Resources, Conservation & Recycling 205 (2024) 107546

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Circularity scoring system: A product specific application to lithium-ion batteries of electric vehicles

José Daniel Cruz Ugalde, Laura Talens Peiró [*]

Sostenipra (2021SGR00734), Institut de Ciència i Tecnologia Ambientals (ICTA-UAB), Universitat Autònoma de Barcelona, 08193, Cerdanyola del Vallès, Barcelona, Spain

ARTICLE INFO

Keywords:
Lithium-ion battery
Circular economy
Standardization
Disassembly
Ecodesign
Material efficiency

ABSTRACT

The transition towards electric mobility has gained significant momentum in recent years, raising concerns on the environmental and social implications of lithium-ion batteries. Specifically, there are ongoing challenges related to the future supply of critical raw materials and the sustainable management of used batteries with remaining capacity. To address this, a 'Circularity Scoring System' is proposed. The method aims to evaluate specific aspects of the battery design and the manufacturer's support infrastructure that currently hamper the implementation of circular economy strategies. A comprehensive list of 25 evaluation criteria was initially compiled from existing standards on material efficiency. Then, 9 criteria were ultimately selected, weighted, and defined to evaluate a battery's potential to undergo three distinct pathways: repair and reuse, remanufacturing and repurpose, or recycling. Through this method, a final score is generated for each circular strategy, providing valuable insights for continually enhancing battery design and, subsequently, their sustainability.

1. Introduction

About 75 % of European Union's (EU) transport-related greenhouse gas emissions comes from road transportation (Albertsen et al., 2021, p. 1), the transition towards zero-emission vehicles has gained a notable inertia within European policymaking, industry research and development, and the consumers market. At a local level, Spanish Climate Change Law is set to increase Catalonia's influx of batteries up to 72-fold in 2040 (Sanclemente et al., 2022), while regionally more than 270 million electric vehicles (EVs) are expected on the EU's roads by 2050 (Joint Research Centre, 2022, p. 3). This trend is observed worldwide, as electrification is defined as an effective way to reduce the direct emissions from transportation. This, together with a higher adoption of renewable sources of energy, will exponentially increase the energy storage market, which is expected to grow 64-fold between 2016 and 2030 (Hill et al., 2019, p. 63).

The electrification of the economy is inherently resource intensive (Luth, 2022, p. 5). It is unclear whether the necessary materials and production capacities will be sustain the projected demand (Kamran et al., 2021, p. 2). In particular, Lithium-ion batteries (LIBs) are rapidly driving up the demand for materials some targeted as critical by the EU. Lithium demand alone is expected to be over 40 times higher in 2040 than 2020 levels, while other minerals like nickel, cobalt, and graphite will increase up to 25-fold in the same period (IRTC, 2022, p. 3). This poses not only supply risks and environmental challenges (Sommerville et al., 2021, p. 2), but also a potential surge in social issues traditionally linked to mining, such as child labor, poor working conditions, and conflicts (Luth, 2022, p. 5).

Given this perspective, the Circular Economy (CE) is widely regarded as the most favorable path moving forward (IRTC, 2022, p. 9). Implementing a CE hierarchy to the End of Life (EOL) management offers the possibility of reclaiming over 70 % of the total energy consumed during the batteries' manufacturing process, and reducing their life-cycle CO_2 emissions by more than 50 % (Islam and Iyer-Raniga, 2022, p. 11; Madlener and Kirmas, 2017, p. 3814). Therefore, Circular Business Models (CBMs) are starting to emerge. (Pagliaro and Meneguzzo, 2019, p. 3). For instance, battery recycling facilities are currently ramping up in the EU (Schmaltz and Jung, 2023) while similarly, second-life energy storage systems are considered a developing market (Luth, 2022, p. 6). However, recycling's profitability is still dependent on operational and design factors of the battery, which poses risks to their economic sustainability (Lander et al., 2021, p. 7). Similarly, most CBMs focused on second-life batteries are still in the piloting and experimentation phase, with limited full-scale facilities (Albertsen et al., 2021, p. 5).

---

* Corresponding author at: ICTA-UAB, Universitat Autònoma de Barcelona, Cerdanyola del Vallès, Barcelona, Spain.
E-mail address: laura.talens@uab.cat (L. Talens Peiró).

https://doi.org/10.1016/j.resconrec.2024.107546
Received 6 September 2023; Received in revised form 4 February 2024; Accepted 6 March 2024
Available online 14 March 2024
0921-3449/© 2024 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

The most cited factor to be hampering the implementation of CE strategies is the battery design. Specifically, the heterogeneity of chemistries, sizes, electrode configurations, shapes and bonding methods compromises the efficiency of the disassembly, which directly impacts the processing costs of the batteries (Ali et al., 2021, p. 5; Harper et al., 2019, p. 84; Lander et al., 2021, p. 7, 2023, p. 1). Therefore, the 'design for disassembly' is considered a key enabler for a circular use of parts and materials in the LIB context, as it can drive the standardization of the battery design, and enable an automation of disassembly and remanufacturing processes (Lander et al., 2021, p. 7; Makwarimba et al., 2022, p. 26; Tao et al., 2021, p. 3; Tazi et al., 2023, p. 48).

Nonetheless, the amount of literature examining the incorporation of CE design criteria into the development of batteries for EVs is limited (Picatoste et al., 2022, p. 107). Even more, vehicle Original Equipment Manufacturers (OEMs) are mostly limiting their extended producer responsibility to paying a fee to recycling companies (Albertsen et al., 2021, p. 6), while agreeing that incorporating design criteria related to the EOL management and standardization of LIB's design have both low implementation potential (Harper et al., 2019, p. 77; Picatoste et al., 2022, p. 107). Three main factors that might be driving this behavior are: decreasing costs of new LIBs (Ali et al., 2021, p. 5; Castelvecchi, 2021, p. 337), the uncertainty in the future value of recovered materials (Albertsen et al., 2021, p. 9; Harper et al., 2019, p. 84), and a primary focus on recycling, rather than further exploring other CE strategies (Islam and Iyer-Raniga, 2022, p. 3).

Therefore, to drive a transformational change, further innovation in policy, markets, technology, infrastructure, and user practices is required (Nurdiawati and Agrawal, 2022, p. 1). This is why the EU has released the 2023 Batteries Regulation, which aims to establish the EU as leader on the CE of batteries (Joint Research Centre, 2022, p. 6). The regulation introduces new requirements for the economic operators of the battery sector, supporting the creation of new markets for materials recycling, while increasing transparency, traceability and accountability through the creation of a Digital Battery Passport (DBP) (European Commission, 2023, p. 8; Luth, 2022, p. 6). Also, it calls for international standardization efforts towards the continuous improvement of due diligence practices within the industry (European Commission, 2023; Hill et al., 2019, p. 7).

These efforts have already started. CEN-CENELEC has released a series of standards on material efficiency for Energy-related Products with the intention of promoting product-specific frameworks to assess the potential to apply the different CE strategies (CEN-CENELEC, 2019a, 2019b, 2020b, 2020a). These have been used as a basis for further developments such as the 'Scoring system for repair and upgrade of products' (Joint Research Centre, 2019), the 'Repair Score Study' for smartphones and tablets (Spiliotopoulos et al., 2021), the French 'Repairability index' (Ministère de la Transition Écologique, 2022), and the 'Ecorating Methodology' (Ecorating, 2023). However, no specific application has been developed for LIBs. Previous literature suggests that scoring systems represent an opportunity to identify hotspots in design for sustainability (Aymerich, 2021, p. 24; Tazi et al., 2023, p. 22). At the same time, they can serve as a tool for buyers to compare functionally equivalent products according to their environmental performance (Aymerich et al., 2022, p. 5). In this sense, matching the design stage with potential market decisions could be a driver for a systemic change in LIBs. Even though there are currently applications being used for other products, criteria proposed in CEN-CENELEC standards requires modifications to generate relevant results when applied to LIB (Casades et al., 2022, p. 22). Furthermore, there is a need for establishing standards containing criteria and guidelines for evaluating LIB for circularity (Joint Research Centre, 2018, p. 53), which is the main objective of this research.

2. Materials and methods

The most widely recognized methodological basis to assess the ability of products to undergo a CE strategy are the EN4555X series by CEN-CENELEC (2019a, 2019b, 2020b, 2020a). They assess the following aspects: ability to remanufacture (EN45553), ability to repair, reuse & upgrade (EN45554), recyclability and recoverability (EN45555), and proportion reused components (EN45556). The EN45554 provides a guide on how to translate the performed assessment into a score. The Joint Research Centre (2019) has used it to measure the repairability and upgradeability of products, including practical examples for three product categories (laptops, vacuums and washing machines). Later, it was applied to smartphones and tablets, within the framework of the preparatory study for a new ecodesign regulation (Spiliotopoulos et al., 2021). Similarly, the French Repairability Index (Ministère de la Transition Écologique, 2022) was introduced as a mandatory assessment of the potential to repair for at least seven product categories, none of which are batteries. And finally, the most recent 'Ecorating' methodology (Ecorating, 2023) tackles the repairability of mobile phones. With this background, the proposed 'Circularity Scoring System' (CSS) is the first one to incorporate more than one CE strategy, assessing not only the potential to repair and reuse but also to remanufacture, repurpose and recycle. An adapted methodology consisting of five non-sequential steps was developed.

2.1. Selection of assessment criteria

First, a list criterion to influence the use of CE strategies on LIBs was made. Each criterion meet three main requirements: be relevant for the assessed CE strategy, be measurable and verifiable at the point of sale, and be driven by the product design or its supporting infrastructure (Joint Research Centre, 2019, p. 21). To comply with these requirements in the context of LIBs, available literature was complemented with real disassembly data from three sampled batteries obtained from the DigiPrime Project (DigiPrime, 2023). Disassembly information included the disassembly sequence, required tool(s), type of junctions, number of operators, and time spent per step. Appendix A goes into further detail on the analyzed batteries and their characteristics. This information, together with the enounced EN4555X Standards CEN-CENELEC (2019a, 2019b, 2020b, 2020a), provided a first iteration of potential criteria, which were then prioritized based on their applicability to LIB.

For this process, three 'prioritization factors' were defined. First, the degree to which a criterion varies among different models of the same product category. For example, the required skills and qualifications to manually intervene a battery are equally regulated regardless of the battery model (Harper et al., 2019, p. 77). Second, the selection of independent criteria. For example, the number of tasks and total disassembly time cannot be both indicators of disassembly complexity as the former is a predictor of the latter. Third, basic criterion should be prioritized over complex ones. For example, when considering spare parts, their availability should be prioritized over their supply lead time.

According to JRC, a maximum of 12 criteria should remain after the prioritization in order to preserve simplicity and representability of the system (Joint Research Centre, 2019, p. 51). Then, it is necessary to determine whether they should be assessed at the part-level, product-level, or OEM level. The decision depends on the desired degree of aggregation at which the criterion will be evaluated. For part-level category, the definition of 'priority parts' becomes necessary. The selected parts must be functionally important, and/or be easily accessible when applying a CE strategy (Joint Research Centre, 2019, p. 17). Then, the overall qualification for these criteria will be the weighted average of the individual qualifications from the priority parts (Joint Research Centre, 2019, p. 51). Lastly, it is important that the list of selected criteria remains relevant to the CE strategies. This selection determines the meaning of 'circularity' within the scoring system and is therefore a critical step in the overall methodology.

Table 1
Summary of the definitions of each CE strategy and their clustering proposal.

Cluster Description	CE strategy	Definition	Sources
1. **Non-invasive interventions of the battery, highly dependent on the State of Health (SOH) diagnostic, and very influenced by the availability of spare parts.**	Repair	The process of restoring a faulty battery to a condition where it can fulfill its intended use, without involving changes that affect safety or original performance	(CEN-CENELEC, 2020b; European Commission, 2023)
	Reuse	Operation by which a battery or its parts are used again for the same purpose for which they were conceived, without involving changes that affect safety or original performance	(CEN-CENELEC, 2020b; European Commission, 2008; Hill et al., 2019)
2. **Invasive interventions of the battery, are highly dependent on the SOH diagnostic, and require high safety standards.**	Remanufacture	An industrial process that transforms used batteries or its parts into new products, involving changes that affect safety or original performance	(CEN-CENELEC, 2020a; European Commission, 2023; Hill et al., 2019)
	Repurpose	The complete or partial use of a battery or its parts for a different purpose or application for which it was conceived	(European Commission, 2023; Hill et al., 2019)
3. **Mostly focused on material recovery, achieving cost-efficiency and does not imply spare parts.**	Recycle	The material recovery operation where the waste battery is reprocessed into materials that can be reinserted into the same or other production streams	(European Commission, 2008)

2.2. Classification of CE strategies

The CSS is solely focused on EOL strategies, as it was found that battery OEMs already prioritize extending the battery's first-life (i.e. durability), increasing safety and reducing cost as primary design principles (Joint Research Centre, 2018, p. 36; Jones et al., 2020, p. 18). Other CE strategies related to the 'sharing economy' have also been identified, such as Renault's battery leasing scheme (Hill et al., 2019, p. 62), and the overall sharing of the vehicle through local mobile apps (BlaBlaCar, 2023). However, these strategies are not primarily influenced by the battery design, as they are more associated with the behavioral use of EV and the support framework provided by the vehicle OEMs. This does not imply that they should be disregarded, but rather indicates that a scoring system aimed at assessing 'sharing economy' strategies would place greater emphasis on support-related criteria than on part and product-related criteria.

When it comes to EOL strategies, there is often a lack of consistency in their definitions across literature and legislation (Ardente et al., 2018, p. 1545). As a result, this methodology includes a proposal to standardize them for the context of LIB, which is summarized in Table 1. Both 'repair' and 'reuse' are non-invasive to prolong the initial lifespan of the battery and its parts. 'Remanufacturing' involves the disassembly and evaluation of battery modules and cells, being invasive form compared to reuse (European Commission, 2023, p. 13). Similarly, 'repurpose' can require varying degrees of battery intervention, but with the particularity of preparing it for a new application. For instance, batteries that are no longer suitable for EVs are being repurposed for Stationary Energy Storage applications (Albertsen et al., 2021, p. 6; European Commission, 2023, p. 61; Kamran et al., 2021, p. 3). This has led to the development of innovative CBMs with various use cases, including storing surplus energy from renewable sources for further use, optimizing energy cost through load-shifting and peak-shaving, and creating mobile charging stations for EVs (Albertsen et al., 2021, p. 6; Madlener and Kirmas, 2017, p. 3813; Schulz-Mönninghoff et al., 2021, p. 1).

As the proposed CSS includes more than one CE strategy, a clustering proposal that would streamline the assessment process for a minimum viable product was defined. Thus, instead of individually analyzing all the strategies, they are grouped based on their operational characteristics. The objective was to simplify the first version of the CSS, aiming to create a smoother dynamic during the validation workshop and the first applications. Furthermore, it was also an effective tool to identify common elements between the strategies, opening a new alternative to perform the CSS. The defined clusters are also presented in Table 1, together with their description. For the purposes of the CSS, each cluster is interpreted as a CE strategy, which means that only three sets of weights are to be defined for each criterion. Fig. 1 offers a visual aid of the key processes and flows involved in the LIBs (battery, vehicle and second life applications).

2.3. Weight of relevance calculation

Weights are an inherent component of scoring systems, since they allow to combine scores from multiple criteria into a single number (Joint Research Centre, 2019, p. 52). However, one of the main innovations of the proposed CSS is the possibility to match the selected criteria with more than one CE strategy. In other words, it considers that a particular criterion may hold varying levels of relevance depending on the CE strategy being assessed. This is mostly because each CE strategy pursues a distinct goal, and therefore can require a different set of requirements to achieve them.

Also, relations of relevance can be product-specific (Joint Research Centre, 2019, p. 52), which means that a criterion that is relevant to a particular CE strategy for LIBs, might not be so for another product category. To account for these potential variations, each combination of criterion-strategy was weighted. To perform it, a panel of experts voted for the level of relevance that each criterion has on the specific CE strategy. A scale from 0 to 5 points was used, from 5 being very high to 0 'no relevant'. The compiled votes were converted into a proportion, meaning that the sum of the weights for each CE strategy must be 1. To achieve it, the following formula was used:

$$W_{i,j} = \frac{R_{i,j}}{\sum_i R_{i,j}}$$

Where:

$W_{i,j}$: Weight of the criterion 'i' over the CE strategy 'j'
$R_{i,j}$: Relevance (0–5) of criterion 'i' over CE strategy 'j'

2.4. Definition of qualification scales

In the context of CSS, qualification scales standardize the process of translating heterogeneous criteria into a fixed numerical range, so that they can be weighted together to obtain a final circularity score. The heterogeneity of criteria means that they can either be quantitative or qualitative indicators. This is why previous standards incorporate the concept of 'rating classes' (CEN-CENELEC, 2020b, p. 29; Joint Research Centre, 2019, p. 37), which can either be numerical ranges (for quantitative variables), or descriptive texts (for qualitative ones). For the CSS, we mostly used the rating classes suggested by the standards, making adaptations when considered appropriate. The qualification scales were normalized into a 1–5 discrete scale, which relevant stakeholders considered suitable for reporting purposes (Joint Research Centre, 2019, p. 182). With this information, the final score for each CE strategy using the following formula is calculated:

$$S_j = \sum_i W_{i,j} \times S_i$$

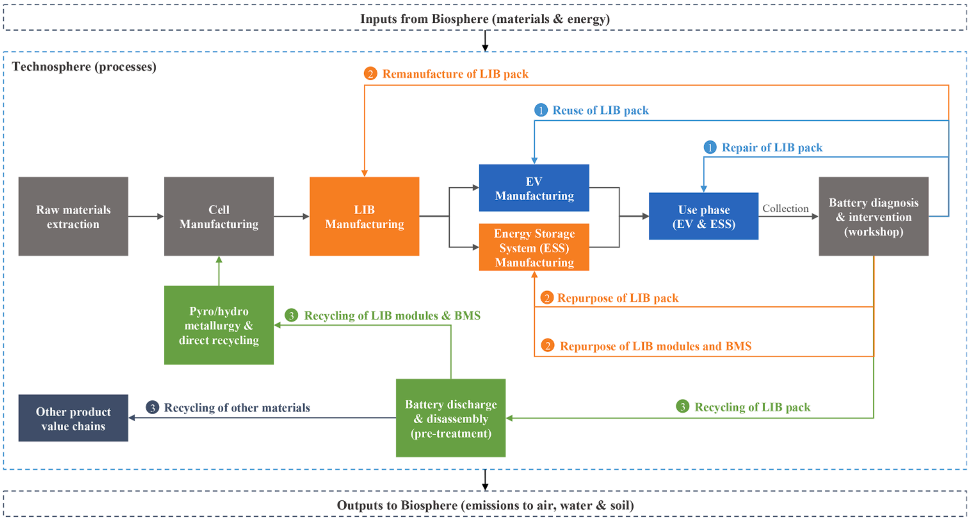

Fig. 1. Interaction between the CE strategies of the CSS.

Where:

S_j: Overall score for CE strategy "j"
$W_{i,j}$: Weight of criterion 'i' over CE strategy 'j'
S_i: Individual score for criteria "i"

2.5. Validation through a multidisciplinary workshop

To ensure broad adoption of the CSS, a participatory workshop was held among experts from the LIB and environmental assessment sectors in order to compile feedback. The workshop pursued four main objectives: validating the list of identified assessment criteria, validating the qualification scales, determining the weights of relevance, and obtaining general feedback on the tool and its relevance. The first two objectives were achieved through a participatory discussion which consisted of a theoretical baseline on the CSS, followed by a moderated space of in-depth debate. The participants were divided into three groups according to the CE strategy clusters, for them to discuss each criterion and its qualification scale. Every comment was compiled through notetaking for it to be evaluated after the workshop. The third objective was fulfilled using the Delphi Group method, an approach to reach consensus particularly in topics where there is limited available information. (Islam and Iyer-Raniga, 2022, p. 27). In order to achieve that, we relied on the expertise of the participants and a systematic process of constructive discussion to conform a collective position (Wrålsen et al., 2021, p. 3). Also, an online voting tool (Mentimeter) was used to enhance interaction during the workshop. The Delphi Group process consisted of three steps. First, each participant voted the weights of relevance as outlined in Section 2.3. Second, results were made available to the members of each group, to enhance discussion and try to achieve consensus. Third, weights were voted again individually, and taken as the final version. As a concluding phase, a wrap-up was conducted to summarize all the information generated and compile overall feedback on the method, including possible next steps. The validated version of the CSS was finally used to develop a Proof of Concept (PoC) to test its functionality. Data from DigiPrime (2023) was used as an input for this first application of the method; input included insights from a plant visit to a battery recycler's facility, interviews to partner organizations, collection and treatment of disassembly data, and the bill of materials (BOM).

3. Results & discussion

The results from both the prework and validation stages of the CSS are summarized in Table 2. They comprise the selected criteria, their category, description, calculation methods (for quantitative criteria), rating classes, qualification scales, weights of relevance, and general comments from the workshop.

3.1. Prework of the CSS

During the prework stage, a comprehensive list of 25 potential criteria was initially identified. Using the 'prioritization factors' described in Section 2.1, the list was then reduced to the final selection of 9 criteria which proved to comply with the specified requirements for the product category of LIBs (shown in Table 2). The most common factor for excluding criteria was the 'avoidance of double counting', which takes place when more than one criterion is found to impact the same design characteristic of the battery, or its support infrastructure. Overall, the complete original list is presented in Appendix B, together with its baseline standard or source, the decision (maintain vs exclude), and its respective justification.

This first stage was found to convey internal discussions that would become fundamental for the rest of the methodology. As an example, the battery's durability and the State of Health (SOH) are two aspects that are frequently deemed as relevant within the LIB context but were not included in the CSS. Based on the requirements for criteria presented in Section 2.1, durability is not relevant for the studied CE strategies because it provides no information about the EOL of the battery. Conversely, although SOH offers crucial information for the EOL strategies, it is not a variable that can be directly driven by the battery design, as it is mostly a consequence of the battery's usage. In this regard, it is essential to highlight the significance of defining 'requirements for criteria' that align with the goal of the CSS. This ensures that relevant discussions occur during the design phase of the methodology and directs improvements in the battery's design as intended when the CSS is implemented.

With the selected criteria, preliminary definitions, calculation methods, rating classes, and qualification scales could be assigned to be used as an input for the validation stage. For seven out of the nine criteria, the characterization required no modification from the baseline standard. For one of them ('Availability of information') the addition of a rating class was required for it to match the one to five scoring scale. However, no consensus was initially achieved for the assessment of the disassembly, for which eleven different methods were found to exist in literature, varying in their applications and data requirements (Casades et al., 2022, p. 9).

Consequently, based on the requirements of the 2023 EU Battery

Table 2
Overall results of the CSS for the LIB product-specific application.

Cat	Criteria	Definition	Method	Rating classes	Scales (1–5)	Weights of relevance per CE cluster			Comments from the Workshop
						1	2	3	
Part-related criteria	**Disassembly depth**	Measure of the disassembly complexity, based on the number of steps required to obtain a product part.	$S_{depth,i} = 1 - \frac{(D_i - 1)}{(D_{ref} - 1)}$ **Sdepth,i:** disassembly depth score for part i. **Di**: minimum number of cumulative steps to obtain part i. **Dref**: reference depth for the product group.	**0,80 – 1,00** **0,60 – 0,80** **0,40 – 0,60** **0,20 – 0,40** **0,00 – 0,20**	5 4 3 2 1	**12 %**	**8 %**	**14 %**	- Use Tasks vs Time as indicator of disassembly. - The maximum qualification should be less than 1; no part will be disassembled in 1 step.
	Fasteners and connectors classification	Classification according to the reversibility and reusability of fasteners, after they have been removed/disconnected during disassembly to obtain a product part.	**Class A:** Reusable, easy to remove. **Class B:** Reusable, difficult to remove **Class C:** Non-reusable, easy to remove **Class D:** Non-reusable, difficult to remove **Class E:** Neither removable nor reusable	**Class A** **Class B** **Class C** **Class D** **Class E**	5 4 3 2 1	**15 %**	**8 %**	**5 %**	- Incorporate measurement of ‘difficulty to remove’ in the qualification scales. * - Incorporate the impact from ’destructive steps’. *
	Necessary tools	Classification according to the availability and accessibility of tools, in order to obtain a product part.	**Class A**: Disassembly requires no tool, is provided, or is a Basic tool. **Class B**: Feasible with product-specific tools. **Class C**: Feasible with other commercially available tools **Class D**: Feasible with proprietary tools. **Class E**: Not Feasible with any existing tool.	**Class A** **Class B** **Class C** **Class D** **Class E**	5 4 3 2 1	**9 %**	**4 %**	**14 %**	- No comments
Product-related criteria	**Reusability% (Rpm)**	Proportion by mass of the product that can be reused, both for the original application and other potential applications.	$R_{pm} = \left(\frac{\sum_k m_{re\_k}}{m_{tot}}\right) \times 100$ **Rpm**: proportion of reusable components by the mass of the product. **mre**: the mass of the reusable component(s) in the assessed product. **mtot**: the total mass of the product.	**80 % - 100 %** **60 % - 80 %** **40 % - 60 %** **20 % - 40 %** **0 % - 20 %**	5 4 3 2 1	**12 %**	**17 %**	**5 %**	- Use Mass vs criticality as base indicator for the%. - Define difference between reuse and direct recycling.
	Technical Recyclability Factor (TRcyc)	Proportion by mass of the product that can be technically recycled.	$TR_{eye} = \frac{\sum (m_k \times TRCR_k)}{m_{tot}}$ **mk**: mass of the recyclable component(s) in the assessed product. **TRCR**: technical recyclability rate of the component/material. **mtot**: total mass of the product.	**80 % - 100 %** **60 % - 80 %** **40 % - 60 %** **20 % - 40 %** **0 % - 20 %**	5 4 3 2 1	**0 %**	**4 %**	**24 %**	- Guarantee updated sources for theoretical recycling rate.
Support-related criteria	**Availability of information - target groups**	Classification according to the availability to obtain the required information for a repair, reuse, remanufacture, or repurpose scenario.	**Class A**: Publicly available. **Class B**: Available to independent repair service providers. **Class C**: Available to manufacturer-authorized service providers. **Class D**: Available to manufacturer only. **Class E**: No information available.	**Class A** **Class B** **Class C** **Class D** **Class E**	5 4 3 2 1	**12 %**	**21 %**	**19 %**	- Question public availability requirement.
	Diagnostic support and interfaces	Classification according to the availability to obtain, update or reset information from the battery’s BMS (or equivalent).	**Class A**: Intuitive interface does not require supporting information **Class B**: Coded interface with public supporting information. **Class C**: Publicly available hardware/software interface **Class D**: Proprietary interface. **Class E**: Not possible with any type of interface.	**Class A** **Class B** **Class C** **Class D** **Class E**	5 4 3 2 1	**12 %**	**17 %**	**19 %**	- No comments

(*continued on next page*)

Table 2 (*continued*)

Cat	Criteria	Definition	Method	Rating classes	Scales (1–5)	Weights of relevance per CE cluster			Comments from the Workshop
						1	2	3	
	Spare parts availability	Classification according to the availability to obtain the required spare parts for a repair, reuse, remanufacture, or repurpose scenario.	**Class A**: Publicly available.	**Class A**	5	15 %	13 %	0 %	- Assess of the price of spare parts. - Assess of supply location.
			Class B: Available to independent repair service providers.	**Class B**	4				
			Class C: Available to manufacturer-authorized service providers.	**Class C**	3				
			Class D: Available to manufacturer only.	**Class D**	2				
			Class E: No spare parts available.	**Class E**	1				
	Spare parts interfaces	Classification according to the universality of the spare parts interfaces.	**Class A:** Standard part with a standard interface.	**Class A**	5	12 %	8 %	0 %	- No comments
			Class B: Proprietary part with a standard interface.	**Class B**	3				
			Class C: Proprietary part with non-standard interface.	**Class C**	1				

* Comments that were directly incorporated into the results and therefore shown in Table 2.

Regulation, information available from the product at the moment of consumption and contrasted it with the currently documented methods. Specifically, the DBP will require batteries to include and disclose its own disassembly sequence (European Commission, 2023, p. 328). However, no specification has been given on how this information should be delivered. Real disassembly data from DigiPrime was used to understand the LIB disassembly sequence. The collected data proved to be complete enough to estimate the 'disassembly depth' as defined by CEN—CENELEC. This was the preferred alternative due to the rigorous validation process that European Standards undergo. Appendix C provides a proposal on how disassembly sequences should be documented for an optimal calculation of disassembly depth.

Finally, since the composition of parts within a battery can vary substantially from one model to another (Talens et al., 2023), it was necessary to define the priority parts to assess the part-related criteria. Battery modules (BM) and the battery management system (BMS) are both parts that not only are present in all the battery packs, but also are highly relevant for the product's functionality, enable the application of CE strategies, and are particularly subjected to failure. BMs hold the battery cells, which power the system and account for a 70 % of the battery's cost (Hill et al., 2019, p. 47); the BMS controls the functioning of the system, and holds diagnostic information about the battery (such as the SOH), which helps determine the best suitable CE strategy to be applied (Albertsen et al., 2021, p. 11; Hill et al., 2019, p. 105). Overall, both parts have proved to be a hotspot of potential failure during the battery's service time (Shu et al., 2020, p. 17). For these reasons, they were both defined as priority parts.

3.2. *Validation of the CSS*

Based on the prework's outcome, the validation of the CSS brought qualitative and quantitative input from the multidisciplinary workshop to be incorporated into the final results (Table 2). In total, 15 experts attended the in-person workshop, their backgrounds are summarized in Appendix D. Observations mostly referred to the methodology, including the definition of criteria, qualification scales, weights of relevance, and general feedback about the future application of the scoring system. Regarding criteria, none of them were added or eliminated. Comments were gathered on the inclusion of the 'required skills' and 'working environment' from the battery dismantlers, but they were dismissed as these factors won't generate differentiation between LIB. However, the most discussed element was the assessment of disassembly, questioning whether to use the number of steps or the total time as the measure for 'disassembly depth'. The main argument was that labor time is closely linked to operational cost, which is a critical factor for a CBM to thrive (Albertsen et al., 2021, p. 10). However, time is also a consequence of the method employed for disassembly, and ultimately of the number of steps that are required to reach a priority part. For instance, there is a strong trend towards the automation of the disassembly process which aims to increase efficiency and safety of CE strategies (Lander et al., 2023, p. 1; Makwarimba et al., 2022, p. 26; Sommerville et al., 2021, p. 9). Nonetheless, not only this is an 'end of pipe solution', but also the efficiency of automation will depend entirely on the battery design. Therefore, we need to focus on battery features that can be changed directly through their design, such as the number of steps, and the type of fasteners employed.

Regarding qualification scales, two criteria underwent revisions. For 'Disassembly depth', experts suggested to lower the maximum scale limit to less than 1, as virtually no part can be removed in a single step. However, the parameter that accounts for variations of the S_{depth} value between parts is the 'reference disassembly depth' (D_{ref}), which also provides consistency to the method when assessing other product categories. Therefore, no change was made in this aspect. Second, 'Fasteners and connectors' had two rating classes added in comparison to the standard, as the 'difficulty to remove' was not being assessed in the original proposal. For further details on this modification, refer to

Table 3
Circularity score for a PoC performed on a real battery pack.

Criteria	Qualification	Score	Source	Comment
Disassembly depth	30 %	**2**	Site visit to recycling company and disassembly sequence from DigiPrime.	**Assumption:** Dref is the Average + 2*STD of sampled batteries from DigiPrime Project.
Fasteners and connectors classification	Class D: Non-reusable, difficult to remove.	**2**	Site visit to recycling company.	Unplanned destructive steps had to be used in some junctions.
Necessary tools	Class A: Disassembly requires no tool, is provided, or is a Basic tool.	**5**	Site visit to recycling company.	Tools for disassembly are within the "Basic tools" identified by Standard EN4555X.
Reusability% (Rpm)	56 %	**3**	BOM provided by recycling company.	Classification of reusable parts based on company's expertise.
Technical Recyclability Factor (TRcyc)	78 %	**4**	BOM provided by recycling company	Theoretical recyclability factors from IEC (2012) and Latini et al. (2022).
Availability of information - target groups	Class C: Available to manufacturer-authorized service providers.	**3**	No data	**Assumption**: Middle-case scenario based on web search.
Diagnostic support and interfaces	Class D: Proprietary interface.	**2**	Site visit to recycling company and interviews.	Site visit to recycling company and Interviews.
Spare parts availability	Class C: Available to manufacturer-authorized service providers.	**3**	No data	**Assumption**: as demanded by the New Battery Regulation.
Spare parts interfaces	Class B: Proprietary parts with standard interfaces.	**3**	No data	**Assumption**: Middle-case scenario based on web search.
Circularity score	Repair & reuse	2.78		
	Remanuf. & repurpose	2.79		
	Recycle	3.14		

Table 4
Results from the sensitivity analysis on the D_{ref} value.

		Required change in D_{ref} to change from one S_{depth} score to another						
	D_i (test)	**2**	**4**	**8**	**16**	**32**	**64**	
	D_{ref} (test)	**4**	**8**	**16**	**32**	**64**	**128**	**Average**
S_{depth} Score	**From 1 to 2**	55 %	55 %	60 %	60 %	60 %	60 %	**58 %**
	From 2 to 3	10 %	15 %	15 %	20 %	20 %	20 %	**17 %**
	From 3 to 4	20 %	35 %	40 %	40 %	40 %	40 %	**36 %**
	From 4 to 5	60 %	90 %	105 %	115 %	120 %	125 %	**103 %**
	Average	**36 %**	**49 %**	**55 %**	**59 %**	**60 %**	**61 %**	**53 %**

Appendix E.

The third element to validate were the weights of relevance voted by the experts. The obtained results were balanced with the expert judgement from the authors, to create a final version of the weight's table, which also included in Table 2. The colors in the table indicate hotspots of influence between criteria and CE strategies. For example, it was found that the recyclability potential is majorly described by the technical recyclability factor, which poses pressure on the battery chemistries and the advancement of recovery technologies. Similarly, the availability of information and diagnostic support interfaces were found to consistently influence all the CE strategies, which supports the Regulation's proposal on making information accessible and readable by the relevant economic operators. Finally, some criteria were found to be irrelevant for a particular strategy, which was expected to happen in a system where several CE strategies are assessed using the same criteria. This demonstrates the difference in nature that every CE strategy has, and therefore the importance of implementing integral assessments like this one, which allow to understand existing the tradeoffs among the EOL management alternatives.

This is why the proposed CSS does not summarize the assessment into one single score. A single score could easily be calculated through a final weighting for each CE strategy cluster, but this would implicitly set an unwanted prioritization between strategies. Besides, CE strategies are not independent from one another. For instance, incrementing battery reuse and repurpose immediately delays the availability of secondary resources from recycling (Aguilar et al., 2022; Bobba et al., 2019, p. 279; Islam and Iyer-Raniga, 2022, p. 35; Nurdiawati and Agrawal, 2022, p. 1); at the same time, having regulated targets only on recycling rates disincentivizes the investment on other strategies (Luth, 2022, p. 6). For these reasons, the results from this CSS must be interpreted with an integral perspective.

3.3. Proof of concept (PoC)

Having compiled a first version of the CSS, the PoC helped illustrate the functioning of the CSS with a real example. For this, a spent battery analysed in the DigiPrime project was selected as case study. Rather than delivering conclusive information on the assessed battery and its potential for circularity, the PoC tested the method itself. Table 3 presents the results for such assessment, while Appendix F details on the required calculations for the quantitative criteria.

Data gathering process is crucial for a successful application of the CSS. While the method itself can be easily automatable through modern technological tools, obtaining trustworthy information about the assessed battery can become a challenging task, especially when there is no direct collaboration with the corresponding OEM. For this PoC, some assumptions were taken to obtain a final score. However, this raises technical and practical requirements to the future DBP, which if intended, could compute a battery's potential for circularity.

Both the workshop and the PoC coincided on the relevance of objectively justifying the selection of technical parameters such as TCRC ('technical recyclability rate') and D_{ref}. In this case, the former was obtained from a previous standard (IEC, 2012), but the latter had to be selected from a small sample of previously disassembled batteries. To understand the influence of D_{ref} selection in the overall score, a sensitivity analysis was performed. Table 4 shows the percentage changes that are required on D_{ref} to achieve a change on S_{depth} score, which on average was a 53 % (considered a tolerable value). However, it should be noted that changes are more sensible between the middle scores (2 and 4), and less sensible as D_{ref} increases. Overall, the impact on the final circularity score is proportional to the weights of relevance for each criterion-strategy combination, meaning that a higher S_{depth} will first benefit Cluster 3, followed by 1 and 2. A tool that has proven useful in the clarification of ambiguous parameters are the 'Best Available

Techniques' (BATs). The establishment of BATs for D_{ref}, TCRC, and the specific methods for disassembly and recycling could ease the application of the CSS. Finally, the assessed battery was found to be more suitable to undergo recycling than the other two clusters, which is aligned with today's reality. This information, together with each criterion's score, can be used by stakeholders to acknowledge that further improvements on the reusability potential of parts, the availability of information on the battery, and availability of spare parts are required for the application of the more resource and energy-efficient CE strategies.

4. Conclusions

This study proposes the 'Circularity Scoring System' as a methodology to score the sustainability of batteries. It uses the existing material efficiency standards as a consistent baseline to define a set of standardized criteria to assess batteries from circular economy perspective. The scoring of some of the proposed criteria could be further adjusted as the number of batteries reaching its first end of life increases, and data becomes more available. Especially data about disassembly to account for a more robust estimate of the disassembly reference depth, and the bill of materials to account for the reusability and the technical recyclability criteria. The methodology shows that a more complete information of products allows for a more complete assessment of their sustainability. As the number of batteries become more available, the availability of methodologies to decide the most convenient circular economy strategy will be more needed. The circularity scoring system has been conceived to provide support in decision making and thus to facilitate the development of new Circular Business models. Its application would also be beneficial at the design stage where design features that hamper circular economy strategies could be avoided, and strength design for circularity practices.

CRediT authorship contribution statement

José Daniel Cruz Ugalde: Formal analysis, Methodology, Visualization, Investigation, Writing – original draft, Writing – review & editing. **Laura Talens Peiró:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

We are grateful to the participants of the workshop celebrated on May 31 2023 in Barcelona. Their input was key for revising the method detailed in this manuscript. Funding for this research was provided by the H2020 project "Digital Manufacturing Platforms for Connected Smart Factories" topic, under Grant Agreement ID 873111 which has received funding from the European Union's Horizon 2020 Framework Program, DT-ICT-07-2018-2019, the ICTA-UAB "María de Maeztu" Program for Units of Excellence of the Spanish Ministry of Science and Innovation (CEX2019-000940-M) and the TALENT UAB Santander program.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107546.

References

Aguilar, F., Billy, R.G., Müller, D.B., 2022. A product–component framework for modeling stock dynamics and its application for electric vehicles and lithium-ion batteries. J. Ind. Ecol. 26 (5), 1605–1615. https://doi.org/10.1111/jiec.13316.

Albertsen, L., Richter, J.L., Peck, P., Dalhammar, C., Plepys, A., 2021. Circular business models for electric vehicle lithium-ion batteries: an analysis of current practices of vehicle manufacturers and policies in the EU. Resour. Conserv. Recycl. 172, 105658 https://doi.org/10.1016/j.resconrec.2021.105658.

Ali, H., Khan, H.A., Pecht, M.G., 2021. Circular economy of Li Batteries: technologies and trends. J. Energy Storage 40, 102690. https://doi.org/10.1016/j.est.2021.102690.

Ardente, F., Talens Peiró, L., Mathieux, F., Polverini, D., 2018. Accounting for the environmental benefits of remanufactured products: method and application. J. Clean. Prod. 198, 1545–1558. https://doi.org/10.1016/j.jclepro.2018.07.012.

Aymerich, A. (2021). Examining the repairability of electr(on)ic products from the customer's and the manufacturer's experience. UAB.

Aymerich, A., Gasol, C.M., Talens Peiró, L., 2022. Repair of electr(on)ic products: current practices in Barcelona. Procedia CIRP 105, 104–109. https://doi.org/10.1016/j.procir.2022.02.018.

BlaBlaCar, 2023. Car Sharing platform: Travel economically and Sustainably. BlaBlaCar. https://www.blablacar.es/.

Bobba, S., Mathieux, F., & Blengini, G.A. (2019). How will second-use of batteries affect stocks and flows in the EU? A model for traction Li-ion batteries. *Resour. Conserv. Recycl.*, 145, 279–291. https://doi.org/10.1016/j.resconrec.2019.02.022.

Casades, M., Talens Peiró, L., Sanclemente Crespo, M., 2022. Review of Disassembly Methods to Assess Batteries of Electric Vehicles.

Castelvecchi, D., 2021. Electric cars: the battery challenge. Springer Nature 596, 336–339. https://doi.org/10.1038/d41586-021-02222-1.

CEN-CENELEC. (2019). *General method for assessing the proportion of reused components in energy-related products* (EN 45556; CS 13.030.50; 29.020; 31.020). https://www.en-standard.eu/bs-en-45556-2019-general-method-for-assessing-the-proportion-of-reused-components-in-energy-related-products/.

CEN-CENELEC. (2019). *General methods for assessing the recyclability and recoverability of energy related products* (prEN 45555; CEN-CLC TC10/Sec/134/DC). https://www.en-standard.eu/csn-en-45555-general-methods-for-assessing-the-recyclability-and-recoverability-of-energy-related-products/.

CEN-CENELEC. (2020). *General method for the assessment of the ability to remanufacture energy-related products* (EN 45553; ICS 13.030.50). https://www.en-standard.eu/csn-en-45553-general-method-for-the-assessment-of-the-ability-to-remanufacture-energy-related-products/.

CEN-CENELEC. (2020). *General methods for the assessment of the ability to repair, reuse and upgrade energy-related products* (EN 45554; ICS 13.030.50). https://www.en-standard.eu/csn-en-45554-general-methods-for-the-assessment-of-the-ability-to-repair-reuse-and-upgrade-energy-related-products/.

DigiPrime. (2023). *Disassembly data from three sampled batteries in Spain* . </Dataset>.

Ecorating. (2023). *Eco Rating 2023: methodology Overview*. https://www.ecoratingdevices.com/Eco-Rating-2023-Methodology-V2-Jan23.pdf.

European Commission. (2008). *Directive on waste*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098.

European Commission. (2023). *Proposal for a Regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020PC0798.

Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., Abbott, A., Ryder, K., Gaines, L., Anderson, P., 2019. Recycling lithium-ion batteries from electric vehicles. Nature 575 (7781), 75–86. https://doi.org/10.1038/s41586-019-1682-5.

Hill, N., Clarke, D., Blair, L., Menadue, H., 2019. Circular Economy Perspectives For the Management of Batteries Used in Electric Vehicles. Publications Office of the European Union.

IEC. (2012). Guidelines for End of Life information provision from manufacturers and recyclers, and for recyclability rate calculation of Electrical and Electronic Equipment. *IEC/TR 62635 Ed. 1.0*.

IRTC, 2022. The Energy-Material nexus: CRM demand, CRM footprints, and Their Interplay.

Islam, M.T., Iyer-Raniga, U., 2022. Lithium-ion battery recycling in the circular economy: a review. Recycling 7 (3), 33. https://doi.org/10.3390/recycling7030033.

Joint Research Centre. (2018). *Standards for the performance and durability assessment of electric vehicle batteries: possible performance criteria for an Ecodesign Regulation.* Publications Office. https://data.europa.eu/doi/10.2760/24743.

Joint Research Centre. (2019). *Analysis and development of a scoring system for repair and upgrade of products: final report.* Publications Office. https://data.europa.eu/doi/10.2760/725068.

Joint Research Centre. (2022). *Clean energy technology observatory, batteries for energy storage in the European Union: status report on technology development, trends, value chains and markets : 2022.* Publications Office. https://data.europa.eu/doi/10.2760/808352.

Jones, B., Elliott, R.J.R., Nguyen-Tien, V., 2020. The EV revolution: the road ahead for critical raw materials demand. Appl. Energy 280, 115072. https://doi.org/10.1016/j.apenergy.2020.115072.

Kamran, M., Raugei, M., Hutchinson, A., 2021. A dynamic material flow analysis of lithium-ion battery metals for electric vehicles and grid storage in the UK: assessing the impact of shared mobility and end-of-life strategies. Resour. Conserv. Recycl. 167, 105412 https://doi.org/10.1016/j.resconrec.2021.105412.

Lander, L., Cleaver, T., Rajaeifar, M.A., Nguyen-Tien, V., Elliott, R.J., Heidrich, O., Kendrick, E., Edge, J.S., Offer, G., 2021. Financial viability of electric vehicle lithium-ion battery recycling. iScience 24 (7), 102787. https://doi.org/10.1016/j.isci.2021.102787. –102787.

Lander, L., Tagnon, C., Nguyen-Tien, V., Kendrick, E., Elliott, R.J.R., Abbott, A.P., Edge, J.S., Offer, G.J., 2023. Breaking it down: a techno-economic assessment of the impact of battery pack design on disassembly costs. Appl. Energy 331, 120437. https://doi.org/10.1016/j.apenergy.2022.120437.

Latini, D., Vaccari, M., Lagnoni, M., Orefice, M., Mathieux, F., Huisman, J., Tognotti, L., Bertei, A., 2022. A comprehensive review and classification of unit operations with assessment of outputs quality in lithium-ion battery recycling. J. Power Sources 546, 231979. https://doi.org/10.1016/j.jpowsour.2022.231979.

Luth, J., 2022. A circular economy approach is needed for electric vehicles. Nat. Electron. 5 (1), 5–7. https://doi.org/10.1038/s41928-021-00711-9.

Madlener, R., Kirmas, A., 2017. Economic viability of second use electric vehicle batteries for energy storage in residential applications. Energy Procedia 105, 3806–3815. https://doi.org/10.1016/j.egypro.2017.03.890.

Makwarimba, C.P., Tang, M., Peng, Y., Lu, S., Zheng, L., Zhao, Z., Zhen, A., 2022. Assessment of recycling methods and processes for lithium-ion batteries. iScience 25 (5), 104321. https://doi.org/10.1016/j.isci.2022.104321.

Ministère de la Transition Écologique, 2022. Indice De Réparabilité. December 1. Indice de réparabilité. https://www.ecologie.gouv.fr/indice-reparabilite.

Nurdiawati, A., Agrawal, T.K., 2022. Creating a circular EV battery value chain: end-of-life strategies and future perspective. Resour. Conserv. Recycl. 185, 106484 https://doi.org/10.1016/j.resconrec.2022.106484.

Pagliaro, M., Meneguzzo, F., 2019. Lithium battery reusing and recycling: a circular economy insight. Heliyon. 5 (6), e01866. https://doi.org/10.1016/j.heliyon.2019.e01866.

Picatoste, A., Justel, D., Mendoza, J.M.F., 2022. Exploring the applicability of circular design criteria for electric vehicle batteries. Procedia CIRP. 109, 107–112. https://doi.org/10.1016/j.procir.2022.05.222.

Sanclemente, M., Van Ginkel, M., Talens, L., 2022. Prospects on end of life electric vehicle batteries through 2050 in Catalonia. Resour. Conserv. Recycl. 180, 106133 https://doi.org/10.1016/j.resconrec.2021.106133.

Schmaltz, T., Jung, A.-C., 2023. Europe Expands Recycling of Lithium-Ion batteries: Focus on Capacity development, Demand Analysis and Market Players. July 26. Fraunhofer Institute for Systems and Innovation Research ISI. https://www.isi.fraunhofer.de/en/blog/themen/batterie-update/recycling-lithium-ionen-batterien-europa-kapazitaeten-bedarf-akteure-markt-analyse.html.

Schulz-Mönninghoff, M., Bey, N., Nørregaard, P.U., Niero, M., 2021. Integration of energy flow modelling in life cycle assessment of electric vehicle battery repurposing: evaluation of multi-use cases and comparison of circular business models. Resour. Conserv. Recycl. 174, 105773 https://doi.org/10.1016/j.resconrec.2021.105773.

Shu, X., Yang, W., Guo, Y., Wei, K., Qin, B., Zhu, G., 2020. A reliability study of electric vehicle battery from the perspective of power supply system. J. Power Sources 451, 227805. https://doi.org/10.1016/j.jpowsour.2020.227805.

Sommerville, R., Zhu, P., Rajaeifar, M.A., Heidrich, O., Goodship, V., Kendrick, E., 2021. A qualitative assessment of lithium ion battery recycling processes. Resour. Conserv. Recycl. 165, 105219 https://doi.org/10.1016/j.resconrec.2020.105219.

Spiliotopoulos, C., Alfieri, F., Laps, E.B.E., Moeseke, T.V., Duflou, J., Dangal, S., Arriola, J.B., Bas, F., Faludi, J., Balkenende, R., 2021. Repair Score Study: Product specific Application to Smartphones and Tablets. Joint Research Centre, European Commission.

Talens, L., Fervorari, M., Alarte, F., Alvarez, B., Sanclemente, M., Colledani, M., Gabarrell, X., 2023. Envisioning the Potential Reuse and Repair of Electric Vehicle Batteries.

Tao, Y., Rahn, C.D., Archer, L.A., You, F., 2021. Second life and recycling: energy and environmental sustainability perspectives for high-performance lithium-ion batteries. Sci. Adv. 7 (45) https://doi.org/10.1126/sciadv.abi7633 eabi7633.

Tazi, N., Orefice, M., Marmy, C., Baron, Y., Ljunggren, M., Wäger, P., Mathieux, F., 2023. Initial Analysis of Selected Measures to Improve the Circularity of Critical Raw Materials and Other Materials in Passenger Cars. https://publications.jrc.ec.europa.eu/repository/handle/JRC132821.

Wrålsen, B., Prieto-Sandoval, V., Mejia-Villa, A., O'Born, R., Hellström, M., Faessler, B., 2021. Circular business models for lithium-ion batteries—Stakeholders, barriers, and drivers. J. Clean. Prod. 317, 128393 https://doi.org/10.1016/j.jclepro.2021.128393.