Scope and relevance of circular economy indicators for the sustainable lifetime management of batteries for electric vehicles

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Scope and relevance of circular economy indicators for the sustainable lifetime management of batteries for electric vehicles

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Abstract:
Circular economy (CE) is aimed at improving resource efficiency to reduce the environmental burden and other negative externalities of production and consumption systems. Focusing on batteries for electric vehicles (EV), various CE strategies can be applied to improve manufacturing efficiencies, develop long-lived products or facilitate life-extension, and enable material reuse and recycling at the end-of-life. However, product design methods not relying on the consideration of CE criteria and indicators could lead to insufficient resource efficiency improvements or undesired consequences, such as rebound effects. This is important because batteries can account for over 40% of the EVs´ life cycle environmental impacts. However, the literature analysing the applicability of CE indicators to EV battery design and management is scarce and limited in scope. This study evaluates 15 product-level CE indicators to determine its importance and viability to inform battery designers and manufacturers in the development of more sustainable products. An Excel-based matrix was built to provide a description of each CE indicator, including its applicability, scoring system and data requirements, and show their links to the hierarchy of CE strategies and life cycle stages. The suitability of the CE indicators to support decision-making was evaluated by ten industrial stakeholders (manufacturers of battery components). The results show that End of Life Indices (Favi et al., 2016) and the Product Circularity Indicator (Bracquené et al., 2020) are the most suitable indicators due to the quality of information provided. However, it is crucial to develop new battery-oriented circular design methods and indicators to support the development of sustainable EV batteries.

Introduction

Electric vehicles (EV) are being deployed worldwide as a key technology solution to decarbonise urban mobility in cities and regions (European Commission, 2019). Nonetheless, EV contribute to multiple environmental impacts, especially due to the influence of the batteries (Xia & Li, 2022).

Resource consumption in battery manufacturing and the energy consumed during operation are important aspects contributing to the environmental impacts of the EVs (Picatoste et al., 2022b). Moreover, critical raw materials(European Commission, 2023) such as cobalt, copper, lithium, manganese, nickel or graphite are key elements for the production of EV batteries and their increased future demand of can stress further supply chain constraints (Carrara et al., 2023).

Therefore, the implementation of circular economy (CE) strategies, aimed at reducing resource use, prolonging and intensifying the use of products and recovering materials from waste streams (Bocken et al., 2016) is key to improve the environmental performance of EV batteries (Baars et al., 2020). The integration of CE in the circular design of EV batteries has been recently explored by Picatoste et al. (2022a) who highlights that design criteria are required to be implemented to improve the EV batteries lifetimes. However, suitable metrics are needed to avoid potential trade-offs as lowering recycling indices due to lifetime extension strategies or risking the durability of the EV battery by excessive lightweighting.

CE indicators are measuring instruments to specifically analyse the transition towards more circular practices (Saidani et al., 2019) and are aimed to support the design and management decision-making (EMF & Granta design, 2015). Scholars and industry experts emphasise the importance of using CE indicators to assess the sustainability performance of EV batteries´ supply chains (Gebhardt et al., 2022). Likewise, the analysis of product-level CE indicators for EV batteries is yet scarce in the scientific literature. This limits the knowledge of available standardised metrics for the assessment of circularity of EV batteries and to support design and management decision making.

Therefore, the objective of this article is to evaluate the perception of industrial stakeholders (designers and manufacturers of batteries for EVs) on the importance and viability of using CE indicators for the design and development of more resource-efficient EV batteries, and to ultimately identify the most suitable indicator(s) for consideration in circular design processes.

Methodology

Figure 1 presents the four-step methodology applied for the selection, documentation and evaluation of CE indicators by the industrial stakeholders.

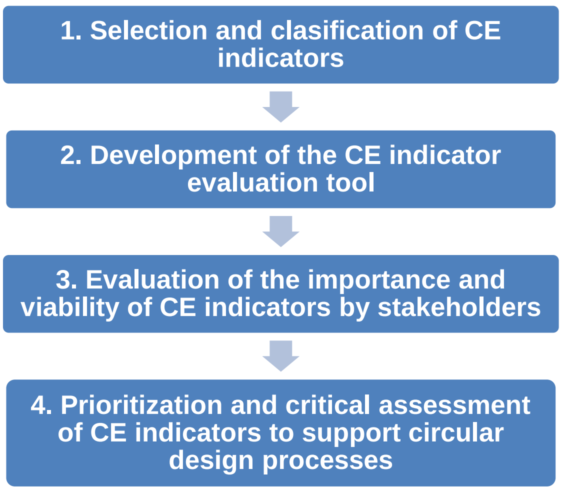

Figure 1. Research methodology. Acronyms: CE (circular economy).

Selection and classification of CE indicators

A SCOPUS search was performed using the four search streams: CE, indicator, battery and electric vehicle and synonymous.

This search yielded 39 hits. However, only one of the articles explicitly proposed or applied CE indicators to analyze the circularity of EV batteries (Schulz-Mönninghoff et al. (2022) using Material Circularity Indicator (MCI) (EMF & Granta design, 2015)and Circularity Transition Indicators (WBCSD, 2021), although at the company- rather than the product-level.

To complement the literature search, six recent and highly cited literature reviews on CE indicators were analysed to identify suitable product-level indicators for the analysis of the circularity of EV batteries (Corona et al., 2019; de Oliveira et al., 2021; Jerome et al., 2022; Kristensen & Mosgaard, 2020; Lindgreen et al., 2022; Saidani et al., 2019).

Finally, the European battery regulation (European Commission, 2006; Halleux, 2022) and the PEFCR (European Commission, 2018) were also reviewed for possible CE indicators.

This resulted in the identification of 127 CE indicators. However, CE indicators for evaluation were selected by applying the following criteria:

- Only consider product-level indicators (micro or nano level).
- CE indicators non-applicable to lithium-ion EV batteries were discarded.
- If a CE indicator had an updated version, the previous one was discarded (e.g. Longevity indicator from Franklin-Johnson et al. (2016) vs Longevity and Circularity indicators from Figge et al. (2018)).
- CE indicators with a qualitative approach were discarded.
- CE indicators not directly available for the user were discarded (e.g., Circular economy indicator prototype (CEIP) (Cayzer et al., 2017), an excel spreadsheet that is provided by the authors after personal request).

Accordingly, 15 indicators were selected and classified according to the life cycle stage (Manfredi et al., 2012) and the CE strategy (Blomsma et al., 2019) as shown in Table 1.

Name of indicator and reference	**Life cycle stages**					**Circular Economy strategies**									
	Raw material	Manufacturing	Transportation	Use phase	End of life	Reduce	Upgrade	Repair	Reuse	Refurbish	Remanufacture	Repurpose	Recycle	Cascade	Recover
Product Circularity Indicator (PCI) (Bracquené et al., 2020)	x	x		x	x	x		x	x	x	x		x	x	
Longevity and Circularity indicators (Figge et al., 2018)	x			x	x	x		x	x	x	x	x	x	x	
Circularity Index (CI) (Cullen, 2017)	x	x			x	x							x		x
Multidimensional Indicator Set (MIS) for WEEE (Nelen et al., 2014)	x	x			x								x		
End of Life indices (EoLi) (Favi et al., 2016)	x	x	x		x				x	x	x	x	x	x	x
Circular Economy Index (CEI) (Di Maio & Rem, 2015)	x				x								x	x	x
Product-Level Circularity Metric (PCM) (Linder et al., 2017)	x	x	x		x				x	x	x	x	x	x	x
Global Resource Indicator (GRI) for life cycle impact assessment (Adibi et al., 2017)	x				x	x							x		x
Reuse Potential Indicator (RPI) (Park & Chertow, 2014)				x	x				x	x	x	x	x	x	
Resource Efficiency Assessment of Products (REAPro) (Ardente & Mathieux, 2014)	x				x	x			x	x	x	x	x	x	
Recycling Rates (Haupt et al., 2017)					x								x	x	
Circular Product Index (CPI) (Saidani et al., 2019)	x	x		x	x	x		x	x	x	x	x	x	x	x
Net losses of metals (Söderman & André, 2019)				x	x				x			x	x	x	x
The Circular Footprint Formula (PEFCR) (European Commission, 2018)	x	x			x	x							x	x	x
The Circular Economy Performance Indicator (CPI) (Huysman et al., 2017)	x				x								x	x	x

Table 1. List of selected indicators, classified by the life cycle stages and circular economy strategies analysed.

Development of the CE indicator evaluation tool

An Excel-based tool was built to list, describe and share the selected CE indicators for evaluation by the industrial stakeholders, following the approach provided by Picatoste et al. (2022a) for the evaluation of circular design criteria.

Each indicator was described, including applicability, score system and link to CE strategies and life cycle stages, and this information was used to ask the industrial stakeholders to evaluate the suitability of each indicator according to the following considerations:

i) Importance (0 to 9): how relevant the indicator is to support decision-making processes for the circular design and sustainable management of EV batteries.
ii) Technical viability (0 to 5): how easy is to gather the required data and perform the required calculations.

By multiplying the corresponding importance and viability scores, the resulting number was considered the suitability category (0 to 45) of the indicator to determine circularity performance of alternative battery design choices to support decision-making.

Evaluation of the importance and viability of CE indicators by stakeholders

European designers and manufacturers of batteries were contacted via e-mail and invited to participate in the evaluation and, upon agreement, the CE indicators evaluation tool was shared.

Instructions to fill the evaluation tool were included both in the e-mail and the evaluation tool itself. To complement this interaction, stakeholders were offered a 1-on-1 online meeting for further explanation (30’) or a “guided evaluation” (90’) in which the stakeholder was accompanied in the process of filling the tool by the authors of this paper who acted as facilitators.

In total, 10 stakeholders of the European EV battery industries, participated in the evaluation of the CE indicators, providing data and comments.

Prioritization and critical assessment of CE indicators to support circular design processes

After the interaction with stakeholders, results were gathered to obtain average scores for all three categories, and classified according to the percentage of the maximum score obtained for each category (9 for importance, 5 for viability and 45 for suitability)

The most and least important and viable CE indicators were found and the reasons for those scores explored, which lead to the analysis of pros and cons for each indicator and the key factors to improve and define the most suitable CE indicators for EV batteries.

Results

Table 2 lists the average results regarding the evaluation of the CE indicators by the industrial stakeholders.

Name of indicator and reference	Imp.	Viab.	Suit.
End of Life indices (EoLi) (Favi et al., 2016)	61%	44%	22.4%
Product Circularity Indicator (PCI) (Bracquené et al., 2020)	68%	38%	21.5%
Circularity Index (CI) (Cullen, 2017)	51%	48%	20.4%
Circular Product Index (CPI) (Saidani et al., 2019)	67%	36%	20.0%
Circular Economy Index (CEI) (Di Maio & Rem, 2015)	44%	52%	19.3%
Longevity and Circularity indicators (Figge et al., 2018)	54%	38%	17.2%
Recycling Rates (Haupt et al., 2017)	48%	42%	16.7%
Product-Level Circularity Metric (PCM) (Linder et al., 2017)	46%	42%	15.9%
Resource Efficiency Assessment of Products (REAPro) (Ardente & Mathieux, 2014)	54%	34%	15.4%
Multidimensional Indicator Set (MIS) for WEEE (Nelen et al., 2014)	56%	32%	14.8%
The Circular Footprint Formula (PEFCR) (European Commission, 2018)	61%	28%	14.3%
Net losses of metals (Söderman & André, 2019)	46%	34%	12.9%
The Circular Economy Performance Indicator (CPI) (Huysman et al., 2017)	54%	26%	11.8%
Global Resource Indicator (GRI) for life cycle impact assessment (Adibi et al., 2017)	39%	32%	10.4%
Reuse Potential Indicator (RPI) (Park & Chertow, 2014)	26%	36%	7.7%

Table 2. Average scores per category for each CE indicator, as a percentage of the max. score

Importance of CE indicators

Four CE indicators were considered of high importance (>60%): Product circularity indicator (PCI) (Bracquené et al., 2020), Circular Product Index (CPI) (Saidani et al., 2019), End of Life indices (EoLi) (Favi et al., 2016), The Circular Footprint Formula(European Commission, 2018).
The main reason for this high importance score was the completeness of the CE indicators, covering multiple life cycle stages and CE strategies (Table 1) to support design decision processes.

Viability of CE indicators

Regarding the viability scores, five indicators were considered medium viable (>40%). For the Circular Economy Index (CEI) (Di Maio & Rem, 2015), Circularity Index (CI) (Cullen, 2017), Product-Level Circularity Metric (PCM) (Linder et al., 2017) and Recycling Rates (Haupt et al., 2017), the ease of data gathering and simple calculations were the main factors for the higher viability score received in comparison to the rest of the indicators.

For the EoL indices (EoLi) (Favi et al., 2016), the viability (44%) is due to much of the required data being based on the economic values of material and energy, which increases the availability of the data.

Suitability of CE indicators

The top five suitable CE indicators (Table 2) were selected for a deeper analysis:

- EoL indices (EoLi) (Favi et al., 2016): suitability 22.4%. This indicator provides quantitative information to select the best design and waste management choices. The required data includes: material and energy quantity and economic costs for manufacturing, the percentage of the material which is reused, refurbished, recycled and incinerated as well as the economic costs of those processes and values of the recovered material an energy. It provides guidance of the economic value of the design and EoL management choices for the EV battery.

- Product Circularity Indicator (PCI) (Bracquené et al., 2020): 21.5% suitability. The PCI is a single number indicator calculated based on the detailed assessment of the material efficiency for every process of the product, from the origin of the raw material, the manufacturing efficiency, the longevity of the battery, reuse/refurbishing of the components and recycling efficiencies. Thus, it was considered the most important CE indicator (68%) for the stakeholders, although viability was not as high (38%) due to the detailed data requirements.

- Circularity Index (CI) (Cullen, 2017): 20.4% suitability. The CI is an indicator focused on the recycling efficiency of the battery and the energy costs of the recycled material compared to the virgin raw material necessary to manufacture. As such, it is easy to calculate (48%) while providing simple yet interesting data (51%) regarding the recycling of the battery materials.

- Circular Product Index (CPI) (Saidani et al., 2019): 20.0% suitability. CPI is a questionnaire based semi-quantitative indicator that provides information on the circularity of the battery and its value chain by integrating technical data as the materials and weight of the product, second life and recycling ratios with qualitative data such as business practices, market analysis or economic and legislative conditions for the product. Thus, the stakeholders considered that the information provided was quite important (67%) but the low viability (36%) was based on the difficulty for the data gathering.

- Circular Economy Index (CEI) (Di Maio & Rem, 2015): 19.3% suitability. The CEI was deemed the most viable indicator (52%) by the stakeholders. It proposes a circularity score comparing the economic value of the recycled material vs. the virgin raw material, which was considered a medium importance (44%) information.

Other CE indicators, including The Circular Economy Performance Indicator (CPI) (Huysman et al., 2017) or the Circular Footprint Formula (PEFCR) (European Commission, 2018), were considered important (54% and 61%) but too complex (26% and 28%) due to requiring environmental impact calculations. Others such as the Global Resource Indicator (GRI) for life cycle impact assessment (Adibi et al., 2017), provided less important information (39%) while not being viable (32%) to calculate due to the inclusion of environmental impact and geopolitical scarcity of materials as data requirements for calculation.

Conclusions

This paper outlines the opinion of 10 industrial stakeholders on the use of CE indicators to support decision-making processes for the circular design and sustainability management of EV batteries.

The evaluation of the importance and viability of 15 product-level CE indicators yielded interesting results regarding the suitability of the selected indicators to drive circular and sustainable innovation.

The two most suitable indicators, the EoL indices (EoLi) (Favi et al., 2016) and the PCI (Bracquené et al., 2020) are considered to provide detailed and complete information (Table 1, Table 2). Likewise, other CE indicators (CI (Cullen, 2017) and CEI (Di Maio & Rem, 2015)) scored high because of the ease of the data gathering and calculation, even if their scope was narrower (Table 1).

Besides, it can be observed in Table 1 that most of the assessed CE indicators lack the holistic approach necessary to analyse the complete lifetime of EV batteries. Thus, the definition of sector-specific CE indicators considering the design and development of EV batteries, adding life cycle perspective and an assessment of battery supply chain and business model's configuration is an important step to focus on for further research on the topic.

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