



# Circular design criteria and indicators for the sustainable life cycle management of electric vehicle batteries<sup>☆</sup>

Aitor Picatoste<sup>a,\*</sup>, Daniel Justel<sup>a</sup>, Joan Manuel F. Mendoza<sup>a,b,\*\*</sup>

<sup>a</sup> Mondragon Unibertsitatea, Faculty of Engineering, Mechanics and Industrial Production, Loramendi 4, Mondragon 20500, Gipuzkoa, Spain

<sup>b</sup> Ikerbasque, Basque Foundation for Science, Plaza Euskadi 5, Bilbao 48009, Bizkaia, Spain

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## ABSTRACT

The implementation of circular economy (CE) criteria and indicators in the design stage of electric vehicle (EV) batteries could optimise their life cycle resource efficiency and environmental performance. However, the viability of using circularity criteria and indicators to develop more environmentally sustainable EV batteries remains unclear due to the lack of scientific and industrial case studies. The goal of this paper is to show the perceptions from relevant stakeholders about the suitability of the implementation of circularity criteria and indicators for EV batteries design and life cycle management (LCM). A total of 24 industrial and academic stakeholders were engaged in individual meetings to assess the importance and applicability of 30 circularity design criteria and 15 product-level circularity indicators, collected through a review of academic papers, policy regulations, and industry reports. According to the consulted stakeholders, i) “focus on quality of performance”, ii) “favour cleaner production”, and iii) “use digitalisation and internet-of-things solutions” were identified as the most suitable criteria for implementation. Regarding circularity indicators, End of Life Indices and the Product Circularity Indicator were considered the most relevant for use due to their coverage of multiple life cycle stages and circularity strategies. However, the results suggest a discrepancy in stakeholders' views regarding the best circular design criteria and the most suitable circularity indicators. Consequently, there is yet a lack of adequate indicators for sustainable EV battery design and LCM incorporating the required circular design criteria. Accordingly, future research should focus on defining and aligning specific circularity criteria and indicators for EV batteries to support and monitor sustainable innovation.

## Abbreviations

CE	Circular economy
EOL	End of life
EU	European Union
EV	Electric vehicle
ICT	Information and communication technology
IoT	Internet of Things
LCA	Life cycle assessment
LCM	Life cycle management
SI	Supporting information
SoH	State of Health

## 1. Introduction

The European Union (EU) is promoting policies and technologies to reduce the greenhouse gas emissions by 55 % for 2030 compared to 2022 (Wilson, 2022). Electric vehicles (EV) represent sustainable alternative to the traditional internal combustion engine vehicles due to their higher energy efficiency and absence of CO<sub>2</sub> tail-pipe emissions (European Environment Agency, 2022), which is crucial to develop carbon-neutral cities and regions (Gallego-Schmid et al., 2020). However, the transition to electric mobility must be accompanied by resource efficiency improvements to ensure that the desired environmental savings will be reached (Esteban and Otero, 2023; Leipold et al., 2022), as EVs are not exempt from environmental impacts due to (for

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\* Corresponding author.

\*\* Correspondence to: J. M. F. Mendoza, Mondragon Unibertsitatea, Faculty of Engineering, Mechanics and Industrial Production, Loramendi 4, Mondragon 20500, Gipuzkoa, Spain.

E-mail addresses: [apicatoste@mondragon.edu](mailto:apicatoste@mondragon.edu) (A. Picatoste), [jmfernandez@mondragon.edu](mailto:jmfernandez@mondragon.edu) (J.M.F. Mendoza).

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instance) the energy, materials and mineral requirements to produce the batteries, which today are not easy to be recycled for material recovery (Picatoste et al., 2022a).

Batteries represent a critical technology for the deployment of EVs (IEA, 2023), with the demand for EV battery raw materials (such as lithium and cobalt) predicted to surpass the current material extraction capabilities globally (100kT lithium and 170kT cobalt) by 2040 (Maisel et al., 2023). Therefore, the EU has developed a new regulation (European Commission, 2023b) to monitor the adequate development of EV batteries. Furthermore, the regulation establishes the development of a battery passport to include information on the material production and consumption of EV batteries (Battery Pass project, 2023).

Circular Economy (CE) solutions aiming at maximizing resource efficiency, while minimizing environmental impacts (Mendoza et al., 2017). Thus, applying circularity design criteria can help reducing resource use, prolonging product lifetime, and facilitating material recycling (Bocken et al., 2016), which can contribute to improve the environmental performance of EV batteries (Baars et al., 2020). For instance, implementing product-level CE strategies such as reducing the material usage (Monteiro et al., 2022), repurposing (Schulz-Möninghoff et al., 2021) or recycling (Mohr et al., 2020) can reduce the life cycle environmental impacts of EV batteries by to 35 %, 22 % and 29 % respectively. These reductions could be further improved by technology developments for the calculation of ageing on the operational phase of EV batteries for battery sharing (Zhou, 2023) or second life (Song and Zhou, 2023).

However, the development of circularity criteria for EV batteries presents significant challenges due to the complex nature of these systems. The production and use of EV batteries involve multiple stakeholders (e.g. component producers) and require the integration of various technologies (hardware, software, etc), making it complex to assess the impact of different design choices (Picatoste et al., 2022a). Additionally, the trade-offs between circularity criteria need to be carefully evaluated to ensure that the benefits of CE principles are maximised and undesirable rebound effects are avoided (Zink and Geyer, 2017). For example, an EV battery can be made more robust using extra material to increase its longevity. However, this could cause the battery to weigh more, which is one of the critical factors for EV impacts on use phase (Mayyas et al., 2017).

Developing a dedicated set of circularity criteria and indicators for EV batteries is essential for guiding the transition towards more sustainable systems. Equally important is capturing stakeholder perceptions, as diverse actors offer valuable insights into feasibility and impact. However, the current literature lacks comprehensive research on both aspects, underscoring the need for further investigation to advance a truly sustainable battery ecosystem. To address these gaps, the research of this article was articulated through two research questions:

- Research question 1: What are the most relevant circular design criteria and indicators that can help improve the circularity and environmental sustainability of EV batteries?
- Research question 2: What is the perception of stakeholders involved in the life cycle management of EV batteries regarding the consideration of circularity design criteria and indicators to support innovation processes, including the perceived trade-offs between circularity, cost, and performance?

The main contribution of this work is a prioritisation of circularity design criteria and indicators based on the EV battery stakeholders' evaluations, as well as an analysis of the results based on each of the expertise groups of stakeholders, including a discussion on the most relevant barriers and opportunities for circular and sustainable innovation.

## 2. Literature review

The scientific literature explored different circularity criteria (Shahbazi and Jönbrink, 2020) and/or indicators (Kravchenko et al., 2020a) to provide guidelines and best practices to industry. Circularity criteria can help develop a product with a circularity mindset, increasing the resource efficiency (CIRCit Norden, 2020a).

Circularity indicators can be used to track the flow of resources over the products life cycles, measure resource efficiency and assess environmental impacts (Geissdoerfer et al., 2017). The use of adequate indicators can, therefore, provide a quantitative metric to optimise the products resource efficiency and thus select the best circularity criteria for EV batteries (Shevchenko et al., 2022). However, research focused on analysing circularity criteria and indicators for EV batteries design, development and life cycle management (LCM) is yet scarce. For instance, Mossali et al. (2020) presented a House-of-Quality study of 22 criteria to improve the circularity of EV batteries and Picatoste et al. (2022b) presented an analysis of 53 circularity criteria to help EV designers in decision-support. However, these articles were limited in the assessment as only design criteria were analysed and did not propose any metrics to evaluate the successful implementation of the proposed circularity criteria.

Cruz Ugalde and Talens Peiró (2024) analysed the EV battery from a circularity perspective in order to better understand the raw material and supply chain challenges for the sector, and propose solutions based on a circularity score. Nonetheless, the criteria were primarily focused on raw material analysis and there was no discussion on which stakeholders favoured each criterion or an analysis of their connection to relevant circularity indicators. Gebhardt et al. (2022) analysed and proposed a new sustainability framework for EV batteries and proposed environmental, social, governance, and economic sustainability aspects to prioritize. Similarly, Wrålsen et al. (2021) identified barriers and drivers for the adoption lithium-ion batteries through innovative business models. Likewise, the approach was focused on broad, large-scale factors rather than on specific, product related strategies. Moreover, similar to the previous works mentioned, it did not offer an evaluation on how to measure the fulfilment of the prioritised aspects for EV batteries sustainability. On the other hand, Schulz-Möninghoff et al. (2022) analysed circularity indicators for EV batteries but considering a company-level, rather than a product-oriented approach. This company-level focus limits the proposal of circularity design criteria for the EV batteries life cycle.

The scientific literature review shoed very little articles specifically calculating circularity indicators for EV batteries. The Material Circularity Indicator (MCI) (EMF and Granta design, 2015) was calculated by Schulz-Möninghoff et al. (2022) for the analysis of the circularity at company level. Cilleruelo Palomero et al. (2024) used the Circularity Index (CI) (Cullen, 2017) and the Material Circularity Indicator (MCI) for EV batteries as a case study for the circularity module in the OpenLCA software. Finally, Picatoste et al. (2024) calculated the Circularity Index (CI) and the Product Circularity Indicator (Bracquené et al., 2020) to compare the circularity performance of different EV batteries.

Finally, legislative sources such as the regulation for EV batteries (European Commission, 2023b), the battery passport design and content (Battery Pass project, 2023), the regulation regarding EOL of vehicles (European Commission, 2023a) or the Eco-design directive for products (European Commission, 2022) could also be used as a reference for circularity criteria for EVs and EV batteries at product level. However, these regulations did not describe the perspective of the industrial EV sector regarding the optimal criteria for implementation.

Consequently, there are no studies available which address a comprehensive and integrated analysis of circularity criteria and indicators from the perceptions of EV battery designers, manufacturers and end-of-life managers. This indicates a knowledge gap on the most suitable circular design criteria for EV batteries across all the life cycle

stages of the EV batteries. Moreover, the scientific community, industrial stakeholders and policymakers would benefit from also identifying the circularity indicators that would be selected by stakeholders to evaluate the results of the applied circularity criteria.

### 3. Methodology

Fig. 1 represents the methodology applied in the research.

First, circularity criteria and indicators with application to EV batteries were identified and selected for evaluation. Secondly, the scope of the selected criteria and indicators was analysed by considering the life cycle stages and CE strategies they address. Additionally, the synergies and trade-offs between circularity criteria and indicators were explored to understand their potential positive and/or negative influence in decision-support. Finally, industrial and academic stakeholders from the EV battery sector were engaged in various workshops to analyse their perceptions on their importance and viability for implementation in sustainable EV battery design, manufacturing and LCM. Based on the outcomes, the future development and use of integrated circularity criteria and indicators was discussed for EV battery design, development and LCM.

#### 3.1. Selection of circularity criteria and indicators for electric vehicle batteries

Scientific, industrial and legislative literature were analysed to compile circularity design criteria and indicators with application to the EV battery industry.

The first step of the research was to perform a revision of academic, industrial and policy literature. A scientific literature search was performed using the SCOPUS database. The search was performed twice with similar structure, one for criteria and another for indicators. It was structured in four streams: in all cases circular economy related keywords (first stream) were crossed with electric vehicle related keywords (second stream), keywords related to batteries (third stream) and keywords related to design criteria or indicators (fourth stream). The search was temporally restricted to articles from 2010 to 2022, to be in line with the current CE definitions and approaches (European Commission, 2020). The search yielded 71 hits for criteria and 51 hits for indicators, although on a deep screening only four were selected for criteria and none for indicators. In addition to Scopus (SCOPUS, 2024), Web of Science (Clarivate, 2025) and literature-based artificial intelligence tools, such as SciSpace (Typeset, 2025) were used to gather a broader

range of relevant articles. These platforms enabled the search to be expanded and diverse sources to be included. Additionally, other sources were incorporated using a snowballing approach (Suescún-Monsalve et al., 2022) to complement the initial findings. Finally, the search was complemented by the assessment of grey literature and relevant regulations on the topic to gather circularity criteria and indicators applicable to EV batteries. The detailed search process and selected articles, industry reports and legislation are described in S1 of the Supporting Information (SI).

The selection of circularity criteria and indicators for assessment was addressed by considering the following criteria:

- Direct applicability to EV batteries (e.g. discarding non-relevant criteria, such as “consider timeless design or emotional attachment” (CIRCit Norden, 2020b))
- Elimination of similar criteria and indicators by considering the most suitable and updated version (e.g. discarding the Material Circularity Indicator (MCI) (EMF and Granta design, 2015) in favor of the Product Circularity Indicator (PCI) (Bracquené et al., 2020) which is an improved version of the MCI).

By applying the proposed specifications, a total of 30 circularity criteria and 15 indicators were considered in the analysis, as described in Table 1 and Table 2 respectively. For more information on the sources used to extract circularity criteria and indicators, see section S2 of the SI. Once the circularity criteria and indicators were selected, they were classified according to the life cycle stage (PRé Sustainability, 2022) and circular economy strategy (Blomsma et al., 2019) that they had influence on.

#### 3.2. Examination of scope of the selected circularity criteria and indicators

The scope of the circularity criteria and indicators was analysed by considering their coverage of life cycle stages and CE strategies. Additionally, the synergies and trade-offs between criteria and indicators were explored to identify possible limitations and opportunities in using them in EV battery design, manufacturing and LCM.

##### 3.2.1. Coverage of life cycle stages and circular economy strategies by the selected criteria and indicators

The life cycle stages (raw materials, manufacturing, transport, operation and EOL) (PRé Sustainability, 2022) and CE strategies defined

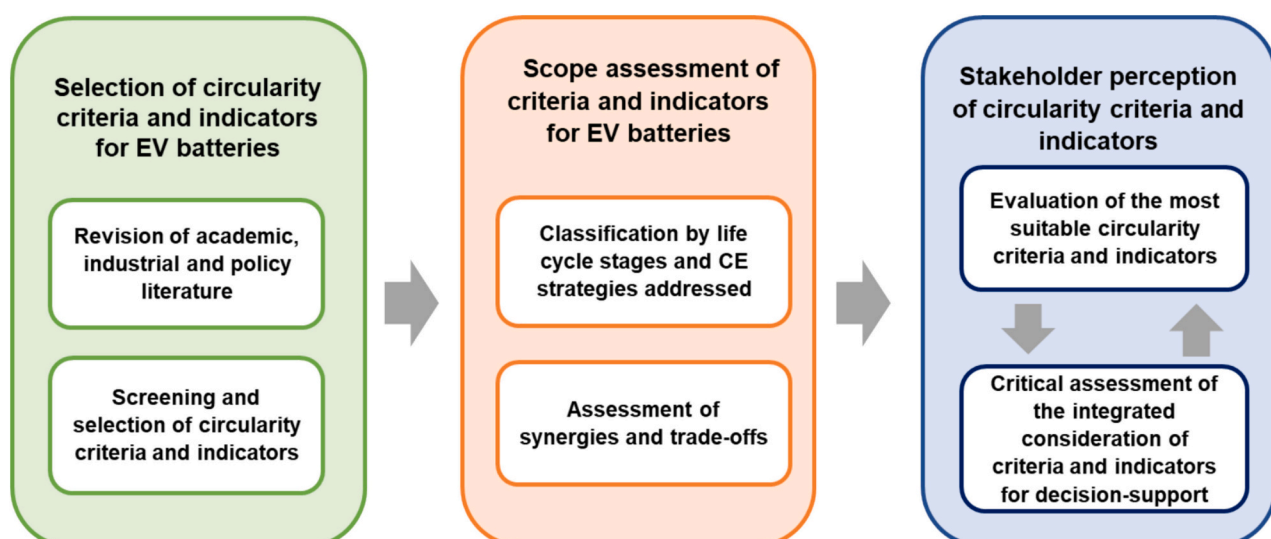


Fig. 1. Research methodology. Acronyms: CE (circular economy), EV (electric vehicle).

**Table 1**  
Circularity criteria coverage of life cycle stages and Circular Economy strategies. Acronyms: EOL (End of Life), SoH (State of Health), IoT (Internet of Things), ICT (Information and Communication Technology).

N°	Criteria	Short explanation	Life cycle stages					Circular Economy strategies									
			Raw material	Manufacturing	Transport	Operation	End of life	Reduce	Upgrade	Repair	Reuse	Refurbish	Remanufacture	Repurpose	Recycle	Cascade	Recover
TOTALS:			8	9	4	13	12	13	14	13	17	16	15	15	14	14	9
1	Avoid glue or adhesives and use joints and connectors that can be easily opened and closed multiple times	Minimize the number of connectors and joints; use fastening systems which can be easily opened and closed multiple times; prioritize latch, snaps, clips and bolts and screws over welding, rivets, folding, staples, gluing which make a joint more difficult to demount		x						x	x	x	x	x		x	
2	Avoid the use of (non-compliant) coatings	Coatings and paints can be used to but also difficult the identification of components and materials. Certain coatings can also polluting the materials for the recycling process.	x				x	x							x	x	x
3	Use durable and robust components and materials. Design for long life.	Choose durable and robust component and material with a long lifespan; the lifespan of the different parts should be recognizable with indicators for wear; Avoid materials that might lose strength, get brittle or get discoloured.	x	x		x					x	x	x		x		
4	Use low impact and/or renewable materials instead of critical and/or hazardous materials.	If there are options of materials with similar characteristics, choose the material that comes from a renewable source (i.e. bio-based plastics) instead of a raw material included in the hazardous materials or critical raw materials list (i.e. cobalt)	x					x							x	x	
5	Use secondary (recycled) materials	Specifically look to maximise the content of recycled materials, focusing on the materials that cannot be substituted. This lowers the stress on the supply chain and improves the circularity of the product	x				x	x							x	x	
6	Minimize the number of incompatible materials to facilitate recycling	Choose materials that have high recycling rate, and available recycling technology and market; increase materials compatibility that only one recycling method needed. Minimize the number of different incompatible materials to facilitate shredding, regeneration and recycling;	x				x							x	x		

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Table 1 (continued)

N°	Criteria	Short explanation	Life cycle stages					Circular Economy strategies									
			Raw material	Manufacturing	Transport	Operation	End of life	Reduce	Upgrade	Repair	Reuse	Refurbish	Remanufacture	Repurpose	Recycle	Cascade	Recover
TOTALS:			8	9	4	13	12	13	14	13	17	16	15	15	14	14	9
7	Consider and anticipate to environmental legislation	avoid moulding and fusing incompatible materials; avoid multi-materials and composites Comply with applicable laws and regulations, such as minimum of recycled material, minimum of recyclable, collection rate use of critical or hazardous material, chemicals that now or later might be banned	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
8	Make products, components and operation tools interchangeable across different models, brands and/or producers. (e.g. standardisation of the charging poles and protocols for different EV batteries)	Batteries can be interchangeable/compatible as products (e.g. different e-vehicles using the same geometry for batteries), components (e.g. same electronic connection for BMS) or require the same tools required (e.g., same type and size of screws for all instead of specific heads for each model)		x		x			x	x	x	x	x	x			
9	Provide accessible electrodes at pack / module level for repair and information gathering	Design easy-access electrodes to evaluate the batteries' condition, for both module and pack level. E.g. having the electrodes visible, under the first protection cover for a direct analysis and detection of the critical state of the battery cells/modules. This can avoid catastrophic failures when the BMS and/or electronics provide mixed information		x		x			x	x	x						
10	Design in modular construction, simplifying product architecture and grouping similar components for easy separation, repairing and dismantling	Divide product into different modules and put all the components that need to be exchanged or upgraded into one single module, thus lowering the effort to selectively dismantle and access specific subcomponents. Easy to open and dismount in a non-destructive way, making disassembly points and components subject to break or fail easily accessible and preferably from one side.		x					x	x	x	x	x	x	x	x	x
11	Make it easy to clean the battery and its components	Avoid areas where dirt might collect like small holes, nooks,				x			x	x	x	x	x	x			

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Table 1 (continued)

N°	Criteria	Short explanation	Life cycle stages					Circular Economy strategies									
			Raw material	Manufacturing	Transport	Operation	End of life	Reduce	Upgrade	Repair	Reuse	Refurbish	Remanufacture	Repurpose	Recycle	Cascade	Recover
	TOTALS:		8	9	4	13	12	13	14	13	17	16	15	15	14	14	9
12	Make spare parts and components easily available in the open market	grooves sharp edges; remember that all components should be wear resistance and withstand the same chemicals and mechanical cleaning processes, liquid and chemicals, as well as temperatures, detergents and cleaning tools Components and subcomponents suitable to be exchanged must be available on the open market to ease repairability, not only by OEM, but also other stakeholders. (e. g. the battery safety switch should be available for specialised shops to re-install if a malfunction occurs)				x			x	x	x	x					
13	Make it easy to identify the materials and components, using eco-labels to ease repair, substitution/upgrade, 2nd life, or recycling processes	Create a system for identification of the individual components by physical marking, barcode, tag or QR-code. Provide additional information about the component/subcomponent regarding material content, the material's age, number of times recycled, additives used.	x	x		x	x		x	x	x	x	x	x	x	x	x
14	Favor cleaner production, processes, machines and equipment	Favor manufacturing processes, machines and equipment which use less energy and materials, generate less wastes and discharges less to air and water; select machines and equipment that require less frequent maintenance and cleaning and are with good working environment and ergonomic.		x													
15	Treat the industrial wastes sustainably	Identify the segment and fraction can those waste be separated to be able to facilitate pre-consumer recycling. Design a production strategy where disposed materials or by-products could be reincorporated to the manufacturing process		x			x	x							x	x	x
16	Design for reduced material (weight and/or volume) and energy consumption	Optimise the use of materials and energy. Renewable materials and energy can	x					x									

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Table 1 (continued)

N°	Criteria	Short explanation	Life cycle stages					Circular Economy strategies									
			Raw material	Manufacturing	Transport	Operation	End of life	Reduce	Upgrade	Repair	Reuse	Refurbish	Remanufacture	Repurpose	Recycle	Cascade	Recover
TOTALS:			8	9	4	13	12	13	14	13	17	16	15	15	14	14	9
17	Push for efficient logistics in all stages of the life cycle	diminish the environmental impacts of a product, however, eliminating the use is the best way to reduce impacts. Identify the adequate mode of transport for all raw materials and manufactured components. Design the packaging of each component as small and stackable possible in order to ease transportation.			x			x									
18	Avoid unnecessary transportation operations	Propose a manufacturing (and collection/repurposing/recycling) structure that minimizes transportation, building in the same facilities as much as possible			x			x									
19	Focus mainly on functionality and quality performance	The product should maximise its performance. For EV batteries, this means: more capacity, shorter charging times, more lifetime, among others.				x		x	x								
20	Consider how the design of the battery enable circular business models for the battery or battery component	Analyse, build and exploit cooperative networks, where design of the battery and/or components can support circular business and strategy. E.g. Evaluate the design needs for a servitisation of the battery as a business model that keeps the ownership for a more efficient collection and control of the lifetime. Another example: a battery producer also acquiring/building a recycling plant and designing the battery optimised for their own recycling process				x		x	x	x	x	x	x	x	x	x	
21	Inform the consumers on their role as users to benefit sustainability	Share with the consumers how their role could impact on the sustainable use of the product. For example, inform users on the most efficient charging and driving protocols for the EV.				x		x	x	x	x	x	x	x			
22	Design and provide technical documentation to accompany the product during all life cycle. It can be a static or dynamic document.	Generate technical documentation to accompany the product during all life cycle, to facilitate life cycle management by separate				x			x	x	x	x	x	x	x	x	x

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Table 1 (continued)

N°	Criteria	Short explanation	Life cycle stages					Circular Economy strategies									
			Raw material	Manufacturing	Transport	Operation	End of life	Reduce	Upgrade	Repair	Reuse	Refurbish	Remanufacture	Repurpose	Recycle	Cascade	Recover
TOTALS:			8	9	4	13	12	13	14	13	17	16	15	15	14	14	9
23	Try to use digitalization, ICT and IoT solutions, available to every stakeholders for the surveillance of the state of the battery and its components, origins of the materials and compliance with regulations (e.g. a digital battery passport)	stakeholders (included consumers), increase the traceability of the actions/ repairs and lifetime changes for the product. Include a complete Bill of materials and a complete of energy of the product and processes. Provide user-friendly manuals and documentation on how to repair, upgrade etc. with signs on how to open the product and exchange components, also an useful guide to component separation and process for the recycling. IoT and digitalization enable collecting data about the usage behaviour and product performance through its lifecycle which help discover latent design errors and understand what components and when are going to fail, so repair and maintenance can be planned with minimum effect on products' performance. Digital location for use phase data, accessible by every stakeholder (including customers) and unique for each battery. With adequate sensorisation, a continuous prognosis of the battery can be performed for increased safety. Combining eco-labelling of components and materials, technical documentation and manuals and advice for consumers in the same digital location would significantly improve the potential circularity of the battery.				x	x	x	x	x	x	x	x				
24	Determine potential battery requirements over its lifetime and design strategies to improve its performance during active use	Think about activity support during the operational stage of the product/service to make the system runs as efficiently as possible e.g., supplying replacement materials, maintenance services, repair				x		x	x	x	x	x	x				

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Table 1 (continued)

N°	Criteria	Short explanation	Life cycle stages					Circular Economy strategies											
			Raw material	Manufacturing	Transport	Operation	End of life	Reduce	Upgrade	Repair	Reuse	Refurbish	Remanufacture	Repurpose	Recycle	Cascade	Recover		
TOTALS:			8	9	4	13	12	13	14	13	17	16	15	15	14	14	9		
25	Provide testing parameters for products next use cycles	and control in post-use scenarios. Think, consider and define the testing procedures for a battery to determine whether it is fit for a second life product					x				x	x	x				x		
26	Develop standardised 2nd life solutions for batteries	Propose standardised 2nd life solutions for the battery to design an adequate end of life procedure directed towards this solution, that are aligned with the current and future legislation regarding the second life of batteries. E.g. the circular economy action plan					x				x	x	x				x		
27	Design a sustainable battery collection strategy	Establish a collection plan to guarantee a high collection rate while ensuring that the cost to the consumer remains equitable compared to alternative methods. Incorporate designs that facilitate easy disassembly from the electric vehicle, transportation, and classification of the battery.					x				x	x	x				x	x	
28	Design the battery, components and materials to support the recycling process in a way that it maximises the quality of the obtained secondary material.	End of life procedures should try to obtain the highest quality materials to reincorporate to the life-cycle of the product. The battery design should identify the needs and implement material, component and technical changes to optimise the recycling processes to recover the purest and “ready-to-use” material, avoiding mixes or types of recovered material to use in a lower quality product.					x								x		x		
29	Design a technical protocol in which the battery modules can be discharged to the minimum state of charge prior to the recycling process (for safety)	Increase the safety of the dismantling and recycling process by discharging the battery to 0 state of charge. The specific process should be defined as the final step previous to the shredding of the modules, and could be done by the BMS or an external electronics process.					x								x		x	x	
30	The transportation and logistics for retired batteries	The transportation and storage of retired batteries, components														x		x	x

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Table 1 (continued)

N°	Criteria	Short explanation	Life cycle stages			Circular Economy strategies											
			Raw material	Manufacturing	Transport	Operation	End of life	Reduce	Upgrade	Repair	Reuse	Refurbish	Remanufacture	Repurpose	Recycle	Cascade	Recover
	TOTALS:		8	9	4	13	12	13	14	13	17	16	15	15	14	14	9
		and materials at the end of the life cycle should be carefully designed due to safety reasons. The battery design should include an electrical and/or mechanical component that guarantees a safe transportation even after critical failure.															

by Blomsma et al. (2019) were considered to evaluate the scope of the circularity criteria and indicators. This was useful, on the one hand, to identify gaps in the definition of criteria and indicators (e.g. narrow approach due to limited coverage of life cycle stages and CE strategies, which could be misleading for sustainability-oriented decision-support). On the other hand, it was useful to support a discussion with the engaged stakeholders (see Section 3.3) to determine their suitability in practice. This classification helped guaranteeing that there were enough circularity criteria to be applied in each life cycle stage, as well as what the circularity indicators were designed to measure. Table 1 and Table 2 provide the list of criteria and indicators, classified by the life cycle stages and CE strategies.

3.2.2. Evaluation of synergies and trade-offs for circularity criteria and indicators

The relationships, either positive (synergies) or negative (trade-offs) among circularity criteria and indicators were evaluated individually to gain deeper insights into their implications. Acknowledging synergies and trade-offs in sustainability initiatives is key, due to the risks of sub-optimal decision-making if conflicts between different criteria and indicators are not managed effectively (Kravchenko et al., 2020b).

The synergy scores aimed at identifying the best criteria and indicators to apply in terms of positive relations between and within each other. First, the synergies of design criteria were analysed to identify those criteria which, when applied, offer the most benefits to other criteria. This approach facilitates the selection of the most impactful criteria for application, considering that would ease the application of other criteria. This analysis was conducted by evaluating each criterion and collecting qualitative feedback from stakeholders. Second, the relation between criteria and indicators was also examined through a two-way analysis. The criteria used by the most indicators were deemed highly important, as their frequent usage indicates widespread consideration for calculation. For indicators, those that encompass most criteria were seen as very comprehensive. This assessment involved examining the variables required to calculate each indicator and comparing them to the list of criteria.

The list of 30 criteria was analysed to identify reinforcing or constraining aspects (Nilsson et al., 2017) caused by the application of one criterion over another. Points were provided to each criterion based on their potential influence, as follows:

- +1: reinforcing (applying one criterion facilitates the application of another),
- 0: no positive or negative relationship,
- -1: constraining (applying one criterion limits the implementation of another),

This allowed to identify the most favourable criteria to be applied in terms of synergies, with some criteria enabling the successful application of other(s). Adding the number of the synergy relations, the criteria with the most positive synergies (for a maximum of 29) would be the one that enables the most of the other criteria. The assessment of these relationships can be consulted in Section S4 of the SI.

The relationship between circularity criteria and indicators was quantitatively explored as well. In this case, it was considered that the indicators' variables for calculation represent the actual link between circularity criteria and indicators. Accordingly, circularity indicators whose variables reflect the set of circularity criteria were considered to be more relevant for a product. The calculation of those indicators would lead to the fulfilment of the circularity criteria or to demonstrate how well that set of criteria is being addressed in practice. Therefore, the variables of the 15 circularity indicators were extracted to link them with the set of criteria, as presented in section S5 of the SI.

In this case, the following scoring system was used to perform the assessment:

Table 2

Circularity criteria coverage of life cycle stages and Circular Economy strategies. Acronyms: CE (circular economy), EOL (end of life).

N°	Name of indicator and reference	Description	Score	Life cycle stages					Circular Economy strategies										Applicability	Data requirements
				Raw material	Manufacturing	Transportation	Use phase	End of life	Reduce	Upgrade	Maintenance	Reuse	Refurbish	Remanufacture	Repurpose	Recycle	Cascade	Recover		
TOTALS:				10	7	1	6	15	8	0	2	8	8	8	8	15	12	13		
1	Product circularity indicator (PCI) (Bracquené et al., 2020)	Takes in account the complete life cycle of a product (including manufacturing efficiencies, longevity, second life and recycling) to provide a single circularity metric.	0 to 1	x	x		x	x	x				x	x	x	x	x	Detailed analysis of the total product circularity	- Total mass of raw material (kg) and fractions of processing losses (%) - Fraction of material losses in manufacturing (%) - Fraction of reused components (%) - Lifetime (e.g. years, cycles) and fraction compared to market standard (%) - Use intensity (e.g. cycles/day) fraction compared to market standard (%)	
2	Longevity and circularity indicators (LCI) (Figge et al., 2018)	(i) The circularity indicator calculates the amount of materials or products kept in the loop through refurbishing and recycling strategies. (ii) The longevity indicator calculates the total lifetime of the materials or products within the production system, including additional time through refurbishing and recycling strategies.	1 to infinite				x	x	x		x		x	x	x		x	Evaluation of resource efficiency, material recirculation and longevity of product system	- Collection rate (%) - Repurposing ratio of collected products (%) - Recycling rate (%) - Lifetime of product (years) - Second life lifetime (Years) - Recycled material lifetime (Years)	
3	Circularity Index (CI) (Cullen, 2017)	Index calculated from two formulas: (i) The ratio of recycled material (ii) The energy cost of the recycling process	0 to 1	x	x				x	x					x		x	Evaluation of resource efficiency and material recirculation	- Raw material quantity (kg) - Energy cost of processing raw material (kWh,J) - Material recovered through recycling (kg) - Energy cost of the recycling process (kWh, J)	
4	Multidimensional Indicator Set (MIS) for WEEE (Nelen et al., 2014)	Set of four indicators: (i) Weight recovery of target material(s) (ii) Recovery of scarce materials	Set of formulas: Numeric result	x				x							x	x	x	Analysis of resource, economic and environmental benefits of	- Mass of each materials of the product (kg) - Mass of each material after	

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Table 2 (continued)

N°	Name of indicator and reference	Description	Score	Life cycle stages					Circular Economy strategies								Applicability	Data requirements		
				Raw material	Manufacturing	Transportation	Use phase	End of life	Reduce	Upgrade	Maintenance	Reuse	Refurbish	Remanufacture	Repurpose	Recycle			Cascade	Recover
TOTALS:				10	7	1	6	15	8	0	2	8	8	8	8	15	12	13		
		(iii) Closure of material cycles (iv) Avoided environmental burdens																	recycling a product	recycling (kg) - Economic importance and supply risk of each material (from the critical raw materials list of the EU) - Market price of raw materials (€) - Market price of recycled materials (€) - Environmental burden associated to raw material production (from LCA) - Environmental burden saved by using recycled material (from LCA)
5	EoL indices (EoLi) (Favi et al., 2016)	Four EoL indices that compare different waste management scenarios for product components: (i) Reuse (ii) Remanufacture (iii) Recycle (iv) Incineration	Set of formulas: Numeric result	x	x	x	x					x	x	x	x	x	x	x	Consideration of all many CE alternatives at the end-of-life of products of a product	- Raw material mass (kg) - Raw material processing energy (MJ/kg) - Raw material economic costs (€/kg) - Energy economic cost (€/MJ) - Cost of manufacturing the product (€) - Cost of transport phase (€) - Value of repurposed product (€) - Cost of disassembly and cleaning of the product (€) - Recycling efficiency (%) - Recycling energy consumption (MJ/kg) - Recycled material cost (€/kg) - Recovered energy from incineration (MJ/kg)

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Table 2 (continued)

N°	Name of indicator and reference	Description	Score	Life cycle stages					Circular Economy strategies									Applicability	Data requirements	
				Raw material	Manufacturing	Transportation	Use phase	End of life	Reduce	Upgrade	Maintenance	Reuse	Refurbish	Remanufacture	Repurpose	Recycle	Cascade			Recover
TOTALS:				10	7	1	6	15	8	0	2	8	8	8	8	15	12	13		
6	Circular economy index (CEI) (Di Maio and Rem, 2015)	Ratio of the material value produced by the recycler (market value) versus the value of new raw materials	Ratio of economic value: 0 to 1	x				x							x	x	x	Examination of economic value recovered at the end-of-life of the product	- Economic cost of producing the raw materials for a new product (€) - Economic value of recycled material (€)	
7	Product-Level Circularity Metric (PCM) (Linder et al., 2017)	Evaluates the economic benefits of CE strategies (reuse, refurbish, repurpose and recycle), comparing the value of the resulting product to the value of the original product.	0 to 1: ratio		x			x				x	x	x	x	x	x	Analysis of economical benefits of circular economy strategies for products	- New product value (raw materials, manufacturing and transport) (€) - Ratio of reused/refurbished/repurposed products (%) - Value of reused/refurbished/repurposed products (€) - Ratio of recycled material (%) - Value of recycled material (€)	
8	Global Resource Indicator (GRI) (Adibi et al., 2017)	A resource depletion indicator that evaluates three main material aspects: (i) Recyclability (ii) Scarcity (iii) Geopolitical availability	Single formula score	x				x	x						x		x	Identification of material substitutions alternatives based on availability, recyclability and supply chain	- Recycling rates (%) - Scarcity (CML method, used in LCA) - Geopolitical availability (Worldwide governance indicators for political stability, n° of exporting countries)	
9	Reuse Potential Indicator (RPI) (Park and Chertow, 2014)	Indicates how much a material is “resource-like” rather than “waste-like” according to the current available technologies. It quantifies technical reusability.	0 to 1				x	x				x	x	x	x	x	x	Analysis of successive use cycles for products and materials, based on the availability (technical and economical) of end-of-life processes	- Bill of materials (kg) - Reuse/recycle process efficiency (%) - Cost of reuse/recycle process (€)	
10	Resource Efficiency Assessment of Products (REAPro) (Ardente and Mathieux, 2014)	Series of indexes to provide information on resource efficiency. - Mass of raw materials (kg), recycled content (%), different component number and hazardous substances - Ratio and environmental impact savings of reused/	Set of formulas: Numeric result	x	x		x	x	x			x	x	x	x	x	x	Detailed assessment (with LCA data support) of the environmental impacts associated to the end of life of products	- Mass of raw materials (kg) - Recycled content (%) - Number of different components of the product (unit) - Ratio of reused/refurbished/repurposed components (%)	

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Table 2 (continued)

N°	Name of indicator and reference	Description	Score	Life cycle stages					Circular Economy strategies										Applicability	Data requirements	
				Raw material	Manufacturing	Transportation	Use phase	End of life	Reduce	Upgrade	Maintenance	Reuse	Refurbish	Remanufacture	Repurpose	Recycle	Cascade	Recover			
TOTALS:				10	7	1	6	15	8	0	2	8	8	8	8	15	12	13			
		refurbished/ repurposed components and material recycling (%)																		- Recycling ratio (%) - Environmental impact savings (LCA) of the reuse/recycle process compared to virgin production - Identification of hazardous substances (through legislation) - Collection rate (%) - Recycling rate (%) - Closed loop recycling rate (%) - Open loop recycling rate (%)	
11	Recycling rates (RR) (Haupt et al., 2017)	Indicators to determine the circulating behaviour of materials based on their recyclability. Analysing collection and recycling rates (open and closed loop recycling)	Set of formulas: Numeric result					x												Comprehensive examination of the recycling process and rates of open vs closed loop material recovery	- Technical data: Materials (kg), design structure, second life ratio (%) and recycling ratio (%) - Organizational (qualitative): Businesses practices, market analysis, facilities characteristics and economic/ legislative conditions
12	Circular Product Index (CPI) (Saidani et al., 2019)	Through a guided questionnaire, it aims at evaluating the circularity potential of industrial products (durable design, re-design or benchmarking phases) as well as providing recommendations for improvement.	0 to 100	x	x		x	x	x		x	x	x	x	x	x	x			Semi-quantitative assessment of the circularity of the product and the product value chain	- Raw material (kg) - Reuse, refurbish, repurpose ratio (%) - Lifetime (years) - Additional lifetime through reuse, refurbish, repurpose (years) - Recycling rate (%) - Functionality: comparison of use phase for reused, refurbished, repurposed components or recycled material. (e.g. closed loop
13	Net losses of metals (NLM) (Ljunggren Söderman and André, 2019)	Comparing end of life management options centred in complex products with many different metals. Raw material (kg), recycle. Rate (%) Reuse, refurbish, repurpose rate (%) - Original lifetime (years), additional lifetime through reuse, refurbish, repurpose (years) and functionality during the lifetime (use intensity)	Set of formulas: Numeric result				x	x				x	x	x	x	x	x			Identification of the hotspots for material losses at the EOL (repurposing, recycling process efficiency)	- Raw material (kg) - Reuse, refurbish, repurpose ratio (%) - Lifetime (years) - Additional lifetime through reuse, refurbish, repurpose (years) - Recycling rate (%) - Functionality: comparison of use phase for reused, refurbished, repurposed components or recycled material. (e.g. closed loop

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Table 2 (continued)

N°	Name of indicator and reference	Description	Score	Life cycle stages					Circular Economy strategies									Applicability	Data requirements			
				Raw material	Manufacturing	Transportation	Use phase	End of life	Reduce	Upgrade	Maintenance	Reuse	Refurbish	Remanufacture	Repurpose	Recycle	Cascade			Recover		
TOTALS:				10	7	1	6	15	8	0	2	8	8	8	8	15	12	13				
14	Circular Footprint Formula (GFF) (European Commission, 2018)	Useful to model waste management scenarios by considering recycled content, material recycling, energy recovery and disposal.	Set or formulas: Numeric result	x	x			x	x									x	x	x	Detailed assessment (with LCA data support) of the environmental impacts associated to the end of life management of products	<ul style="list-style-type: none"> <li>- Ratios (%) of virgin, recycled and recyclable material in the product</li> <li>- Ratio (%) of material derived to recycle, energy recovery and disposal at EOL</li> <li>- Functionality: comparison of use phase for recycled material. (e.g. closed loop or open loop recycling)</li> <li>- Environmental impacts (LCA) of virgin material processing</li> <li>- Environmental impacts (LCA) of recycling process</li> <li>- Environmental impacts (LCA) of energy recovery process and substituted energy source</li> <li>- Environmental impacts (LCA) of the disposal of material to landfill</li> </ul>
15	Circular Economy Performance Indicator (CEPI) (Huysman et al., 2017)	The ratio of the actual obtained environmental benefit (i.e. of the currently applied waste treatment option) over the ideal environmental benefit according to technical quality.	Single formula: Numeric result	x				x	x									x	x	x	Compare the current waste management choices to the best possible options, based on environmental impacts	<ul style="list-style-type: none"> <li>- Qualitative knowledge regarding the waste management options for the product</li> <li>- Recycling efficiencies (%) of the considered waste management options</li> <li>- Environmental impacts (LCA) of raw material sourcing</li> <li>- Environmental impacts (LCA) of the considered waste management options</li> </ul>

- +1: the circularity criterion is considered within the indicator as a variable and, if applied, would improve circularity performance
- 0: no relationship between the circularity criteria and the indicators variables

For example, to calculate the Circularity Index (Cullen, 2017), one of the required variables is the recycled content of a product. Thus, the criterion “Use secondary (recycled) materials” would score “+1” for both the criterion and the indicator, as the criterion and the variable are the same in practice.

Notably, the synergy between circularity criteria and indicators had two aspects. The total scores would be different for the criteria synergies with indicators and for indicators which have synergies with criteria. For criteria, the more indicators considering a criterion (for a maximum of 15) the more important, as applying the criteria would improve more indicators. For indicators, the more criteria an indicator included (maximum of 30) the more complete, as it would consider more aspects of circularity for its calculation. In this way, each criterion could have up to 29 positive relationships with other criteria, be assessed by up to 15 indicators, and each indicator could incorporate up to 30 criteria. The assessment of the relationship between criteria and indicators can be found in section S6 of the SI.

The scoring approach was kept simple due to the broad and qualitative nature of the criteria and indicators. This single point provided helped indicate their relationship, without including quantitative factors which were difficult to grasp for the complete life cycle of EV batteries. These assigned scores were subsequently revisited during stakeholder interviews for validation (section 3.3), ensuring a more robust final assessment.

### 3.3. Analysis of the electric vehicle battery stakeholders' perceptions on the application of circularity criteria and indicators

According to the literature, there is limited knowledge available on how to incorporate circularity criteria and indicators into product design and LCM processes (Shahbazi and Jönbrink, 2020). Thus, this research activity comprised the evaluation of the suitability of the circularity criteria and indicators for implementation by the EV battery stakeholders based on their perceptions, which allowed to define best practices and future research and industrial requirements for circular and sustainable EV battery innovation and LCM.

The product circularity assessment tool developed by CIRCit Norden (2020a) was used as baseline to build an evaluation matrix for the analysis of the circularity criteria and indicators by the industrial stakeholders. As this tool focus only on the evaluation of general product circularity criteria, the tool was adapted to incorporate both the gathered circularity criteria and indicators with application to EV battery design, manufacturing and LCM.

#### 3.3.1. Circularity criteria and indicators evaluation process

The 30 circularity criteria and 15 indicators were evaluated based on:

- Importance: referring to the relevance of the criterion/indicator to develop circularity innovations by EV battery stakeholders, using a geometrical scale of 0 (not important), 1 (low importance), 3 (moderately important), and 9 (high importance).
- Viability: understood as the techno-economic capacity for the implementation of the criterion or the calculation of the indicator, using an arithmetic scale from 0 (not viable) to 5 (highly viable).

Accordingly, the product of these two evaluation categories was defined as the suitability of the circularity criterion or the circularity indicator for practical use by the industry ( $Suitability = Importance \cdot Viability$ ). This equation and the Importance and Viability categories

were based on the CIRCit Circularity Assessment Tool (CIRCit Norden, 2020a). However, the CIRCit Tool was built to compare different design concepts and their circularity performance level based on circularity criteria, while the goal of this research was to evaluate the perceptions of EV battery experts regarding both circularity criteria and indicators for decision-support. Therefore, the scoring system of the CIRCit assessment tool was adapted by using a viability scale from 0 to 5, based on the eco-design implementation assessment guidelines defined by Rodrigues et al. (2017). Secondly, the “importance” category was evaluated through a 0,1,3,9 scale based on multicriteria decision making methods (Azzabi et al., 2020). This way, the most important criteria and indicators were highlighted. The suitability score was given as the product of the scores given by industrial stakeholders to the questions: “How important do you consider this criterion/indicator for the sustainability of EV batteries (0-1-3-9 scale)?” and “How viable (techno-economically) do you consider the application of this criterion/indicator to EV batteries (0-5 scale)?”. The capacity of stakeholders to measure the required data for the indicator is embedded within the viability score to ensure a comprehensive assessment. This score captures stakeholders' capacity to gather the necessary data and their ability to use these data points to calculate the indicators.

By integrating both data collection feasibility and calculation complexity, the viability score provides a complete representation of practical applicability. Then, the suitability score for each circularity criterion and indicator is presented as a percentage of the maximum achievable score. For example, a criterion or indicator that scored high (9) in importance and medium (3) in the viable for use in practice, it would result in a score of 60 % suitability (21 points out of 45 total points), while another one with moderate importance (3) and high viability (5) would score 33 % in suitability (15 points out of 45). This way highly suitable criteria and indicators could be prioritised.

#### 3.3.2. Engagement of industrial and academic stakeholders

A total of 24 industrial and academic stakeholders were contacted to complete the circularity criteria and indicators evaluation matrices. With regard to industry stakeholders, 19 respondents (79 %) are participants from the LIBERTY project (LIBERTY project, 2022), and they represent a suitable sample of European manufacturers of EV batteries and components. These industrial stakeholders ranged from product engineers to managers, with global presence in most of the cases. The sample of stakeholders consulted was expanded by incorporating 5 additional experts from both academic and industrial backgrounds for more insight on battery materials and chemistries, battery performance and EOL management, as described in Table 3.

The contacted stakeholders were engineers or profiles with similar technical expertise on their field, with most of the field having over 10 years of experience. Stakeholders were contacted via e-mail and, upon agreement, the matrices for the evaluation of the circularity criteria and indicators were sent, including instructions to perform the evaluation. These matrices are shown in detail in section S3 of the SI. Once the evaluation matrices were completed, an e-meeting (90') was developed

**Table 3**

Number, expertise and experience of the stakeholders engaged in the research.

Stakeholder groups and years of expertise	<10 years	10–20 years	>20 years	Total
Battery cell chemistry, materials and manufacturing	1	2	1	4 (17 %)
Battery mechanical components	–	5	1	6 (25 %)
Battery electric components	1	4	1	6 (25 %)
Battery management system/ electric performance	–	4	–	4 (17 %)
Regulation expert	1	–	–	1 (4 %)
Battery recycling and EOL management	–	2	1	3 (13 %)
TOTAL respondents	4	17	3	24 (100 %)

with the stakeholders, where details on the criteria and indicators evaluation as well as general questions were discussed for an accurate assessment. Finally, a physical workshop (120') was held with 16 of the stakeholders from the LIBERTY project to present the results and exchange opinions regarding the practical use of circularity criteria and indicators for the sustainable development and LCA of EV batteries.

Regarding the size of the interviewed population, Lewis (1994) and Aguayo (2024) highlighted that 5 participants are enough to identify 80 % of the usability problems for a product, tool or process. Nevertheless, small sample sizes may increase the variability and limit the applicability of the results (Cazañas, and S., and Parra, E., 2017), which could be seen a limitation of this paper. Nonetheless, Apraiz et al. (2021) showed that with 10 participants, 80 % of the expert population is reached, and with 20 participants of qualitative testing almost 95 % of the issues related to the evaluated parameters are covered. Therefore, the 24 interviews conducted in this study can be considered sufficient to derive generalisable conclusions for EV batteries. Nevertheless, a larger sample size could further enhance the robustness and reliability of the findings.

The 24 stakeholders provided comprehensive insights into the EV battery sector, as they were selected for their expertise across different stages of the battery life cycle, ensuring a well-rounded and in-depth understanding of the industry's perceptions. Still, the sample size of the study could be increased for future research, as discussed in Section 4.4. The research findings were examined in an integrated manner to construct a comprehensive inventory and characterization of circularity criteria and indicators for EV batteries. This analysis was complemented by a discussion on decision-making support for industrial stakeholders, policymakers, and researchers of EV battery sector.

This research combined desktop and action research methodologies to analyse circularity criteria and indicators for EV batteries and gather stakeholder perceptions on their suitability. Desktop research involved a review of academic literature, policy documents, and industry reports to collect and classify relevant criteria and indicators. Concurrently, an action research approach was used to engage stakeholders through consultations and interviews, ensuring their insights informed the analysis. 24 stakeholders with different expertise on the EV battery sector provided a comprehensive perspective on the feasibility and prioritisation of the proposed criteria and indicators. The findings from both phases were integrated to identify alignment and discrepancies, forming the basis for the final discussion and conclusions. Consequently, these results could be used as a reference and guidance for battery professionals and stakeholders interested in establishing sustainable EV battery production and management systems, offering insights into both what circularity criteria and indicators to prioritize and the best use in practice for each of them. Comparable methodologies were employed by Mossali et al. (2020), who listed criteria and examined their synergies, and by CIRCit Norden (2020a), which evaluated criteria in two categories to enhance circularity.

Consequently, these results could be used as a reference and guidance for battery professionals and stakeholders interested in establishing sustainable EV battery production and management systems, offering insights into both what circularity criteria and indicators to prioritize and the best use in practice for each of them.

## 4. Results and discussion

First, a comprehensive analysis of the scope, synergies and trade-offs of the circularity criteria and indicators is presented. Secondly, the perceptions of the stakeholders for their practical use in the industry is evaluated. Finally, the results are discussed from an integrated perspective to identify best practices for industrial innovation and research.

### 4.1. Scope assessment of circularity criteria and indicators for electric vehicle batteries

#### 4.1.1. Classification by life cycle stages and circular economy strategies

Fig. 2 shows the major life cycle stages and CE strategies addressed by the sample of circularity criteria and indicator evaluated (section 3.2.1). For more detail on the circularity criteria and indicator coverage see Table 1, Table 2 and Section S3 of the SI.

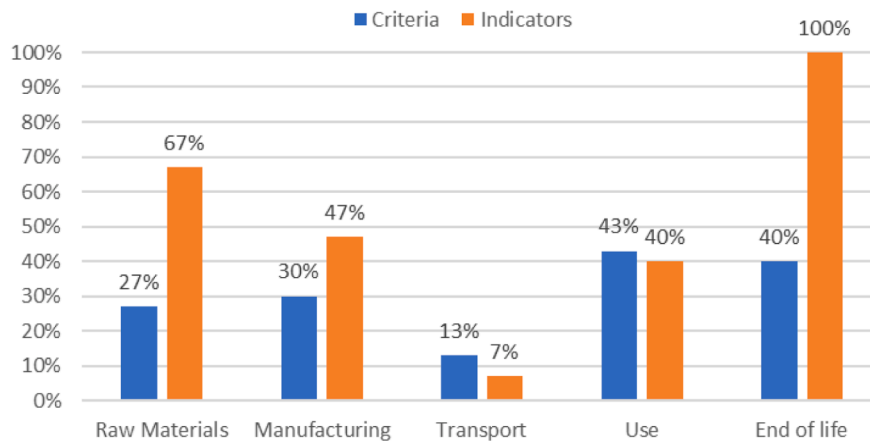
When analysing the life cycle stages covered by the circularity criteria, Fig. 2 showed that the use phase of EV batteries was the most emphasized, being covered by 43 % of the selected criteria. Battery manufacturing and raw material selection followed, with 30 % and 27 % of the criteria addressing these stages, respectively. For indicators however, they mostly focus on the EOL stage (100 %), followed by the raw material (67 %) and the manufacturing (47 %) stages. Regarding the CE strategies, the circularity criteria were evenly distributed in terms of the strategies addressed (between 30 % and 57 %), while the indicators showed a predominance of the recycling strategy (100 %), in line with the EOL focus shown previously. All the circularity indicators consider recycling process as part of their calculations. However, none of the 15 indicators considered all the life cycle stages nor all the CE strategies for EV batteries. Therefore, the applied actions to improve the circularity of EV batteries might not be adequately measured by the current circularity indicators available in the literature. Thus, their effects during the battery lifetime could be incorrectly analysed, not being able to assess the positive (or negative) impacts on circularity of the innovative approach for the EV battery. For example, a technological improvement of the lifetime of the battery would not be considered by the Circularity Index (CI) (Cullen, 2017). The added longevity would improve the circularity and environmental performance of the battery but the CI, being focused on the raw materials and recycling, would not provide a way to include it in its calculations.

#### 4.1.2. Assessment of synergies and trade-offs

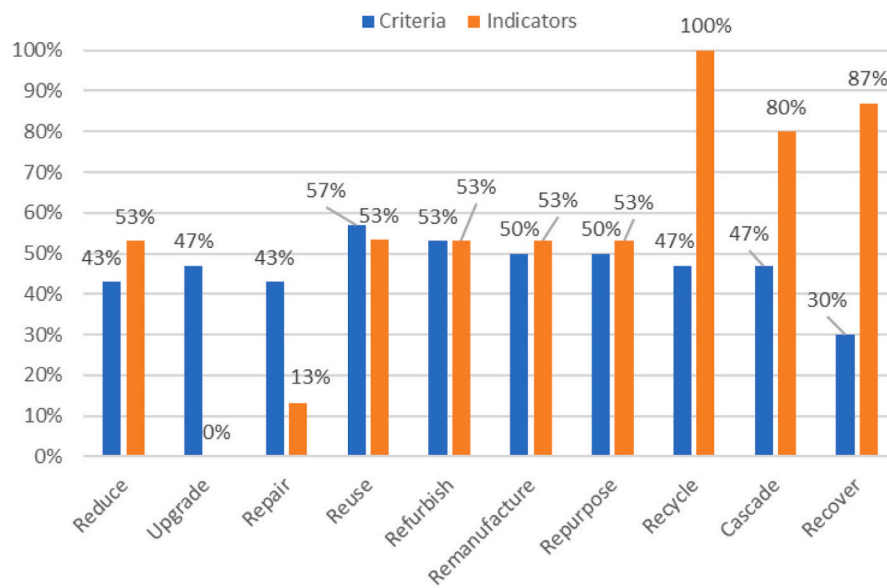
The criteria and indicators with the most synergies (positive relationships) are shown in Table 4. These relationships were calculated according to the scores presented in section 3.2. This table presents the top four criteria and indicators based on the relations between them. First, the criteria that makes easy to implement some of the other 29 criteria. Second, the criteria that is included in most of the 15 indicators' calculations. Third, the indicators that include the most of the 30 criteria in their calculations. For example, "designing the battery to maximise the recycling" eases the application of "minimize the number of incompatible materials to facilitate recycling" by considering the disassembly and recycling processes at the early stages of the battery design. Similarly, 10 other criteria could be benefited by the application of this criterion. Regarding the indicator calculations, 14 out of the 15 circularity indicators include a variable that is improved by maximizing the recycling of the materials and components, for example the rate of material recovery in PCI. For indicators, the CPI includes variables related to 23 of the selected criteria in their calculation, which makes it the most complete indicators.

The criteria that facilitated the most the application of other criteria were the quality of recycling, as well as not-so-technical criteria as the legislation, the analysis of circular business models or the interchangeability of tools and components of the battery. Criteria that enable circularity through regulation or management (Milios, 2018) show the most positive relationships with other criteria. Looking at the positive synergies with circularity indicators, the criteria that are most oriented to battery recycling were the ones scoring the highest. Circularity indicators consider multiple aspects of EOL stage and "recycling" CE strategy of the battery, enabling the application and calculation of recycling-oriented criteria (see section 4.1.1).

When considering the indicators with better synergies, it is important to note that the more complex indicators had an advantage. It was easier to build synergies as they considered a greater number of variables. The



(a)



(b)

**Fig. 2.** Scope of circularity criteria and indicators according to the life cycle stages and CE strategies addressed. (a) Percentage of criteria and indicator covering each of the life cycle stages of the battery. (b) Percentage of criteria and indicator covering each of the CE strategies for the battery.

Circular Product Index (CPI) (Saidani et al., 2019) includes the highest number of design criteria for its calculation (23 out of 30 criteria). This is caused by the high number of variables and relatively qualitative nature of the indicator. The CPI includes qualitative criteria such as “Consider how the design of the battery enable circular business models for the battery or battery components”, while other indicators such as the Product Circularity Indicator (PCI) (Bracquené et al., 2020) only consider quantitative data, such as the recycling rate or the amount of virgin material in their calculations, related to 11 out of 30 criteria. The complete analysis of the criteria and indicators synergies and trade-offs is shown in Sections S4, S5 and S6 of the SI.

#### 4.2. Stakeholder perceptions of circularity criteria and indicators

The suitability scores provided by the EV battery stakeholders for the circularity criteria and indicators are shown in Table 5 for the top 4

criteria and indicators, according to the responses by each expertise group (Table 3). Stakeholders assessed all criteria and indicators based on their expertise, providing scores to “Importance” and “Viability” (see Section 3). The suitability score is the product of these two categories. Although each expertise group provided different scores to the criteria and indicators, the average suitability was used to select the criteria and indicators that were best considered across all the evaluations, aiming for a holistic view of the EV battery life cycle. For the complete evaluation of all the criteria and indicators, see Sections S7 and S8 of the SI.

##### 4.2.1. Suitability of circularity criteria

Stakeholders favoured circularity criteria that could be applied in a wide range of battery components and life cycle stages. The criteria of “Focus mainly on functionality and quality performance” (88 %) was considered the most suitable. EV users place significant emphasis on specific requirements of the operation stage like driving range, charging

**Table 4**  
Top 4 highest scoring criteria and indicators in terms of their positive effects and/or influence in the implementation of other criteria and measurements.

Cross-assessment	Description	Priority criteria and indicators based on their effect in other criteria and indicators	Synergy Score
Criteria vs. Criteria	Criteria that, if applied, facilitates the implementation of other criteria	Consider and anticipate to environmental legislation	15/29
		Design the battery, components and materials to support the recycling process in a way that it maximises the quality of the obtained secondary material.	11/29
		Make products, components and operation tools interchangeable across different models, brands and/or producers. (e.g. standardisation of the charging poles and protocols for different EV batteries)	9/29
		Consider how the design of the battery enable circular business models for the battery or battery component	9/29
Criteria vs. Indicator	Criteria that, if applied, facilitates the calculation of indicators	Design the battery, components and materials to support the recycling process in a way that it maximises the quality of the obtained secondary material.	14/15
		Minimize the number of incompatible materials to facilitate recycling	14/15
		Design a sustainable battery collection strategy	8/15
		Use secondary (recycled) materials	6/15
Indicator vs. Criteria	Indicators that include most circularity criteria within their variables	Circular Product Index (CPI) (Saidani et al., 2019)	23/30
		Product circularity index (PCI) (Bracquené et al., 2020)	11/30
		EoL indices (EoLi) (Favi et al., 2016)	10/30
		Longevity and circularity indicators (LCI) (Figge et al., 2018)	6/30

time, and driving performance (Neaimeh et al., 2017), thus being a priority for designers and manufacturers. However, improving these aspects (related in part with the energy density of the batteries) is currently linked with the use of critical raw materials, including cobalt (Chu et al., 2022). When applying this criterion, the added impacts and the restrictions on the selected raw materials (European Commission, 2023c) must be taken into account to avoid environmental burden shifting (Mendoza et al., 2017).

The “digitalisation” criterion (70 % suitability) refers to the capacity of the information and communication technologies to support data gathering, treatment and sharing on key parameters of the EV batteries (Berger et al., 2023). For an adequate implementation of such technologies, sensors track key metrics like temperature, state of charge, and state of health (SoH), enabling diagnostics, predictive maintenance, and lifecycle monitoring. Cloud-based systems facilitate data sharing among stakeholders and could be standardised under the digital battery passports projects (Berger et al., 2023). However, implementing data-driven systems can be resource-intensive, requiring robust data pipelines, high-

performance computing, and sophisticated modelling tools (Utama et al., 2023). Moreover, establishing common protocols and standards across multiple stakeholders in the supply chain is a complex task, often hindered by fragmentation and varying technological capabilities (Barman et al., 2024).

The circularity criteria focused on the data sharing and surveillance was considered key for most of the expertise groups, although the mechanical component manufacturers did not value the criteria highly (36 % suitability) due to the lack of connection to the materials or manufacturing stages of the life cycle of their component. For instance, one mechanical component stakeholder highlighted that “*The lifetime operation data and SoH estimations are not interesting for our component, and it does not include many valuable materials so a battery passport will not affect as much*”. The SoH of battery and performance would not affect a mechanical component (e.g. the battery housing). Still, other expert groups provided high suitability scores (see Table 5), indicating how monitoring the SoH of the battery cells, electric components or performance aspects could improve both the environmental sustainability and costs of the EV battery life cycle (Pradhan and Chakraborty, 2022). However, the position of the sensors needed must be carefully assessed for an adequate disassembly (Wegener et al., 2014), at risk of not being able to do it properly.

Naturally, the criterion “*Consider and anticipate to environmental legislation*” (69 % suitability), it was considered important by all the stakeholders. The legislation on EVs and batteries defines many characteristics EV batteries must adhere to, such as the regulation on batteries and waste batteries (European Commission, 2023b), the Directive of End of Life of Vehicles (European Commission, 2023a), or the Critical Raw Material Act (European Commission, 2023c). Non-compliant batteries, materials, or manufacturing techniques could face potential bans, particularly in the EU (European Commission, 2023b). Therefore, linking the design criteria with CE indicators is a natural step to take in this direction, as the regulations affect every stage of the life cycle of the EV battery. When discussing this criterion, a battery material and chemistry expert commented that “*legislation and regulations are a way to increase the viability of a technology, especially for complex products as EV batteries*”.

The criterion “*Favor cleaner production processes, machines and equipment*” (68 % suitability), could be applied to improve the battery manufacturing process by incorporating closed-loop recycled materials or utilizing greener energy and/or more efficient energy processes. These could have a significant positive impact on the overall environmental performance of EVs, saving up to 25 % of CO<sub>2</sub> emissions (Qiao et al., 2017). For instance, the use of higher energy-density batteries has the potential to reduce manufacturing impacts up to 15 % (Hall and Lutsey, 2018), due to the reduction of total mass of materials used. Additionally, higher energy densities would increase the autonomy of the EV (H. Liu et al., 2023), thus enabling the “quality of performance” criterion. Nonetheless, industrial stakeholders highlighted the lack of standardisation and consistent research on the topic (Y. Liu et al., 2021). In this sense, a battery materials expert indicated that “*Until the material technologies and manufacturing processes are completely developed, we cannot afford (not the time not the cost) to push for a new chemistry or process*”.

Considering the complete list of criteria (Table S7 of the SI), one of the best scoring criterion was “*Consider how the design of the battery enable circular business models for the battery or battery component*” (78 % suitability). Nevertheless, only 3 out of the 24 stakeholders evaluated this particular criterion, whereas it was not the area of expertise of other EV battery participants. One of the mechanical components manufacturers stated: “*This depends on the business model of the battery owner, the component manufacturers have currently no vision on what the ownership model is*”. Therefore, the criterion was not discussed in this section as the responses from the stakeholders were considered not representative enough.

Regarding the less suitable design criteria, many of them are related to the raw materials stage of the battery. Specifically, “*Use secondary*

**Table 5**

Most suitable design criteria and indicators, classified according to the expertise group of consulted stakeholders (Table 3). Acronyms: EOL (end of life), ICT (information and communication technologies), IoT (internet of things).

Circular design criteria	Average suitability	Cell chemistry and materials	Mechanical component	Electric component	Lifetime performance	Regulation expert	EOL management
Focus mainly on functionality and quality performance	88 %	70 %	87 %	97 %	100 %	0 %	80 %
Try to use digitalisation, ICT and IoT solutions, available to every stakeholders for the surveillance of the state of the battery and its components, origins of the materials and compliance with regulations (e.g. a digital battery passport)	70 %	90 %	36 %	87 %	85 %	60 %	47 %
Consider and anticipate to environmental legislation	69 %	67 %	90 %	53 %	70 %	40 %	73 %
Favor cleaner production, processes, machines and equipment	68 %	57 %	72 %	39 %	90 %	60 %	80 %

Circularity Indicators	Average suitability	Cell chemistry and materials	Mechanical component	Electric component	Lifetime performance	Regulation expert	EOL management
Product circularity indicator (PCI)	30 %	13 %	38 %	40 %	20 %	40 %	0 %
EoL indices (EoLi)	30 %	40 %	27 %	22 %	50 %	40 %	7 %
Circularity Index (CI)	29 %	60 %	24 %	18 %	50 %	4 %	33 %
Recycling rates (RR)	26 %	4 %	9 %	16 %	50 %	13 %	100 %

(recycled) materials” (19 % suitability) has been considered not viable by most of the stakeholders. “At the moment there are no guarantees that the secondary materials are of enough quality to be included in critical components” (Battery cell chemistry, materials and manufacturing expert). Another criteria, such as “Minimize the number of incompatible materials to facilitate recycling” (39 %) or “Avoid the use of (non-compliant) coatings” (34 %) are also considered less suitable due to “the materials and compositions are pre-defined most of the times, there is not much room for choice.” (Battery electric component manufacturing expert). Surprisingly, even recycling and EOL management experts consider the material choice a challenge, declaring that “The recycling processes are not standardised yet so the selected material might be compatible or not, depending on the specialised recycler”. The EOL experts have a comprehensive understanding of their processes from a material perspective and are highly aware of the requirements for efficient recycling. However, EOL experts showed concern on the upstream implementation of these requirements. Specifically, they lack confidence that their material-related needs will be consistently considered during the design phase or that battery components will be standardised in the near future. From their perspective, without upstream alignment criteria on recycling technology may have limited beneficial impact. This underscores a critical barrier to circular design implementation, emphasizing the need for improved integration and collaboration across the value chain to ensure that material choices in battery design align with downstream recycling capabilities.

#### 4.2.2. Suitability of circularity indicators

After the stakeholder evaluation, only four circularity indicators out of 15 were considered to have a higher than 25 % suitability for use. Table S8 of the SI shows the most suitable indicators per expertise group highlighted for a more disaggregated analysis.

Indicators Product Circularity Indicator (PCI) (Bracquené et al., 2020) and EOL indices (EoLi) (Favi et al., 2016) were considered the best indicators, with 30 % suitability each. These indicators scored high in importance (62 % and 56 %) by all the expert groups, although the viability scores were lower due to the amount of data required for calculation. The more life cycle stages and CE strategies considered, the better evaluation score provided by the stakeholders. A battery management expert declared that “The indicators analysing the complete life cycle of the EV battery are surely more interesting to calculate, thus avoiding partial assessments”. The main difference between these indicators is that the PCI requires detailed data on manufacturing and EOL but it is highly

focused on material efficiency. Contrarily, EoL indices include energy consumption requirements, economic costs and economic values for the recovered materials through second life use or recycling.

Surprisingly, the other two indicators considered, the Circularity Index (CI) (Cullen, 2017) and Recycling Rates (RR) (Haupt et al., 2017), suitable for use by the stakeholders showed opposite characteristics. Where the Product Circularity Indicator (PCI) (Bracquené et al., 2020) and EoL indices (EoLi) (Favi et al., 2016) were complex to calculate but quite complete indicators, the Circularity Index (CI) (Cullen, 2017) and Recycling Rates (RR) (Haupt et al., 2017) were simpler to calculate with a limited scope. They scored 29 % and 26 % suitability, respectively due to their high viability score (44 % and 38 %), which meant that the stakeholders considered data gathering and calculation to be manageable. These indicators were highly appreciated by the battery recycling and EOL management expert group, especially in comparison to the rest of the 15 indicators. As one of the EOL expert stakeholders expressed: “These are the only numbers we have control of, the ones that we know and are able to use to identify critical points to improve in our processes”. The Recycling Rates (RR) were solely focused on the EOL stage of the EV battery, therefore the recycling experts considered it 100 % suitable. However, other stakeholders criticized its lack of diversity. The Circularity Index (CI) showed more equilibrated evaluations (see Table 5), as more aspects of the EV battery life cycle were included. It specifically targets the recycling efficiency of batteries, while also comparing the energy costs associated with recycled materials to those of virgin raw materials used in manufacturing.

The circularity indicators that were considered less suitable for use in practice were the Reuse Potential Indicator (RPI) (Park and Chertow, 2014) (9 % suitability) and the Global Resource Indicator (GRI) for life cycle impact assessment (Adibi et al., 2017) (17 % suitability), as they were given low importance due to their limited scope, focused on the reusing of components and materials or the criticality of the materials used (23 % and 35 % importance respectively). For the Circular Economy Performance Indicator (CPI) (Huysman et al., 2017) (19 % suitability) and the Net Losses of Metals (NLM) (Ljunggren Söderman and André, 2019) (16 % suitability), the low score was related to the inclusion of environmental impacts in the assessment of the circularity. As a battery mechanical component manufacturing stated: “Requiring an environmental impact assessment to calculate the circularity for us loses the point of the circularity indicators, we could do a life cycle assessment of the EV battery and have more detailed information”. This seems counter-intuitive, as it would lead to a partial assessment of environmental

performance. Nonetheless, one of the key priorities expressed by stakeholders was that circularity criteria should serve as a simpler, more accessible alternative to a full LCA for tracking environmental improvements. Requiring an environmental impact assessment as part of circularity measurement was seen as counterproductive, as it introduced complexity and time demands similar to those of conducting a full LCA. In such cases, stakeholders felt that resources would be better allocated to performing a comprehensive LCA rather than duplicating efforts.

Nevertheless, environmental considerations are critical for sustainability. In this study, circularity criteria and indicators were approached from the resource efficiency perspective for EV batteries. Nonetheless, adopting circular economy practices does not automatically guarantee environmental benefits (Picatoste et al., 2024), indicating the need for more rigorous assessment in future research. The results from this article represent a preliminary step, providing a set of criteria and indicators for EV batteries. The scientific literature does not provide articles integrating circularity criteria and indicators and LCA (Picatoste et al., 2022a, 2022b), which remains essential for future improvements towards a comprehensive sustainability evaluation.

#### 4.3. Critical assessment of the integrated consideration of criteria and indicators for decision-support

The integrated analysis of circularity criteria and indicators enables a holistic point of view. This would lead to best practices when applying criteria and indicators to the design and LCM of EV batteries.

At the environmental and CE fields, engaging stakeholders is pivotal in empowering research to facilitate the societal shift towards sustainability (Knaggård et al., 2019). Especially for the EV sector, considering the large vehicle fleets worldwide and the increasing market in the near future, a successful development of a sustainable industry must be based on the commitment, involvement and efforts of key stakeholders (Cao et al., 2021). However, when assessing the correlation between the stakeholder perceptions for the circularity criteria and indicators, there were some gaps regarding the coverage of life cycle stage and CE strategies (section 4.1.1). The results indicated that the most suitable criteria were focused on the manufacturing or operation stages of the EV battery, while the most suitable indicators were mainly focused on the EOL, as discussed in section 4.2.

For example, the 30 criteria covered all stages and CE strategies, while the indicators were mainly focused on the EOL stage and recycling strategies. This attention to EOL is interesting to understand the gap in the holistic application of circularity and the perceptions of the stakeholders. Criteria related to recycling such as *“Design the battery, components and materials to support the recycling process in a way that it maximises the quality of the obtained secondary material”* and *“Minimize the number of incompatible materials to facilitate recycling”* showed good synergy both with other criteria and with indicators. However, stakeholders did not consider them suitable (42 % and 39 % respectively). As expressed by a battery material expert: *“We have no knowledge of what happens with the cell once we ship it, we do not know how it will be assembled, used or recycled. Having better recycling sure is important, but we do not know how to improve from our side”*. Even if the indicators were focused on the EOL and the criteria proposed reinforce each other, the lack of a complete life cycle structure for the battery limits the circularity efforts at the EOL stage.

The limited vision of each stakeholder also created key differences in their perceptions of the suitability of criteria. For example, EOL expert stakeholders considered transport-related criteria 100 % suitable (*“Push for efficient logistics in all stages of the life cycle”* and *“Avoid unnecessary transportation operations”*), while the average results for all stakeholder groups was 46 % in both cases. This was mainly related to their position at the end of the value chain, as a recycling expert highlighted: *“We really need an adequate take back and sorting scheme to be efficient in our activity”*.

Another example identified during the interviews was related to the

potential use of renewable materials. One chemistry expert stated that *“Using certain bio-based materials can very beneficial for the impacts of the battery compared to the current state of the art”*, while an EOL expert considered that *“The current recycling technology is not ready to treat these kind of materials, which could pollute the recycling process and hinder the recoverability of valuable metals. These materials are not important nor viable at the moment”*. As a conclusion, this indicated a lack of holistic view on the value chain when considering the complete life cycle of the EV battery. The actual implementation of circular and sustainable innovations requires a multi-stakeholder approach to assess the potential effects of every change in the technology and/or business model of the EV batteries (Chirumalla et al., 2022).

The identified lack of communication between different stakeholders regarding the optimisation of the battery life cycle was also one of the main reasons for the high suitability scores of non-technical criteria, such as *“Consider and anticipate to environmental legislation”* and *“Consider how the design of the battery enable circular business models for the battery or battery component”*. Moreover, these two criteria enabled many other circularity criteria, reinforcing the application of 15 and 9 respectively. However, only 20 % of the indicators included them, due to these criteria being rather qualitative and not being easy to integrate in numerical calculation. Therefore, if a stakeholder would want to apply these criteria, there is a lack of available metrics to measure their effectiveness on the EV battery.

Likewise, the suitability of different circularity indicators yielded mixed results. On the one hand, complex and complete indicators such as the Product Circularity Indicator (PCI) (Bracquené et al., 2020) or the Circular Product Index (CPI) (Saidani et al., 2019) were considered suitable. These complete indicators also covered most of the life cycle stages of the battery and the possible CE strategies to be applied and included many of the circularity criteria in their calculations (11 and 23 respectively, out of 30 criteria). On the other hand, easier to calculate indicators such as the Circularity Index (CI) (Cullen, 2017) and Recycling Rates (RR) (Haupt et al., 2017) were also considered suitable, while their coverage of the life cycle of the EV battery and different circularity criteria was seen to be quite limited. A strong framework is needed to simplify the use of circularity indicators, while still addressing the complete life cycle of products (De Pascale et al., 2021). In this sense, a battery electric component manufacturer indicated: *“We do not really use circularity indicators so my perceptions are based on what would interest me the most. However, getting the data would be difficult. Ideally an indicator will be set by the EU and we will be able to ask for and calculate the adequate data”*.

The discussion of the results leads to consider the evaluation matrices as one of the key contributions of this research. These matrices serve as a practical tool for electric vehicle EV stakeholders, both industrial and academic. By using these matrices, stakeholders could evaluate their interest in applying circularity criteria or using indicators based on their own importance and viability scores.

The list and classification of criteria and indicators shown in Table 1 and Table 2 can be a starting point for stakeholders to familiarise themselves with key circularity design and life cycle management concepts, classifications and solutions, to support decision-making processes, which is key to ensure the development of more sustainable EV batteries (Cruz Ugalde and Talens Peiró, 2024). Any EV battery stakeholder should use the provided criteria and indicators by considering the complete set of lifecycle stages and potential circular economy solutions, rather than focusing on isolated stages. For example, at the raw materials stage, battery cell manufacturers could focus on criteria such as the use of recycled materials and minimizing the environmental impact of extraction. To measure its application, indicators would include data-points related to the percentage of recycled content and/or the amount of high-impact raw materials such as cobalt or copper employed, which is a key aspect for environmental performance of EV batteries (Dunn et al., 2021). For the manufacturing stage, efficiency of processes and adequate architecture of the product could be criteria to follow (Kornas

et al., 2020), with indicators tracking data relative to energy use per unit produced or the proportion of components designed for easy disassembly and recycling. In the operation stage, the goal is to optimise battery performance and maintenance to extend the battery's lifespan. This could be measured by indicators considering the longevity of the battery and/or the ease of maintenance and reparation (Picatoste et al., 2024). Finally, at the EOL stage, circularity criteria could promote battery collection and material recovery maximisation. Indicators for this stage should include the recovery rate of valuable materials and/or the proportion of batteries actually recycled versus landfilled. In contrast to the work by Cruz Ugalde and Talens Peiró (2024), this article analysed circularity criteria and indicators covering the complete life cycle of the EV battery. Therefore, the number of analysed criteria was higher and could not be integrated in a “Circularity Score”, although the correlation with existing circularity indicators was made through the synergy and trade-off analysis.

By applying these criteria and indicators across all life cycle stages, a more sustainable and circular system for EV batteries can be achieved, reducing waste, conserving resources, and minimizing environmental impacts (Cruz Ugalde and Talens Peiró, 2024). The synergy analysis between criteria and indicators identifies those that, when applied, have the most positive effect in others. In contrast to the work by Mossali et al. (2020), this article included criteria that are not focused in the technology aspect as well as evaluating circularity indicators. This led to selecting criteria that could be applied at multiple life cycle stages as the most synergetic ones (e.g. “consider and anticipate legislation”). Likewise, industrial and research stakeholders could select criteria/indicator that showed high synergetic scores with other relevant criteria for EV battery design efficiency. (Mossali et al., 2020). Finally, the insights gained from these matrices also enable stakeholders to evaluate the perceptions of different stakeholders' groups. The results indicate that one of the main challenges for holistic CE application for EV batteries is the lack of communication between stakeholders. Therefore, a decision maker having access to perceptions of stakeholders that they typically do not interact with could enhance the inclusivity and comprehensiveness of their sustainability efforts. This research would empower stakeholders to make informed decisions, ultimately advancing the adoption of sustainable practices in the EV industry.

#### 4.4. Limitations of the study and best practices for future research

One major limitation for the research was the lack of precision of the selected criteria, which could affect decision-making processes by the EV battery stakeholders, as also highlighted by (Arora et al., 2018). For example, a battery material expert commented: “*You propose a cleaner production of the battery as one circularity criterion to consider. But what does this mean in practice? Should we go for a dry or wet synthesis?*”. The potential adoption of this circularity criterion was not clear enough in this case as it lacks the specific mention on the type of cleaner production technique to be potentially implemented. Consequently, the list of circularity criteria lacks the level of precision necessary for direct application in some cases, which requires further research to develop an standard and comprehensive practical circularity criteria database and/or set of guidelines for use by the industry. However, at the same time, considering general or broad circularity criteria can facilitate ideation processes to identify best solutions, as suggested by CIRCit Norden (2020a). Likewise, as no previous assessment on the application of circularity criteria for EV batteries was encountered in the literature, the research outcomes are useful and meaningful by themselves. The lack of precision on the description of criteria also affected the synergy and trade-off analysis (Baars et al., 2023). For example, there is a well-known trade-off for different chemistries of EV batteries, where batteries using cobalt (a critical material) have more autonomy (a key performance characteristic). However, this constraint is only related to battery materials, therefore the criteria related to “quality of performance” and “avoid critical materials” were not defined as constraining

each other in this holistic analysis. Another limitation identified in the study was the relatively small sample size of the survey. While this did not critically undermine the findings (Aguayo, 2024), it suggests that future research would benefit from increasing the sample size. Including stakeholders from every stage of the industry, academia, customers, business managers, and policymakers would provide a more comprehensive representation. This approach would enhance the robustness and applicability of the results, contributing to more effective circularity practices in the EV battery sector.

Finally, the cost motivation for stakeholders was not explicitly addressed in the research as a standalone criterion, which could represent a limitation for this study. However, this aspect was instead embedded within the broader “viability” score during the criteria and indicators evaluation phase. “Viability” represented both technical feasibility and economic factors of implementing a criteria or indicator. Nonetheless, Wolf et al. (2024) emphasize the complex relationship between profitability and circularity in battery design, highlighting that economic incentives can sometimes yield counter-intuitive outcomes that may be detrimental to circularity. For example, the low-cost battery chemistries hinder the circularity, because they offer little to no profitability under current recycling methods. Other more expensive chemistries, however, could lead to great savings at the EOL stage (Gutsch and Leker, 2024).

#### 4.5. Integrated discussion of the circularity criteria and indicators

Finally, the best practices gathered from this integrated analysis and the complete assessment of the perceptions of the stakeholders were identified. Regarding the circularity criteria, this work gathered and prioritised criteria to be applied by every EV battery stakeholder for the best circularity performance both for their expertise category and across the life cycle of the battery. Additionally, it was considered that the most efficient circularity criteria would need to guarantee that other criteria are reinforced when applied. This was tackled by the qualitative analysis of synergies and trade-offs of all the selected criteria. Although some of the circularity criteria were deemed too broad to directly apply, too technical criteria could be too narrow in their approach to be viable for all stakeholders, so they should be considered carefully. The results regarding circularity criteria could be used by different stakeholders once adapted to their needs and capabilities regarding EV battery technologies. Likewise, these results could be foundations to build upon for specific stakeholders, as sector-wide quantitative scores and qualitative perceptions were gathered regarding design criteria.

When measuring the correct application of the selected criteria through circularity indicators, the best practices also include the need for an indicator that stakeholders would select as highly suitable. The results of this work indicate that there was not a circularity indicator that would cover all the life cycle stages, circular economy strategies, or most of the circularity criteria. Therefore, the conclusion of this research is that the EV battery sector requires a new or adapted indicator to cater to the requirements. Although complex, this indicator would be highly important and therefore suitable for all stakeholders. Additionally, inclusion of the most suitable criteria within the chosen indicators should be explored, being the indicator(s) able to encourage the correct application of the selected criteria. Considering the circularity criteria and indicators available, generating a sector-specific shortlist of criteria would be ideal for a holistic approach to the EV battery, while the creation of a tailor-made indicator, or selecting a standard indicator covering all the criteria in the shortlist could be the best practice to guarantee the correct application of the CE strategies.

Likewise, the different interests of the EV battery stakeholders should be adequately surveyed for a balanced evaluation of the circularity criteria and indicators proposed in this research. The wide range of expertise of the consulted stakeholders (see Table 3) was an approach to gather stakeholders' perceptions from a holistic perspective for the evaluation. However, a more nuanced approach could be used to

account for the economic interests of each stakeholder and look for a balanced evaluation. Future research could benefit from employing a multicriteria decision-making system for the analysis of criteria and indicators, as well as design decisions on EV batteries (Baars et al., 2023). Moreover, an adequate classification of the different stakeholders' groups and interests could be a key aspect of the future sectorial analysis, in order to provide more precise information to EV battery designers, business managers and policymakers (Yang et al., 2023). These proposals would define a framework for the application of circularity criteria and indicators in EV batteries and bridge the gap between each of the stakeholders' expertise and the different perceptions gathered, encouraging that the circularity mindset is embedded in all the life cycle stages of the EV battery.

Regarding the indicators, the suitability of EOL indices (Favi et al., 2016) and Product Circularity Indicator (Bracquené et al., 2020) was highlighted due to the importance of the information provided, although the data requirement for calculations was considered challenging. Contrarily, the Reuse Potential Indicator (Park and Chertow, 2014) was not considered useful to implement CE improvements for EV batteries, as it was deemed difficult to calculate and centred around reuse, which was not an interesting CE strategy for several stakeholders.

Analysing the synergies, EOL criteria such as “maximise the recycling quality” and “minimise the incompatible materials for recycling” were calculated by the most indicators due to their focus on EOL. It was also seen to reinforce 36 % and 26 % of the criteria, respectively. However, they were given low suitability scores by the stakeholders (42 % and 39 % suitability respectively). The indicator that included the most criteria in its calculation was the Circular Product Index (Saidani et al., 2019), although the stakeholders' evaluation considered it was difficult to calculate, providing an average suitability score (24 %).

With these results, this article aims to offer an understanding of the CE approach towards EV batteries. Still, the discrepancy of the stakeholders' priorities between the design criteria and the indicators used requires the development of robust mechanisms. Best practices were identified to close said gap and offer EV battery designers and life cycle managers means to adequately correlate the choices they made with suitable metrics of success. A short-list of circularity criteria covering the complete life cycle of the EV battery should be considered by the industry and academics, while also having a tailor-made circularity indicator available that included the selected criteria in its calculation. This would enable a direct measurement of the effect of the application of circularity criteria in the design and LCM of the EV battery.

The insights from this study have direct societal implications by informing more sustainable policies, industry guidelines, and educational initiatives centred on circularity in EV batteries. Policymakers can leverage the prioritised criteria and stakeholder-informed recommendations to enact regulations that incentivise practices such as digital battery passports or the use of recyclable materials. Industry stakeholders can adopt these findings to enhance collaboration across the value chain, optimise resource management, and reduce environmental impacts. By promoting circularity principles in both battery design and end-of-life management, this research contributes to broader societal goals, including lowering waste generation, minimizing dependence on finite resources, and supporting sustainable economic growth. These efforts also foster public trust in cleaner mobility solutions, ultimately enabling a smoother transition to low-carbon transportation.”

This paper bridges the gap between theory and practice by combining a review of circularity criteria and indicators with stakeholder engagement across the EV battery value chain. The theoretical framework identifies key circularity criteria from academic, policy, and industry sources, while the practical approach gathers stakeholder insights through interviews to assess the feasibility and relevance of these criteria. Ultimately, the study provides a pathway for embedding circularity at every stage of the EV battery life cycle, ensuring that environmental and societal benefits are achieved alongside technological advancements.

## 5. Conclusion

Scientific, industrial and policy-related literature was explored to identify 30 circularity criteria and 15 indicators that could be used by the EV battery sector. The selected criteria and indicators were analysed to understand their scope and main characteristics regarding the life cycle stages and circularity strategies covered. The perceptions of industrial and research stakeholders regarding the practical application of circularity criteria and indicators for EV battery design, manufacturing and life cycle management were explored. By examining the perspectives of various stakeholders involved in different stages of the EV battery life cycle, results provided valuable insights into the current understanding and priorities related to the circularity maturity and potential for innovation of the sector.

This research showed that broad design criteria covering multiple battery life cycle stages or focused on the use stage, such as “*Consider and anticipate to environmental legislation*” and “*Focus mainly on functionality and quality performance*”, were widely supported by the stakeholders. This support arises because these criteria were applicable across multiple components and scenarios, allowing them to be easily adapted to various battery and operational contexts. Nonetheless, the practical application of these criteria often required clearer guidance and more precise definitions, as each implementation must account for varying stakeholder priorities, performance requirements, and supply chain constraints. The Product Circularity Indicator (PCI) emerged as the most suitable due its completeness, yet the complex nature of the indicator and intensive data-collection requirements limited its viability for calculation. Other indicators, including recycling-based measures such as EOL indices (EOLi), illustrated how EOL processes could drive circular innovation, but stakeholders felt that they had little control over these processes, emphasizing the need for stronger communication across the value chain for the application of holistic strategies that would really ease the application of EOL criteria and strategies. The findings highlighted a need for collaborative strategies to translate circularity criteria into specific technical actions, develop strategies for key data sharing, and clarify how regulatory frameworks could support design decisions. Also, the creation of a sector-specific, holistic indicator would help industry actors navigate the trade-offs between cost, performance, and environmental impact.

Future research should focus on refining circularity criteria into actionable guidelines, enlarging the sample of stakeholder perspectives, and integrating life cycle assessment with circular business models to balance economic drivers with environmental benefits. By bridging these gaps, the EV battery sector can move towards more robust and resource-efficient design, manufacturing, and EOL management practices. Moreover, in future applications of the selected circularity criteria and indicators, EV battery business cases could be built, demonstrating the combined use of both to develop sustainable products. These steps underscore the importance of collaboration, research, and policy initiatives to foster circular practices in the EV battery industry, ultimately contributing to the transition towards a more sustainable and resource-efficient future.

### CRedit authorship contribution statement

**Aitor Picatoste:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Daniel Justel:** Writing – review & editing, Supervision. **Joan Manuel F. Mendoza:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

### Declaration of competing interest

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

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.spc.2025.02.013>.

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