study for electric vehicle batteries

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ABSTRACT

With the growth of electric mobility, automotive manufacturers are nowadays facing the challenge of implementing a Circular Economy (CE) for electric vehicle (EV) batteries. Meanwhile, no consensus exists on how to assess material circularity and assign responsibilities across different business processes of the organization. To address this gap, the present study uses an illustrative case study of an automotive manufacturer seeking to improve the material circularity of its' electric vehicle battery portfolio. Following a 3-step framework inspired by the British Standard BS 8001:2017, we investigate how business processes in relation to product development, supply chain, production, end-of-life and business models can contribute to the material circularity of EV batteries in different scenarios. Among the key contributions, the study firstly provides guidance for companies on how to model material circularity for batteries at company-level based on EV market projections. Secondly, our findings show that by combining a closed-loop production with different end-of-life strategies such as remanufacturing, repurposing and recycling, automotive manufacturers can increase material circularity for critical battery materials from 5% today to 23% by 2030. Thirdly, we specify how different business processes can contribute to increasing material circularity, including a) which business processes collaborate, b) the affected material streams (i.e. inflow or outflow), c) through which activities and d) to what extent, i.e. the impact on the quantitative results for material circularity. Based on the findings, we discuss limitations of the study and derive pathways for future research on how to assist companies in an accelerated transition towards a CE.

1. Introduction

In order to achieve sustainable consumption of resources in industry, scholars refer to the concept of a Circular Economy (CE), which aims at keeping products and materials at their highest utility at all times (Murray et al., 2015). A CE combines different principles, such as "closing, slowing and narrowing material loops" (Bocken et al., 2016), which together ensure the minimization of resource input and waste, emission, and energy leakage (Geissdoerfer et al., 2017).

Generally, research emphasizes that ensuring a widespread adoption of a CE in industry is a multi-disciplinary task in both research and practice and requires both inter- and intra-organizational collaboration (Geissdoerfer et al., 2017; Korhonen et al., 2018; Rizos et al., 2016). For companies, this suggests that different stakeholders need to work together in a coordinated and structured manner in order to implement circularity of material flows in an organization. Nevertheless, frameworks for implementing, monitoring and further developing CE strategies in the practical context of organizations are scattered (Halonen et al., 2019; Kovacic et al., 2019; Morseletto, 2020). While attempts to develop standards for guiding companies are made on a conceptual level (BSI, 2017), these are found to lack integration with assessment methods and therefore do not support organizations in setting quantifiable targets for material circularity (Pauliuk, 2018). As a consequence, until today only few companies have adopted systematic approaches for measuring progress on CE implementation at organisational level (Opferkuch et al., 2021).

In this context, the automotive sector is particularly under pressure to adopt frameworks for assessing material circularity, given that the transition to electric mobility, pushed by both industry and legislation, is expected to cause tremendous shifts in vehicle supply chains today and through 2035 (European Parliament, 2022; World Economic Forum, 2019). Therefore, batteries and vehicles are identified as a key sector for

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implementing CE principles within the EU's circular economy action plan (European Commission, 2020a). For that, numerous strategies for improving the material circularity of EV batteries are outlined in literature, reaching from design strategies, e.g. design for manufacturing, reparability and longevity (Picatoste et al., 2022) to end-of-Life (EoL) options such as remanufacturing, repurposing and recycling (Blömeke et al., 2022; Olsson et al., 2018).

Hence, Automotive manufacturers face the challenge of aligning a number of different CE strategies for EV batteries towards an overall target. The underlying challenge is twofold: On the one hand, it requires methods for assessing material circularity at an organizational level in order to accommodate the variety of measures that can be taken. On the other hand, the next question is *who* in that company can – or should - do *what* in order to contribute to achieving that target, or in other words, it is currently not clear, *which* action by *which* business process is responsible for *which* lever on the material circularity of a company. While some studies in scientific literature provide methods for assessing battery material flows (Bobba et al., 2019; Neidhardt et al., 2022; Richa et al., 2017) to our knowledge there are no studies which assist companies in linking material circularity performances for batteries to the responsible decision-makers within the organization. Based on this rationale, this paper aims at addressing the following research question:

How can different business processes of an automotive manufacturer contribute to improving the material circularity for critical battery materials at company-level?

By addressing this research question, we aim at shedding light on the implications for automotive manufacturers when implementing material circularity for EV batteries by involving all relevant business processes within the organization. For that, this study uses recent EV market projections to develop an illustrative case of an automotive manufacturer seeking to assess the CE performance of its' EV battery portfolio. By applying a method for assessing material circularity at company-level and testing different scenarios of EoL strategies implementation, the study illustrates how different business processes within an organization, such as supply chain, production or business model, can jointly work towards a CE for batteries in the future.

The study is structured as follows: section 2 presents existing literature and outlines the research gap in detail. Section 3 outlines the overall research approach, the development of the case study and introduces key assumptions for modelling material flows of the company. In section 4, we present results for the material circularity at company-level in different scenarios and analyze the contribution of the various business processes. Finally, we discuss key contributions, limitations and directions for future research in section 5.

2. Literature review

2.1. Implementing material circularity in industry

In the pursuit of implementing a CE, different actors are seeking for "integrative decision support tools to identify and tap potentials of CE transition scenarios on company and inter-company level" (Lieder and Rashid, 2016, p.48). While this has led to the adoption of frameworks such as the EU monitoring framework at policy-level (European Commission, 2018), research does not find them suitable for companies due to the missing link to business performance and the need for translating results into strategic action (Pacurariu et al., 2021).

Based on this issue, the research field of CE indicators has evolved continuously over the last years (Saidani et al., 2019) aiming at the investigation of available quantitative metrics, which can assist companies in assessing material circularity as part of their CE decision-making (Corona et al., 2019; OECD, 2020). While reviews present, compare and classify CE indicators, which have been developed in both scientific and grey literature, no method has prevailed as an industry standard so far (De Oliveira et al., 2021; Moraga et al., 2019; Parchomenko et al., 2019; Roos Lindgreen et al., 2020; Saidani et al., 2019; Sassanelli et al., 2019; Verstraeten-Jochemsen et al., 2020).

As a consequence, reporting on the implementation of material circularity in industry and in policy-making today is mostly based on qualitative measures or focuses on waste treatment and recycling alone, thus only representing a fraction of the strategies and measures in scope of a CE (Calisto Friant et al., 2021; Niero and Kalbar, 2019; Opferkuch et al., 2021). Hence, there is lack of frameworks which allow companies to describe the various activities for stirring material circularity and establish a clear link to business decisions. In this regard, some studies find that CE indicators do not cover all dimensions of sustainability (Corona et al., 2019; Kristensen and Mosgaard, 2020), whereas others show that results for material circularity do not always rhyme with results of environmental impact assessments (Lonca et al., 2018; Niero and Kalbar, 2019; Roos Lindgreen et al., 2021; Walker et al., 2018). This suggests that quantitative assessment methods for material circularity can offer novel insights for decision-makers on whether and how the implementation of a CE supports other sustainability goals.

Moreover, despite the relevance of testing the role of CE indicators in decision-making, only few studies have addressed the process of translating material circularity results into action at an organizational level. When studying CE indicators, some authors focus on qualifying methods at product level based on their methodological characteristics (Linder et al., 2017), while others aim at supporting the selection of CE indicators based on the specific context of application (Elia et al., 2017; Kravchenko et al., 2020; Nika et al., 2021). However, we identify a knowledge gap on the description of which activity of a company contributes in which way to the improvement of its material circularity, or in other words, who in an organization is responsible for which lever on implementing material circularity. For this purpose, company-level CE indicators are of particular interest, since they aim at summarizing all activities associated with the material circularity of a company and potentially aggregating them in a quantitative score (Roos Lindgreen et al., 2020; Verstraeten-Jochemsen et al., 2020).

2.2. Material circularity for EV batteries

Establishing a CE for EV battery materials is a focus area in scientific research for numerous reasons. Firstly, the battery comprises a significant share of the cost of an EV, mostly due to the volatility of market prices for specific materials such as Lithium and Cobalt (European Commission, 2020b). Secondly, despite the overall benefits of EVs over internal combustion vehicles in terms of greenhouse gas emissions (Hoekstra and Steinbuch, 2020), batteries are responsible for additional environmental and social impacts in the supply chain of the vehicle, e.g. due to energy use in cell production and unregulated working conditions at the material extraction stage (Lebedeva et al., 2016). Lastly, several materials are considered critical in terms of security of supply for European manufacturers due to geopolitical dependency of supply chains and slow ramp-up of global mining capacities (European Commission, 2020b). All together, these issues provide incentives for manufacturers to establish closed battery material loops and thereby reduce the environmental, economic and social risks associated with primary battery material supply in the future.

In order to implement a CE for EV batteries, different actions can be taken to reduce the overall material demand of a company, e.g. by establishing alternative supply chains for secondary material, increasing the share of recycled content and reused components, as well as minimizing the amount of waste in production (Schulz et al., 2021; World Economic Forum, 2020). Moreover, specific focus is dedicated to the available strategies at the battery end-of-life (EoL), which mainly include the following options (Kurdve et al., 2019; Olsson et al., 2018; Richa et al., 2017):

- Remanufacturing and reuse of batteries in EVs,
- Repurposing and further use in stationary battery energy storage systems,

- Recycling and closed-loop production in collaboration with battery cell manufacturers.

To ensure a successful transition to electric mobility, manufacturers require frameworks for systemically assessing and stirring material circularity for batteries across a number of different business processes of the organization. Given the lack of studies addressing this issue, we find that there is a need for case studies on EV batteries, which investigate the contribution of various activities at an automotive manufacturer to an overall material circularity target. The underlying rationale is to encourage manufacturers to adopt more structured and effective approaches for managing and communicating progress on CE implementation.

3. Material and methods

3.1. Research approach

In order to study how different business processes can contribute to improving the material circularity of battery materials, a case study offers the possibility to collect insights on real-world phenomena in order to derive implications for theory in a specific field (Ridder, 2020). As such, the present case study aims to provide detailed guidance on modelling battery material flows while at the same time linking results to the corresponding business processes for CE in an organization. Furthermore, a case study enables the collection of specific insights for applying the study framework in practice, including the required assumptions, data sources and interpretation of results.

To achieve this, we develop the study framework presented in Fig. 1 by following a 3-step approach inspired by the British Standard BS:8001:2017, which provides a flexible framework for implementing the principles of a CE in an organization (BSI, 2017). In the scoping phase, the framework suggests to start from the definition of system boundaries, followed by four steps: i) mapping of material flows, ii) the identification of value networks and stakeholder relationships, iii) the definition of CE leverage points and iv) the clarification of objectives for taking action (BSI, 2017). For the framework used in this study, the first step therefore is the analysis of material flows (step 1). In order to match material circularity results with stakeholder needs (Kravchenko et al., 2020), define key questions at business process level, which need to be addressed by a suitable CE indicator. This combines the second and third step of the BS:8001 as it links considerations at business process level with actions towards a CE. We thus adopt this approach and define key questions, which reflect the different stakeholders' needs within an organization and their context-specific challenge in relation to CE (step 2). Lastly, we calculate the implications on the material circularity in the corresponding scenario and formulate answers to the defined key questions based on the results (step 3) (see Fig. 1).

It should be noted that our study framework is not specific to the case of batteries, but can be used to assess the contribution of business processes to the material circularity in different cases. In the present study, the framework is applied to a case of an automotive manufacturer, which is introduced in the following section.

3.2. Development of the case study

In order to analyze the contribution of different business processes to the material circularity of a company, all relevant battery material flows of an automotive manufacturer need to be included. However, such information is considered strategically relevant and hence sensitive data, which causes a lack of availability of primary data published by industrial players. Therefore, an illustrative case based on secondary data was developed, considering actual market projections for EVs in Europe by 2030 from different sources as discussed in (Neidhardt et al., 2022) and (Dunn et al., 2021). Specific assumptions are made based on previous studies, which are selected based on the experience of the authors. An illustration of the relevant parameters is presented in Fig. 3, meanwhile detailed information on all relevant material flows are presented in section S1 in the supplementary material (SM).

Within the case study, the focus lies on the cathode materials of the battery. These include Cobalt (Co) and Lithium (Li), which are considered critical materials due to their limited availability on global resource markets (European Commission, 2020c), as well as Nickel (Ni) and Manganese (Mn) because of an expected competition for high-grade materials and base metals across multiple sectors (European Commission, 2020b; Lebedeva et al., 2016).

In terms of the material demand, we define a specific battery technology mix for product portfolio, which includes three types of products: two battery electric vehicles (BEV) (with 20 kWh and 67 kWh battery capacity, respectively) and a plug-in hybrid electric vehicle (PHEV) with 15 kWh battery capacity. The cell chemistry is based on lithium-nickel-manganese-cobalt-oxide (NMC). Due to innovation in battery cell chemistry, different technologies are available within the scope of the study (see Table 1).

The growth of sales volumes for the time between 2010 and 2030 shows that due to innovation in battery cell technology, NMC811 is the main technology used for market entries after 2025 whereas market returns are still dominated by NMC622 until 2030 (see Fig. 2). For the company in the case study, we assume a market share of 6% for all three product types. This is based on the actual, average market share of main

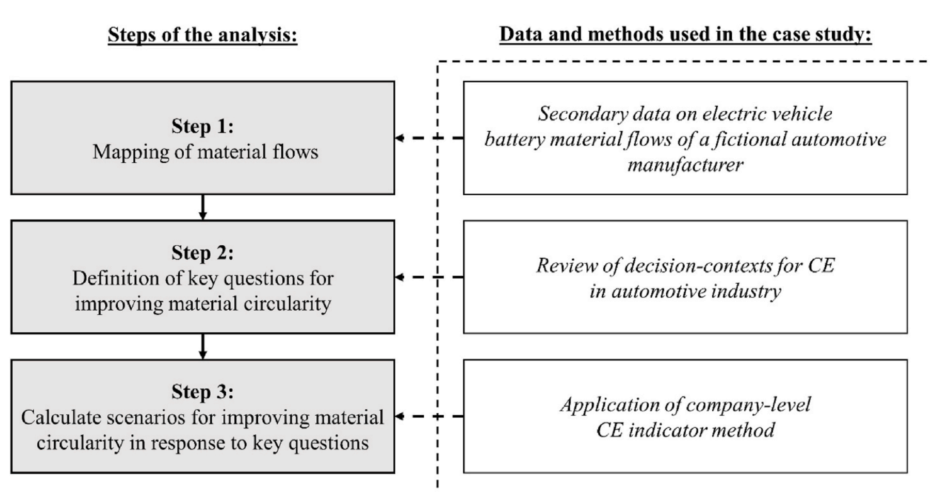

Fig. 1. Study framework for analysing the contribution of business processes of an organization to material circularity at company-level.

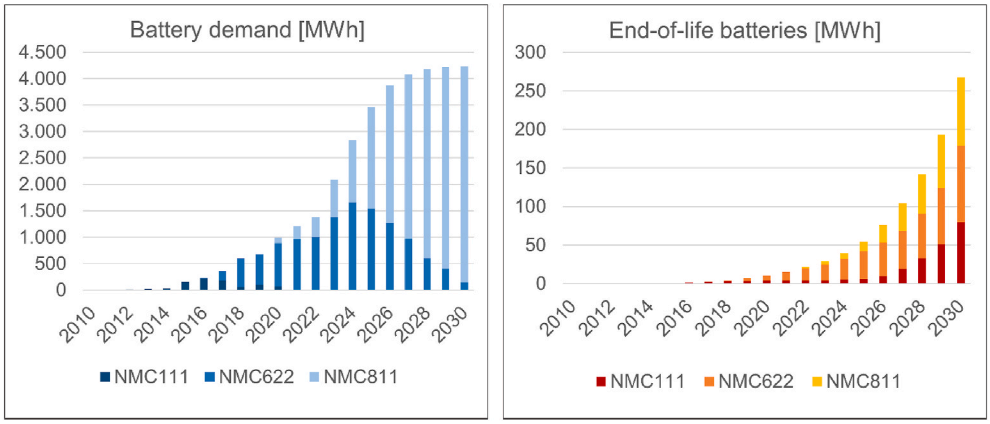

Fig. 2. Total lithium-ion battery demand and market returns in MWh for the case company for the period 2010–2030 in Europe based on Neidhardt et al. (2022).

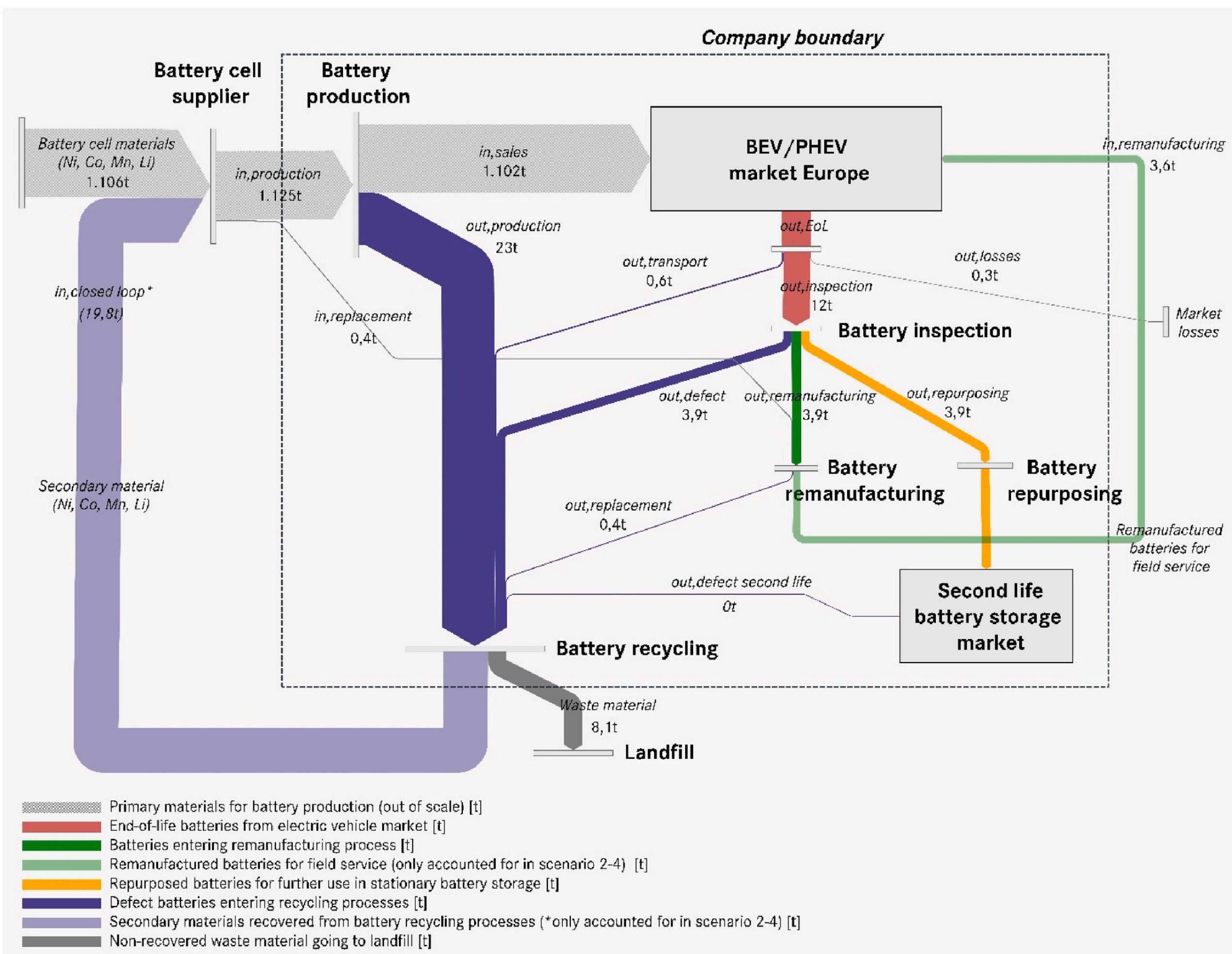

Fig. 3. Exemplary material flows in the case study for the year 2020 in tons. Note that for illustration purposes, the flows "primary material", "in, production" and "in, sales" are out of scale due to high volumes. The flows "in, closed loop" and "in, remanufacturing" are only included in the calculations for scenarios 2–4.

manufacturers in Europe such as BMW and Mercedes-Benz (Statista, 2022). Further details on the market share are provided in section S1 in the SM1. Plotting the development of battery material flows by 2030 shows that due to innovation in battery cell technology, NMC811 is the main technology used for market entries after 2025 whereas market returns are still dominated by NMC622 until 2030 (see Fig. 2).

3.3. Step 1 – mapping of material flows

In the first step, the material flows resulting from the battery portfolio of the case company are described in detail. The following section introduces the relevant parameters. The resulting material flows in the year 2020 are illustrated in Fig. 3.

Table 1
Material composition per lithium-ion battery type in tons for the materials Nickel (Ni), Manganese (Mn), Cobalt (Co) and Lithium (Li) in battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV); based on Neidhardt et al. (2022).

Battery type	Ni	Mn	Co	Li
BEV, small, 20 kWh				
NMC111	0,008	0,007	0,008	0,003
NMC622	0,012	0,004	0,004	0,003
NMC811	0,015	0,002	0,002	0,002
BEV, large, 67 kWh				
NMC111	0,027	0,025	0,027	0,01
NMC622	0,041	0,013	0,013	0,009
NMC811	0,05	0,006	0,006	0,007
PHEV, 15 kWh				
NMC111	0,006	0,006	0,006	0,002
NMC622	0,009	0,003	0,003	0,002
NMC811	0,011	0,001	0,001	0,002

3.3.1. *Battery production*

The produced battery quantities (*in, production*) and sold quantities (*in, sales*) per vehicle type and material are modelled based on market forecasts. For each material type, we consider the expected recycled content of the cell materials, which is based on the availability of recycled post-consumer EoL batteries. Post-industry waste occurring at battery cell manufacturing level is not included in the scope of the study. The expected reduction of primary material demand through recycled materials by 2030 reaches from below 5% (IEA, 2021) to a maximum of 10% for Li, Co and Ni in 2030 (Buchert et al., 2019). Other authors state an average range for the years 2020–2029 between 2 and 6% depending on the material (Xu et al., 2020). Based on these data sources, we assume a recycled content of 2% (Ni), 5% (Mn), 3% (Co) and 3% (Li) in the year 2020 based on (Xu et al., 2020), followed by a linear increase to 10% for all materials by 2030 based on (Buchert et al., 2019) (see Fig. S2 in the SM1).

The battery waste flows consist of two main streams: waste from battery- or vehicle production processes (*out, production*) and batteries, which reach their EoL in the market (*out, EoL*). The amount of production waste is determined as a percentage of the production volumes, which is assumed to be constant at 2% based on (Li et al., 2017). To model the annual waste streams for batteries reaching their EoL in the market, a statistical distribution of the lifetime of an EV with an expected value of 15 years is used based on (Hoekstra and Steinbuch, 2020) (see Table S7 and Fig. S3 for detailed information).

Regarding the EoL flows, it is assumed that a certain share of the EoL batteries are lost in the markets and are thus not available for further use for manufacturers. Whereas this value is neglected in (Neidhardt et al., 2022), others refer to studies on vehicles of unknown whereabouts (Oeko Institute, 2016) and assume market losses of 10–20% between 2020 and 2030 (Bobba et al., 2019). Based on these sources and given the uncertainty, we build an average between an optimistic scenario of no losses and a mean of 15% over the time frame of the study and thus assume a constant share of 7% losses. Out of those, 2% are considered inaccessible and thus not entering any recycling process at all (*out, losses*). Additionally, a constant share of 5% of EoL batteries is assumed to be ineligible for transportation due to functional damage (*out, transport*) and cannot enter a detailed inspection by manufacturers. Instead, these batteries are recycled directly under local market conditions and in accordance with minimum regulatory requirements (EU 2006).

All remaining batteries are assumed to be inspected for further treatment. In terms of the available EoL options, this study follows the approach by (Richa et al., 2017) and initially assume a uniform distribution, i.e. an equal split of EoL battery quantities, on three main routes: i) remanufacturing, ii) repurposing and iii) recycling. The specific assumptions for modelling each strategy are detailed in the following sections.

3.3.2. *Remanufacturing*

Remanufacturing describes the process of reusing a product with a performance that is the same of a new product (Ardente et al., 2018; Cooper and Gutowski, 2017). For the case of batteries from EVs, a 85–90% recovery rate in terms of mass is currently possible for remanufacturing in case of single cells with non-linear aging (Kampker et al., 2016). For the case study, we assume that 34% of the batteries recovered from the market enter a remanufacturing process (*out, remanufacturing*) with a cell replacement rate of 10%, i.e. a recovery rate of 90% at cell level (Richa et al., 2017). The replacement cells are included as an additional material demand to the required material for the production of new batteries (*in, replacement*). Remanufacturing of battery production waste is not considered.

3.3.3. *Repurposing*

Repurposing is defined as "utilizing a product or its components in a role that it was not originally designed to perform" (BSI, 2009). In the context of battery life cycles, repurposing describes the possibility to further use batteries in stationary battery energy storage systems at the end of their useful life in a BEV (Jiao and Evans, 2017; Martinez-Laserna et al., 2018). In this way, batteries can provide services to electricity grids for another 10–20 years before entering a recycling process (Bobba et al., 2019; Kamath et al., 2020). For the case study, we assume that 33% of the EoL batteries, which return from the market and enter the inspection process, are being repurposed at 100% recovery rate at cell level (*out, repurposing*). Repurposing of EoL batteries from production waste is not considered. After 10 years of use in stationary battery storages, repurposed batteries enter the recycling process available at that time (*out, defect second life*).

3.3.4. *Recycling*

The recycling of batteries is subject to European legislation (EU, 2006), which is currently under revision to better support a CE in the future (European Commission, 2020). For battery recycling, different processes are presented in literature (Brückner et al., 2020; Velázquez-Martínez et al., 2019). Currently a pyro-metallurgical treatment followed by hydro-metallurgical refining is the most common process applied in industry. In the future, a combination of mechanical pre-treatment and hydrometallurgical recycling can be expected to gain importance, given the higher efficiency of this process (Dunn et al., 2021). For the modelling in the case study, we therefore assume a mix of the two processes, in which the share of mechanical treatment and hydrometallurgical recycling gradually increases from 5% in 2020 to 50% by 2030 (Velázquez-Martínez et al., 2019) (see Fig. S3 in the SM). Furthermore, it is assumed that 33% of EoL batteries from the market are classified as defect and thus directly enter a recycling processes (*out, defect*) (Richa et al., 2017). Additionally, EoL batteries from production failures, as well as replaced cells from the remanufacturing process fully enter recycling. Lastly, batteries which have been repurposed also enter the recycling process after 10 years.

In terms of the effects of secondary material production for the recycled content of batteries, establishing a so-called "closed-loop production" implies that a company uses the material recovered from recycling its own products (Lüdeke-Freund et al., 2019). A company can thereby exclusively increase the availability of recycled content for battery production. In the case study, it is assumed in scenario 2–4 that the respective secondary material is available in the year in which the battery waste occurs (*in, closed loop*). The same applies to remanufactured batteries, which are used as service replacements (*in, remanufacturing*). This is a simplified assumption, which does not take into account physical material flows between recycling company and battery cell producer or other industries.

3.4. Step 2 – Definition of key questions

The analysis of the stakeholder network and the CE-related decision-contexts for batteries is based on (Schulz et al., 2021). The study uses 22 stakeholder interviews from different functions to describe the key challenges in relation to a CE for batteries. These are assigned to specific business processes involved in CE initiatives as presented by (Kravchenko et al., 2019). Besides modelling a business-as-usual (BaU) scenario to calculate the projected development of the material circularity without taking specific action, we use the results of (Schulz et al., 2021) to define four key questions and scenarios, which each represent a decision-context for CE within the company (see Table 2). Detailed information on the development of the key questions is provided in section S2.1 in the SM.

Firstly, the BaU scenario accounts for the projected sales and return quantities, the availability of recycled content and the evolution in recycling technologies as described in the previous section. The key question in scenario 1 then relates to product development and supply chain management and aims to assess the implications of the used battery cell technology on the company's material circularity. Secondly, the key question in scenario 2 relates to the link between supply chain and EoL processes and seeks to analyze how recycling and re-use of own products in a closed-loop production can increase the material circularity of the company. Thirdly, the key question in scenario 3 addresses the goal to optimize the product design for manufacturing, production and EoL processes, e.g. through design for disassembly or reparability. Lastly, the key question in scenario 4 relates to decision-makers on business models and EoL processes, who jointly need to assess the configuration of EoL strategies, i.e. the allocation of EoL batteries on remanufacturing, repurposing an recycling, in order to achieve the highest benefits for the company as a whole.

3.5. Step 3 – Calculating material circularity

In terms of the selection of the method for calculating the material circularity in step 3, a report by (Verstraeten-Jochemsen et al., 2020) indicates two methods, which serve as performance indicators enabling the identification and tracking of opportunities. The first one is the Circular Transition Indicators (CTI) framework developed by the World Business Council for Sustainable development (WBCSD, 2021). The framework is based on inflows and outflows of materials in a company, which are described through a set of different indicators. The second one is the "Circulytics" framework developed by the EllenMcArthur Foundation (EMF) as a scorecard-based tool which goes beyond the assessment of material flows and analyses the degree to which a company has implemented CE principles in its entire operations (EMF, 2020). In this regards, the complementary, quantitative metric is the material circularity indicator (MCI), which is a product-level CE indicator that can be extended to a company-level view on material circularity (EMF and Granta Design, 2019).

In our case we chose to apply the CTI framework, as it is specifically designed as a company-level CE indicator. This selection is confirmed by a recent review, stating that the CTI is the most complete and transparent option of methods for assessing the level of circularity at organizational level (Valls-Val et al., 2022). A thorough description of the calculation process and the detailed formulas for the CTI framework is provided in (WBCSD, 2021). To validate the selection, we will compare the results to the company-level MCI as part of a sensitivity analysis (see section 3.6). A summary of the used parameters for both methods is presented in the SM (see Tables S2–6 and Tables S10–12). For the case study, the required input data was calculated manually in Microsoft Excel and later implemented in the CTI online tool, which is a web-based tool that assists users in aggregating the material flow data in scope and carries out the computation of the overall material circularity (see example in the SM1) (Circular IQ, 2020). The main parameters are the circular inflow, i.e. the percentage of the total inflow in mass (M_{in}), which qualifies as circular, e.g. recycled- or renewable materials, as well as the circular outflow, i.e. the share of total mass of the outflows (M_{out}), which qualifies as circular, e.g. reused or recycled materials. The calculation of the total material circularity (C_M) of the company is then carried out as follows:

$$C_M = \frac{(M_{in} * \text{ circular inflow } [\%]) + (M_{out} * \text{ circular outflow } [\%])}{M_{in} + M_{out}} \quad \text{Eq. 1}$$

The resulting material circularity at company-level in each scenario is then used to formulate a response to the identified key questions. Table 2 provides an overview of the modelling approaches for each scenario and the parameters, which are adapted in comparison to the BaU scenario. Detailed information is provided in section S2.2 in the SM.

3.6. Sensitivity analysis

The results obtained for the CTI are evaluated in a two-fold sensitivity analysis (see SM section S3). Firstly, it follows from Eq. (1) that if

Table 2
Summary of scenarios, key questions, and modelling approaches for calculating material circularity for lithium-ion batteries in electric vehicles based on the business processes involved and the corresponding material flow parameters.

Scenario	Business processes involved	Key question	Modelling approach	Adapted parameters (compared to BaU)
Business-as-usual (BaU)	–	–	–	–
Scenario 1	Product development, supply chain	How can **innovation in battery cell technology** improve the material circularity of the company?	Assume that all NMC622 cells can be produced with NMC811 technology;	*In, production*
Scenario 2	Supply chain, End-of-life	How can the company use **closed-loop-production** to improve the material circularity?	Add recycled materials and remanufactured batteries as additional circular inflow in the year they occur;	*In, closed loop* *In, remanufacturing*
Scenario 3	Product development, production, End-of-life	How can **design for reparability** improve the material circularity of the company?	Increase potential recovery for remanufacturing to 95%; Reduce production waste from 2% to 1%;	*In, closed loop* *In, remanufacturing* *Recovery potential (remanufacturing),* *Out, production*
Scenario 4	Business models, End-of-life	How can the **configuration of EoL strategies** improve the material circularity of the company?	Change configuration of EoL strategies; Switch to 100% mech. + hydro recycling by 2030;	*In, closed loop* *In, remanufacturing* *Actual recovery (recycling)* *Out, defect* *Out, remanufacturing* *Out, repurposing*

the inflows of a company are higher in mass than the outflows in a certain year, the inflows have a higher effect on the total material circularity. Indeed, as it can be observed in Fig. 2, the sold batteries quantities are significantly higher than the market returns for the years 2020–2030 within the case study, which can be explained by the ongoing ramp-up of EV markets. This is a particular case since such imbalance of inflows and outflows would not occur for established technologies. Furthermore, it can be expected that this effect will decline with growing EoL battery quantities for the time beyond 2030. Therefore, the sensitivity analysis includes a computation of the material circularity assuming a 50-50 equilibrium of inflows and outflows in order to reflect on the effects of the early stage of EV markets on the company-level CE indicator results for batteries.

Secondly, we test the implication of the selection of the CE indicator by applying the MCI framework to the system under investigation and comparing it to the CTI results. For that, we firstly obtain the product-level MCI for each battery type and year. Afterwards, we aggregate the results at company-level by computing a weighted average based on the amounts of batteries sold per type in the respective year. For the interpretation of results, it must be noted that the MCI accounts for lifetime extension. In the case study, we assume that only repurposing extends the lifetime of batteries above the market average, whereas remanufacturing is accounted for under the parameter “fraction of the product collected for reuse” as described in the MCI methodology (EMF and Granta Design, 2019). As this aspect is not included in the scope of the CTI method, the corresponding effect of lifetime extension is reported for each MCI result (see section S3.2 in the SM for details).

4. Results

The results for the material circularity calculations in the BaU scenario are presented in Fig. 4. Firstly, it shows the inflow- and outflow modelling results in the CTI online tool for the year 2020 (top). The circular inflow for cathode materials of battery cells is still low with approximately 3% in 2020, which is due to low availability of recycled content. At the same time, the circular outflow is characterized by a high potential recovery of 95%, which is due to the theoretical availability of high-value EoL strategies. The actual recovery lies at 75%, which can be explained by the high share of EoL batteries from production waste entering pyro-metallurgical recycling processes in 2020. The EoL batteries from market returns split equally on remanufacturing, repurposing and recycling, but are still low in volume. Due to the higher mass in the inflow, the total material circularity of the battery cell portfolio of the case company in 2020 results to 5%. Additionally, the detailed results for the circular inflow and circular outflow for the years 2020, 2025 and 2030 are presented in Fig. 4 (bottom). The comparison shows how the circular inflow increases to 10% by 2030 whereas the circular outflow increases to 85,5%. While the former is linked to the increased availability of recycled content on regular material markets, the latter results from higher recycling efficiencies as well as higher shares of EoL batteries entering efficient remanufacturing and repurposing processes. Note that over the timeframe of 10 years, the net inflow increases from

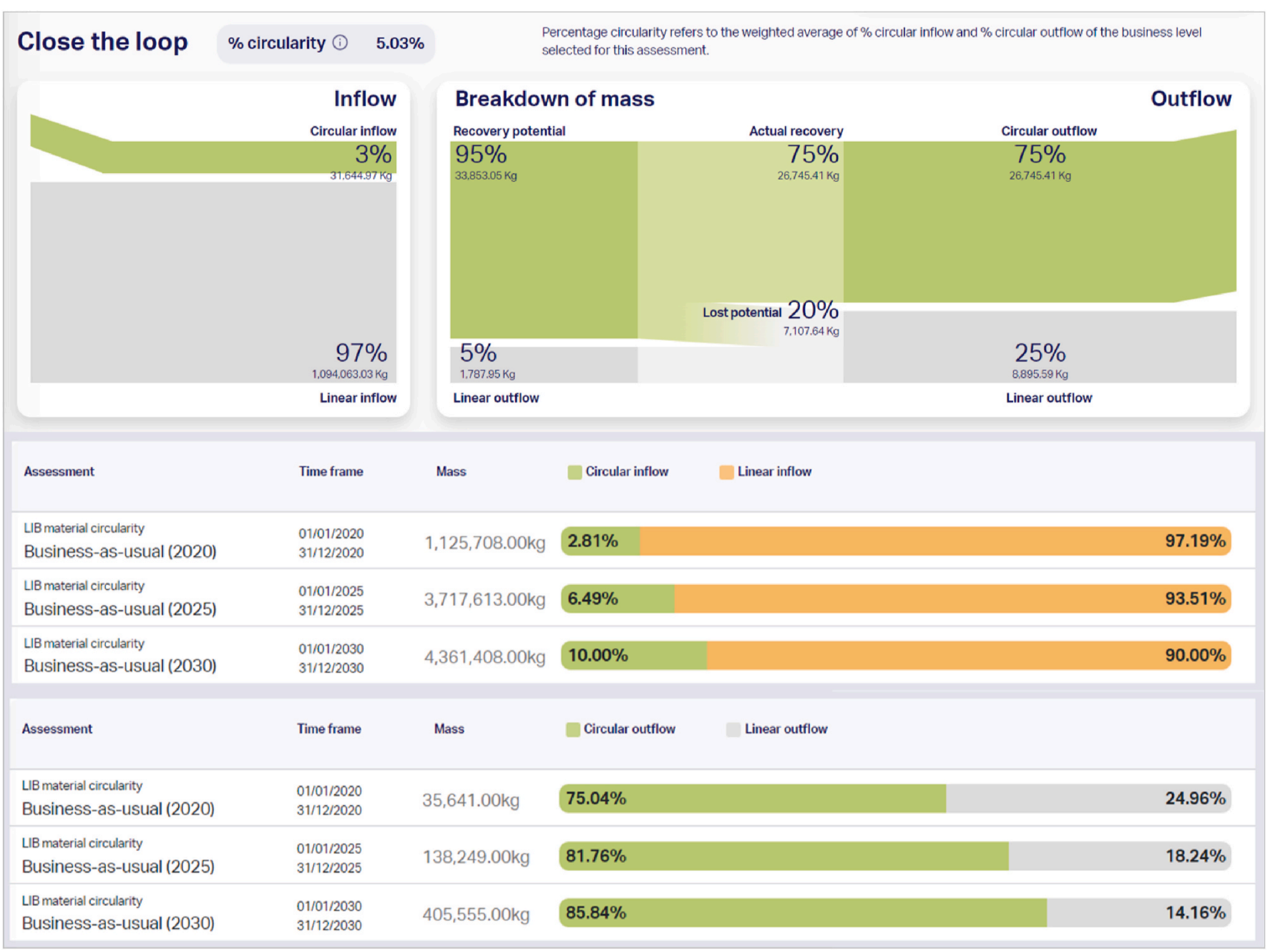

Fig. 4. Results of the circular transition indicators (CTI) for the close the loop module in the business as usual scenario. Illustration of mass flows for the year 2020, rounded to whole numbers (top); detailed results for circular inflow and circular outflow for the years 2020, 2025 and 2030 (bottom); graphs retrieved from the CTI online tool (Circular IQ, 2020).

1.126t to 4.361t per year, i.e. roughly by a factor 4, while at the same time, the outflow increases from approximately 36t to 405t. For the total material circularity, this means that the relative weight of the outflow increases, resulting in a total material circularity of 9% in 2025 and 16,5% in 2030 (see Fig. 5).

The results for the other scenarios are reported in Fig. 5. The findings for each scenario, including the resulting response to the defined key question are presented in the following sections. Detailed results for each scenario are reported in Figs. S7–10 in the SM.

4.1. Scenario 1 – Battery technology innovation

Based on the assumptions presented above, the material circularity of the case company in scenario 1 is 4,9% in 2020, 9% in 2025 and 16,4% in 2030. In response to key question 1, the results suggest that using an innovative and resource efficient NMC811 cell technology instead of NMC622 does not yield significant improvements in terms of the headline indicator for material circularity of the company compared to the BaU scenario. This is because for the share of recycled content, which represents the main lever of improving circular inflow, changing to NMC811 does not provide additional benefits. At the same time, changes and potential benefits in the required amounts of Co, Mn and Li are indeed visible to product development and supply chain business processes, but only when observing the net material consumption of the company (see Fig. S10 in the SM). This implies that a material circularity expressed in percent alone is not sufficient to address the key question in product development and supply chain business processes. Instead, targeting specific critical materials requires a monitoring of absolute quantities per material stream rather than aggregated metrics.

4.2. Scenario 2 – Closed-loop production

In scenario 2, the total material circularity is 7% in 2020, representing an increase by 2% compared to the BaU scenario. Furthermore, the results are 11,5% in 2025 (+2,5%) and 21,8% in 2030 (+5,3%). In response to key question 2, this indicates increasing potential benefits from establishing a closed-loop production from recycling and reuse of own products for the case company by 2030. At business process level, this means that EoL management of batteries can deliver a growing additional share of secondary materials to the battery production in the future. In this sense, the results enable the business processes to take relevant actions such as ensuring access to EoL batteries and supporting the integration with the battery supply chain to close material loops.

4.3. Scenario 3 – Design for reparability

As an extension of scenario 2, improving the battery design towards reparability in scenario 3 leads to a material circularity of 5,7% in 2020, 10% in 2025 and 20,6% in 2030. While this suggests improvements in comparison to the BaU scenario, the results are lower compared to scenario 2. This indicates that improving the reparability of the battery reduces the material circularity of the company. The underlying cause of the drawbacks can be found by observing the net material flows, showing that less recycled material is available for a closed-loop production in scenario 3 (see Tables S13–17). In relation to key question 3, the results thus suggest that actions taken by business processes in product development, production and EoL to improve the design for reparability of batteries can delay the occurrence of waste streams in production, which potentially leads to drawbacks in terms of material circularity. This indicates an inter-dependency between production-related business processes seeking to minimize EoL flows on the one hand, and supply chain processes in need of recycled materials for a closed-loop production on the other hand.

4.4. Scenario 4 – EoL strategies

In scenario 4, the collaboration of business model and EoL processes enables a new configuration of EoL strategies for batteries. By affecting outflows through the optimization of remanufacturing, repurposing and recycling, the new configuration of EoL strategies yields a total material circularity of 7,1% in 2020, 11,8% in 2025 and 23,7% in 2030. This represents an improvement to both the BaU scenario and in relation to scenario 2, in which EoL batteries from market returns are equally distributed among remanufacturing, repurposing, and recycling. Consequently, it can be stated that favoring high-value EoL strategies such as remanufacturing benefits the material circularity of the company on the short-term. Furthermore, when combined with highly efficient recycling processes, a prioritization of recycling by 2030 can support a closed-loop production and thereby further increase material circularity. In relation to key question 4, the results indicate that a strategic allocation of batteries to different EoL strategies can contribute to an optimized material circularity of the company. Additionally, the

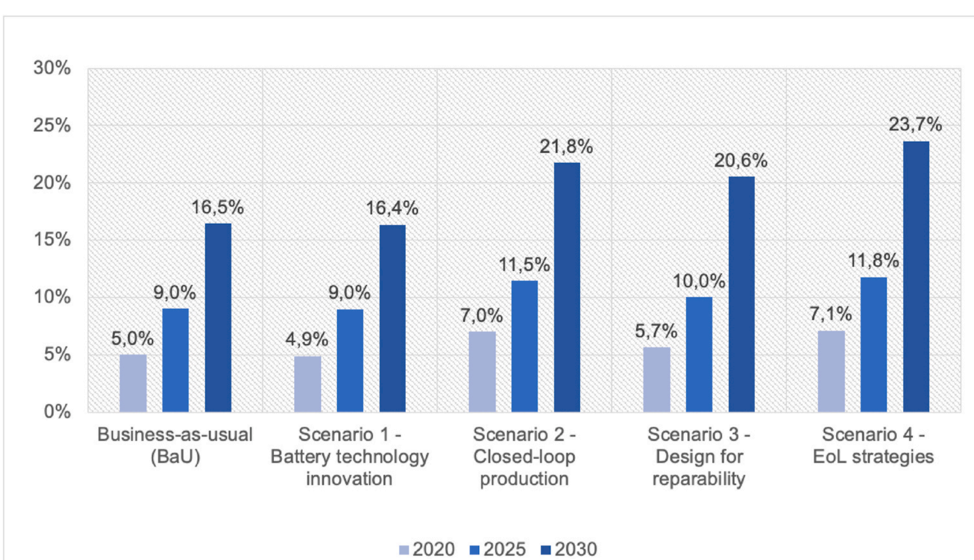

Fig. 5. *Modelling results for the total material circularity of the case company for the BaU and scenarios 1–4 in 2020, 2025 and 2030. Calculations based on the circular transition indicators framework* (WBCSD, 2021).

results suggest that this aspect becomes particularly important with growing numbers of market returns from 2030 onwards. In this regard, the assessment enables business processes related to business models and EoL operations to understand the effects of prioritizing remanufacturing, repurposing and recycling, taking into account the effects on the availability of secondary materials.

4.5. Sensitivity analysis

The results of the sensitivity analysis are presented in Fig. 6. For the CTI results with an adjusted weighting of inflows and outflows, the material circularity takes higher values in the range of 39–54% compared to approximately 5–24% for the mass-based weighting (see Fig. 6, top). This can be explained by the higher relevance of the circular outflow for the total material circularity. Additionally, the total increase between 2020 and 2030, e.g. by 16,6% in scenario 4 in the mass-based weighting, is lower in the adjusted weighting with appr. 13% for scenario 4, which again is because increasing outflow quantities do not cause changes in the weighting over time. Notably, scenario 3 does not show drawbacks in comparison to scenario 2 as in the BaU scenario. This indicates that a reduction of material availability for closed-loop production has a lower effect for systems, in which inflows and outflows are in equilibrium.

Additionally, the results for the company-level MCI are presented in Fig. 6 (bottom). Similarly, to the results for the weighted CTI, values are higher in the range between 53 and 63%, out of which 2–6% result from lifetime extension through battery repurposing depending on the scenario. Meanwhile, the trends follow the developments of the CTI in all scenarios, with scenario 1 showing the lowest change compared to the BaU scenario and with scenario 4 showing the highest. It is notable that differences between the scenarios investigated are relatively low, indicating that the aggregated company-level MCI is not well suited for prioritizing the various measures to improve material circularity in the case study.

The sensitivity analysis reveals two main findings. Firstly, the higher nominal values for the CTI with adjusted weighting suggest that an interpretation of inflow- and outflow based CE indicator methods requires taking into account the state of the market of a given technology. Secondly, the comparison between the CTI and the company-level MCI illustrates that CE indicator methods can show similar, nominal results in terms of material circularity for a certain product system, but at the same time differ in their applicability for scenario analysis at company-level.

4.6. Response to the research question

In response to the research question, Fig. 7 describes the contribution of the business processes of an organization to the material circularity of the company. Based on the findings outlined in the previous section, the specific contributions are described for each scenario based on the following aspects: i) the necessary collaboration among business processes, ii) the activities these can carry out to improve material circularity, iii) the material flows addressed (i.e. inflow or outflow) and iv) the quantification of the impact on material circularity in comparison to the BaU scenario.

Firstly, the contribution of the business processes product development and supply chain is the reduction of critical material requirements, e.g. through the introduction of new battery technologies with low-cobalt content or increased recycled content. As described in section 4.1, these activities affect the absolute material inflows of the company, but do not yield benefits on the company-level material circularity within the case study. Hence, product development and supply chain processes should focus on monitoring and evaluating available battery technologies and ensuring quick introduction in the existing portfolio.

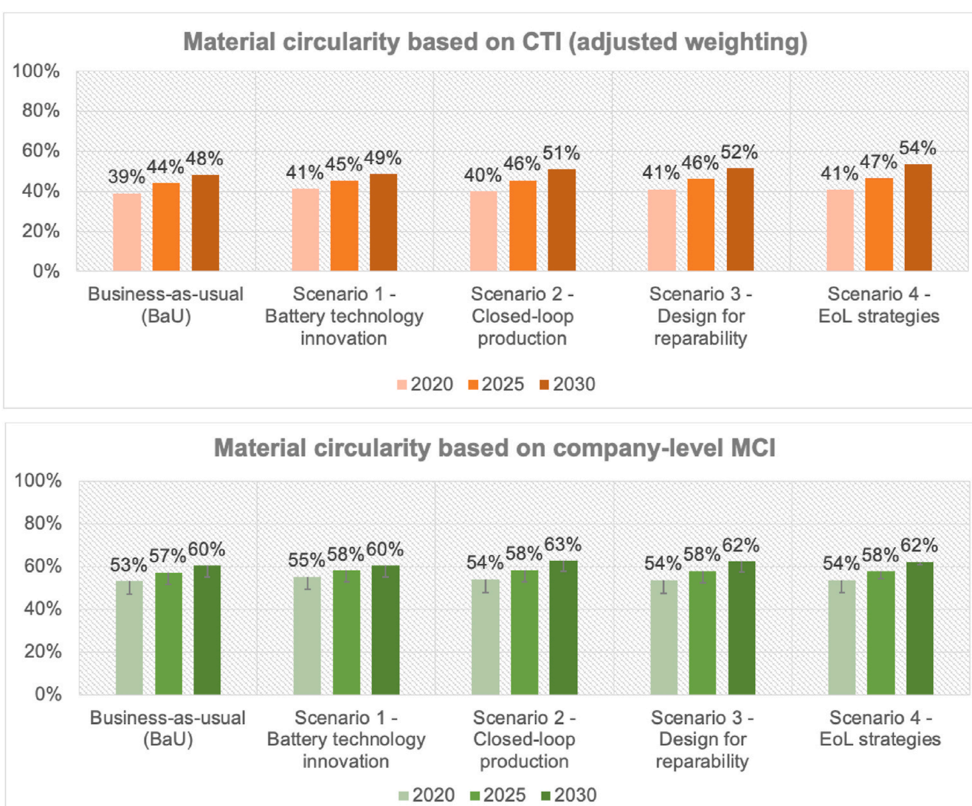

Fig. 6. Results of the sensitivity analysis. Material circularity based on Circular transition indicators (CTI) method with adjusted weighting of inflow and outflows (top). Material circularity based on company-level material circularity indicator (MCI). Error bars report the effect of lifetime extension through battery repurposing (bottom).

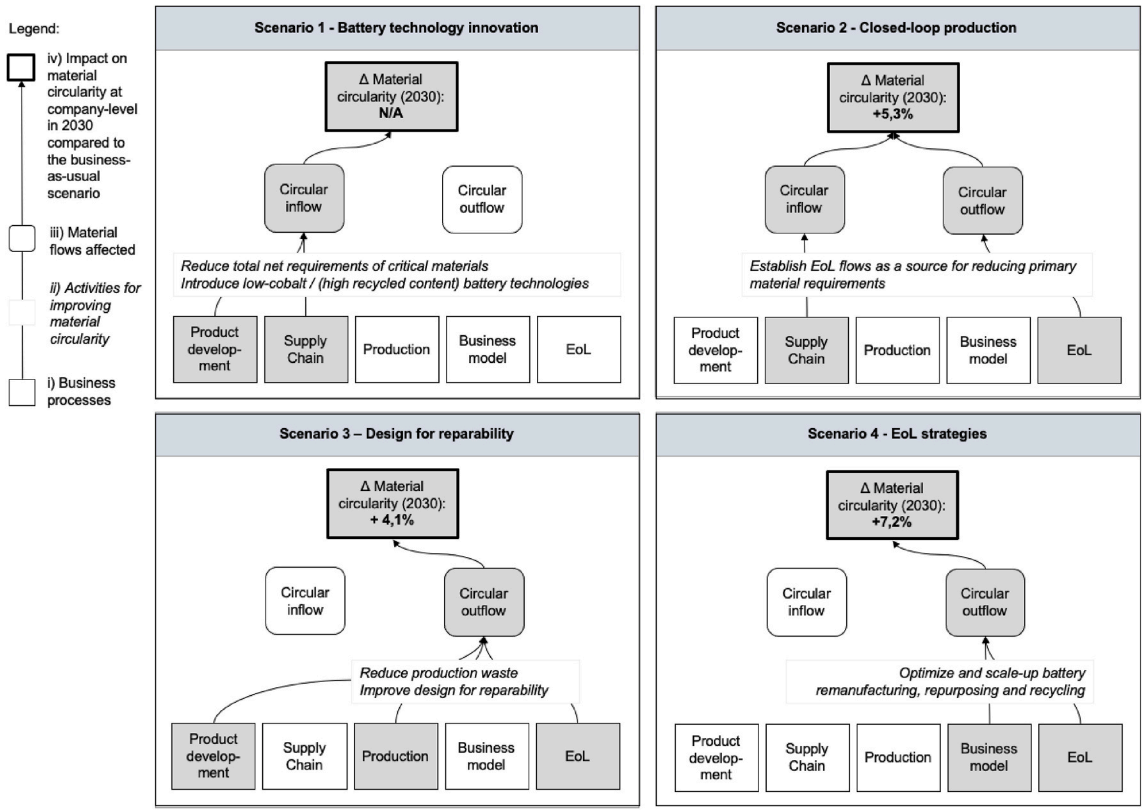

Fig. 7. Description of the contribution of different business processes to battery material circularity at company-level. Boxes marked with grey illustrate the mechanism (i) business processes, ii) activities, iii) material flows affected and iv) impact on material circularity) for each scenario.

Secondly, the case study illustrates how supply chain and EoL processes contribute to company-level material circularity for batteries through their responsibility for implementing a closed-loop production, i.e. establishing EoL battery flows as a source for reducing primary material requirements. This affects both inflows and outflows of a company and can increase material circularity of the future battery portfolio by 5,3% by 2030 compared to the BaU scenario.

Thirdly, business processes in product development, production and EoL contribute to company-level material circularity by jointly managing outflows of a company, which originate from internal operations such as production processes. In this regard, our results reveal how reducing production waste, e.g. through improvements in process- and product design, simultaneously reduces availability of EoL batteries for closed loop-production. Consequently, the maximization of recycled content partly depends on the activities on waste prevention in production and thus requires alignment and planning of waste quantities among business processes in EoL operations.

Lastly, the contribution of business processes involved in business models and EoL operations is given by the alignment of EoL strategies towards a common material circularity target. To achieve that, both business processes jointly should optimize and scale up battery remanufacturing, repurposing and recycling. In this regard, methods for assessing material circularity should consider the specific mechanism of each EoL strategy for increasing material circularity. This includes the introduction of new process technologies for closing material loops such as efficient recycling processes as presented in response to key question 4, as well as lifetime extension through battery repurposing as shown in the sensitivity analysis.

5. Discussion

5.1. Theoretical and practical contributions

Firstly, we provide a case-based example for how to calculate the material circularity for batteries at company-level based on material flows in Europe by 2030. It thereby complements existing studies (Richa et al., 2017) and offers guidance for practitioners. Moreover, the study shows how to link material circularity results to business processes in a scenario-based approach, which is not specifically addressed in existing descriptions of CE indicator methods (EMF and Granta Design, 2019; WBCSD, 2021). While this requires bringing together qualitative data and quantitative assessments, the 3-step procedure and the Excel-based tool developed (cf. SM2) indeed enable future studies to carry out similar assessments for the case of batteries in a structured way.

Secondly, we provide quantitative results on the expected material circularity for critical battery materials by 2030. In this regard, we show how companies can increase material circularity from appr. 16% in a BaU scenario to appr. 24% by 2030 by establishing a closed-loop production together with an optimized distribution of batteries on different EoL strategies. Our results thereby add to existing studies on estimating battery material flows (Neidhardt et al., 2022) and confirm previous findings, e.g. that prioritizing battery remanufacturing and repurposing over recycling has only minor effects on secondary material availability before 2030 (Bobba et al., 2019). Additionally, the results provide a point of reference for companies when monitoring market developments, which is recognized as a necessary step to adjust strategies accordingly (Blömeke et al., 2022; Jiao and Evans, 2017). For that, the quantitative results can serve as a benchmark across manufacturers or can be interpreted in relation to future battery legislation (European Commission, 2020). Hence, the study supports companies in prioritizing CE strategies for gaining competitive advantage and to ensure compliance.

Thirdly, we specify how business processes can contribute to material circularity, including a) the necessary collaboration, b) the affected material flows and c) the expected impact in comparison to the BaU scenario. While our study depicts the material circularity of a company as a combination of numerous overlapping and interdependent effects, the findings can guide companies in organizing collaboration among actors by setting targets at company-level, thus adding to description in existing frameworks (BSI, 2017; Morseletto, 2020). This is particularly relevant for the alignment of EoL strategies for batteries, which has been identified as a key aspect in both the results of the present study and in previous work (Olsson et al., 2018; Richa et al., 2017; Schulz-Mönninghoff et al., 2021). Lastly, our findings also outline the need for exchange of information across business processes due to inter-dependencies among the targeted decision-makers. This resonates with the findings of (Roos Lindgreen et al., 2020), stating that as much as 27% of the CE indicator methods assessed in their study do not mention the targeted end users, thus requiring more efforts in understanding the roles associated with actions for CE.

5.2. Limitations and directions for future research

The main limitations of the study method is that the findings are based on an illustrative case derived from EV market projections. The underlying reason is that many of the data points required for modelling battery material flows at company-level are strategically sensitive data. Despite the availability of secondary data sources to fill gaps resulting from confidentiality issues, future research should investigate how to ensure that manufacturers can publish such data without competitive disadvantage. Establishing common data platforms could be an enabler in this regard.

Furthermore, the limitations deriving by the selection of the method to assess material circularity reveal the importance of testing CE indicators extensively before implementation. On the one hand, the results in scenario 1 indicate limitations of the CTI to allow conclusions on critical material use based on an aggregated material circularity score, hence requiring integration with absolute values. On the other hand, the sensitivity analysis reveals how the company-level MCI provides little descriptive power for prioritizing among the scenarios tested. Here, future studies should define criteria of suitability for each method, potentially taking into account other aspects than material flows (Elia et al., 2017). Generally, more work is needed to further develop industry standards for analyzing material flows in the context of a CE. To achieve that, our findings underline the importance of providing further guidance and rules for defining a BaU, modelling future material flows, accounting for material flows in a closed-loop production and scenario analysis.

Furthermore, previous studies identify inter- and intra-organizational collaboration as a main barrier for CE adoption in industry (Korhonen et al., 2018), whereas the use of indicators can be subjective and depends on the interpretation of users (Saidani et al., 2019). In our study the interaction of actors with the suggested CE indicators in practice has not been part of the investigation. Future research should thus build on existing studies focusing on the actors in a CE (Babri et al., 2018; Schulz et al., 2021). In this regard, dedicating more efforts to investigating how CE indicators can be integrated in new forms of collaboration and co-design among stakeholders in a CE seems to be a promising avenue for future research.

5.3. Concluding remarks

This study investigates the contribution of different business processes within an organization to material circularity for the case of EV batteries. For that, it offers an illustrative case of analyzing battery material flows at an automotive manufacturer in relation to typical CE-related key questions, which together describe the playing field for the much-needed transition towards resource-efficient mobility in the future. While thus underlining the need for a holistic assessment of a company's material circularity, the results also reveal the limits for decreasing primary material requirements through remanufacturing, repurposing, and recycling with a total potential of less than 25% by 2030. Consequently, the adoption of company-level material circularity metrics suggest the necessity for the deployment of other CE strategies such as de-materialization, servitization and narrowing of material loops (Bocken et al., 2016; Rizos et al., 2016) in order to ensure a sustainable management of resources as part of the electrification of the mobility sector (World Economic Forum, 2020). In this sense, our results present a pathway for integrating CE considerations in all business processes of a company and thereby stir action towards unlocking the full potential of the concept of a CE in the automotive industry.

CRediT authorship contribution statement

Magnus Schulz-Mönninghoff: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing, Formal analysis, Visualization, Project administration. **Michael Neidhardt:** Investigation, Data curation, Validation, Writing – review & editing. **Monia Niero:** Conceptualization, Methodology, Writing – review & editing, Validation, Resources, Supervision.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.135232.

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