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Overcoming data gaps for an efficient circular economy: A case study on the battery materials ecosystem

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ABSTRACT

Data exchange and utilization are considered fundamental for the efficient development of industrial ecosystems. However, there are significant data gaps that currently prevent the implementation of circular economy models in practice. The present work is a first attempt to identify the sources of such barriers, using the battery materials industrial ecosystem in Finland as case study. A visual grounded theory model was created to formally analyze the collected interview answers from representatives of companies along the value chain. In summary, it was found that: i) companies gather information relevant for other stakeholders; ii) there are no incentives to openly share data, which is considered a valuable asset; iii) actors lack clarity on which data is relevant at a system-level; and iv) there is no consensus on which format can data be shared to efficiently promote circular economy strategies. To address the identified barriers, it is hereby proposed for the first time that parametrization is a strategy to promote data exchange between stakeholders. As an illustrative example, statistical entropy is presented as a mean to exchange data of battery material composition. Properly designed parameters could be used to codify relevant data without a negative impact on the confidentiality of companies, while at the same time providing clarity of purpose for the circular economy. Thus, this article introduces a novel perspective for the implementation of bottom-up data exchange practices in industry.

1. Introduction

The impact of data flow in our modern society has gained such relevance that "*dataism*" has been named the "techno-religion of the 21st century" by anthropologist and best-selling author Yuval Noah Harari (2015). *Dataism* can be defined as the philosophy that places information flow as the supreme value and considers the probability of success of any system in terms of the efficiency of data flow. It is important to emphasize that according to this philosophy, systems are not meant to simply generate or collect data, but rather develop effective means by which such data is transmitted. This raises the question on whether the current data flows in industrial ecosystems are efficient, especially between actors at various stages of the value chain. By definition, the concept of circular economy (CE) requires the analysis of material life cycles at a systemic level (Velázquez-Martínez et al., 2019a), creating new demands for analyzing, utilizing, and sharing industrial data (Gupta et al., 2019; Kristoffersen et al., 2020). As digital technologies are seen paramount for CE implementation, they also pose new challenges for information logistics in the field (Kristoffersen et al., 2021).

Nevertheless, there has been little attention paid on the gaps and barriers preventing the flow of relevant data throughout the whole value chain in CE systems (Hakanen and Rajala, 2018). Currently, materials are transferred from one actor to another in the value chains, but the associated data generated during each transformation and utilization stage is not (Hakanen et al., 2017; Lieder et al., 2017). It is thus paramount to start identifying the perceived data gaps in CE in a systematic fashion in order to propose practical alternatives to overcome them (Acerbi and Taisch, 2020).

The present work identifies the perceived limitations of data utilization in CE, building on the case study evidence derived from the Finnish battery materials ecosystem. The rechargeable batteries ecosystem was chosen due to its present socioeconomic importance, particularly regarding the ambitious global targets on the electrification of transportation (Pagliaro, and Meneguzzo, 2019; Baars et al., 2021). In addition, Finland counts with industrial activities throughout the entire value chain of batteries. As will be seen however, the findings are not specific to this product or geographical region and reflect the needs for data exchange in a broader context to support the implementation of

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circular solutions.

2. Background

The CE concept has surged into mainstream academic discussion during the last two decades (Blomsma and Brennan, 2017), although such thinking links back at least half a century (cf. Boulding, 1966). The perceived environmental benefits of CE have driven researchers, practitioners, and governments to search for options to transform traditional linear economy toward CE (Sauvé et al., 2016). After a thorough review of CE definitions, Kirchherr et al. (2017) concluded that the CE can be considered an economic system where the four "R-principles" of waste management (i.e., reduce, reuse, recycle and recovery) are implemented to achieve a sustainable consumption of raw materials. Although usually considered a strategy supporting sustainable development, CE focuses primarily on economic prosperity and resource efficiency (Geissdoerfer et al., 2017; Makov and Vivanco, 2018).

CE is thus an industrial ecosystem that can be defined from the perspective of micro-, meso- or macroscopic systems depending on the geographical limits set for it (Kirchherr et al., 2017). The strategies to implement CE solutions can be *bottom-up*, following the own initiatives of the involved economic actors, or *top-down*, driven by regulatory demands. The *bottom-up* perspective is of particular interest in the present study since it responds to organic changes within the industrial ecosystem and is thus less prone to face resistance from the relevant economic actors. Adequate data and information resources are required to support appropriate decisions from the different evaluation perspectives (Acerbi and Taisch, 2020).

Various types of data have been identified as beneficial for CE implementation. For instance, the review by Luoma et al. (2021) distinguished four types of data clearly associated with CE needs: customer behavior data; product/service lifetime data; system performance data; and material flows data. The importance of different types of data depends on the application, but their successful utilization is not trivial, as it should address systemic-level demands. Enhancing CE would transform previous linear supply chains to more open instances of cross-sectoral collaboration (Köhler et al., 2022), requiring alignment of interests among the organizations to facilitate sustainable development (Herrero-Luna et al., 2022). The organizations thus become increasingly reliant on active collaboration among different actors in realizing, providing, and partaking in the value creation (Chesbrough et al., 2018). In consequence, new capabilities to transform the raw data into useful information are required (Chen et al., 2015), potentially with the support of external partners (Gao et al., 2020; Kristoffersen et al., 2021). This amplifies the need for trust among the actors in the value chain (Rajala et al., 2018). While trust is strongly driven by social aspects and people, it has been noted that the strategies for CE and circular manufacturing tend to ignore them as fundamental parts of the ecosystem (Acerbi and Taisch, 2020).

Moreover, despite its presumed importance for the CE (Luoma et al., 2021), limited attention has been placed on how data could be utilized in increasing circularity at a systemic level. Data can provide value in various types and forms within the CE (Gupta et al., 2019) but too often the studies have focused on a single strategy rather than employing a holistic perspective over the whole system (Acerbi and Taisch, 2020), calling for more attention toward the overall systemic logic (Fehrer and Wieland, 2021). For instance, data can promote circularity by providing the necessary input to determine circularity parameters (Harris et al., 2021; Velazquez Martinez et al., 2019b). Clearly, data and actions are linked to CE by advancing the different R-principles of waste management and benefit from distinctive promotion means that advance one or several of these principles (Bressanelli et al., 2018). This paper extends these views by identifying the perceived data gaps and the limitations of data utilization in the circular economy of rechargeable batteries.

3. Methodology

This exploratory, qualitative case study aims to identify data gaps and their effects on circular economy implementation in the investigated industry. The research applies methodological prescriptions on theory-elaborating case studies (Ketokivi and Choi, 2014), abductive reasoning (Dubois and Gadde, 2002), and inductive data analysis (Gioia et al., 2013). The study focuses on developing a contextual understanding of the research setting and connecting deeply with the research participants, in an attempt to "see the world from their viewpoints" (Corbin and Strauss, 2015, p. 27). This research focuses on rechargeable batteries – a notable instance for CE targets (Baars et al., 2021; Velázquez-Martínez et al., 2019a) – with the Finnish battery "ecosystem" chosen as the primary case due to the reasons mentioned above. Finland is considered as a frontrunner in having the regulatory emphasis and political statutes on improving the circularity of batteries, being one of the first countries to publish a national battery strategy (The Finnish Ministry of Economic Affairs and Employment, 2021). Finland has companies operating in all the steps in the primary value chain: materials, batteries and cells, applications, reuse, and recycling. The industry is hosted in an ecologically and socially stable environment, with plentiful mineral resources and technological know-how, especially related to metals and minerals processing. However, some challenges still exist, and more work is called for to explore and unleash synergies within the industry and actors. Both nationally and internationally (The Finnish Ministry of Economic Affairs and Employment, 2021). Continuing the research about the role of data in facilitating CE (Kristoffersen et al., 2021), this study focuses on the potential of data as a facilitator of CE and investigates the 'data gaps' in the context of Finnish rechargeable battery industry as the main unit of analysis.

This research relies on abductive reasoning for the purpose of theory elaboration (Ketokivi and Choi, 2014). Hence, the overall goal of the data collection was to obtain views and information from all the stages of the value chain. This approach to data collection follows the principles of *theoretical sampling*, to "collect data from places, people, and events that will maximize opportunities to develop concepts in terms of their properties and dimensions, uncover variations, and identify relationships between concepts" (Corbin and Strauss, 2015).

Theory elaborating research seeks to match existing theoretical concepts and perspectives with the context-specific observations from the case. The purpose of the researcher is not to produce new theory, nor test it, but rather to interpret the contextual idiosyncrasies of the case as practical representations of the more general theory and concepts (Ketokivi and Choi, 2014). In this process, the researcher moves continuously between the empirical and conceptual world, learning closely from the particular case (Dubois and Gadde, 2002), but also challenging the existing views (Ketokivi and Choi, 2014). This study focused on elaborating the theoretical concepts explicating the relationships within CE and data-driven businesses. The abductive, theory elaborating reasoning was supported with a scrutinous inductive data analysis, following the prescriptions set by Gioia et al. (2013) to provide a systematic and transparent data structure to visualize the data coding and categorization. The overall research process is depicted in Fig. 1, indicating how the research combined abductive and inductive analyses.

The research data collection relied on semi-structured interviews ($n = 22$), conducted in May–June 2021. The informants were company representatives within the battery value chain and external experts with a broader knowledge of the ecosystem. The interviews were recorded and transcribed verbatim, producing over 200 pages of text. At least one representative from each step of the value chain (materials, batteries and cells, applications, reuse, and recycling) was interviewed. The following criteria was set to support our analytical trail (Corbin and Strauss, 2015): the informants had to i) work with data-related topics; ii) possess hands-on knowledge about the data needs, availability, and utilization within the company; and iii) have an upper or middle management role in the company. Details of the interviewees and the

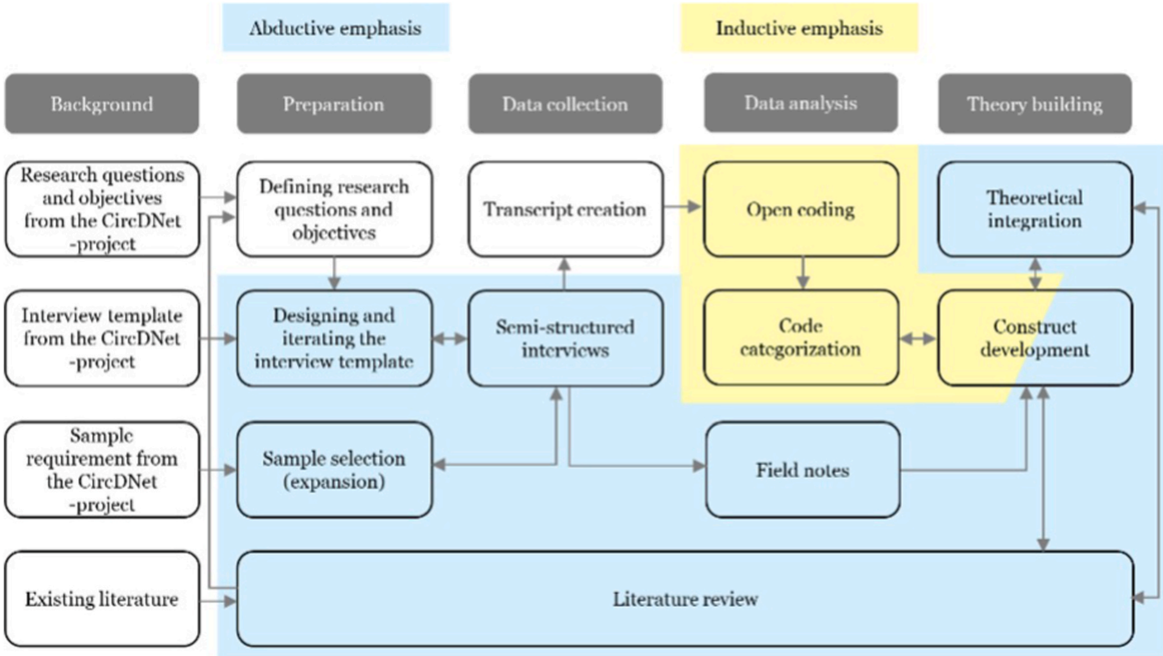

Fig. 1. Visualization of research methodology (Ikonen, 2021).

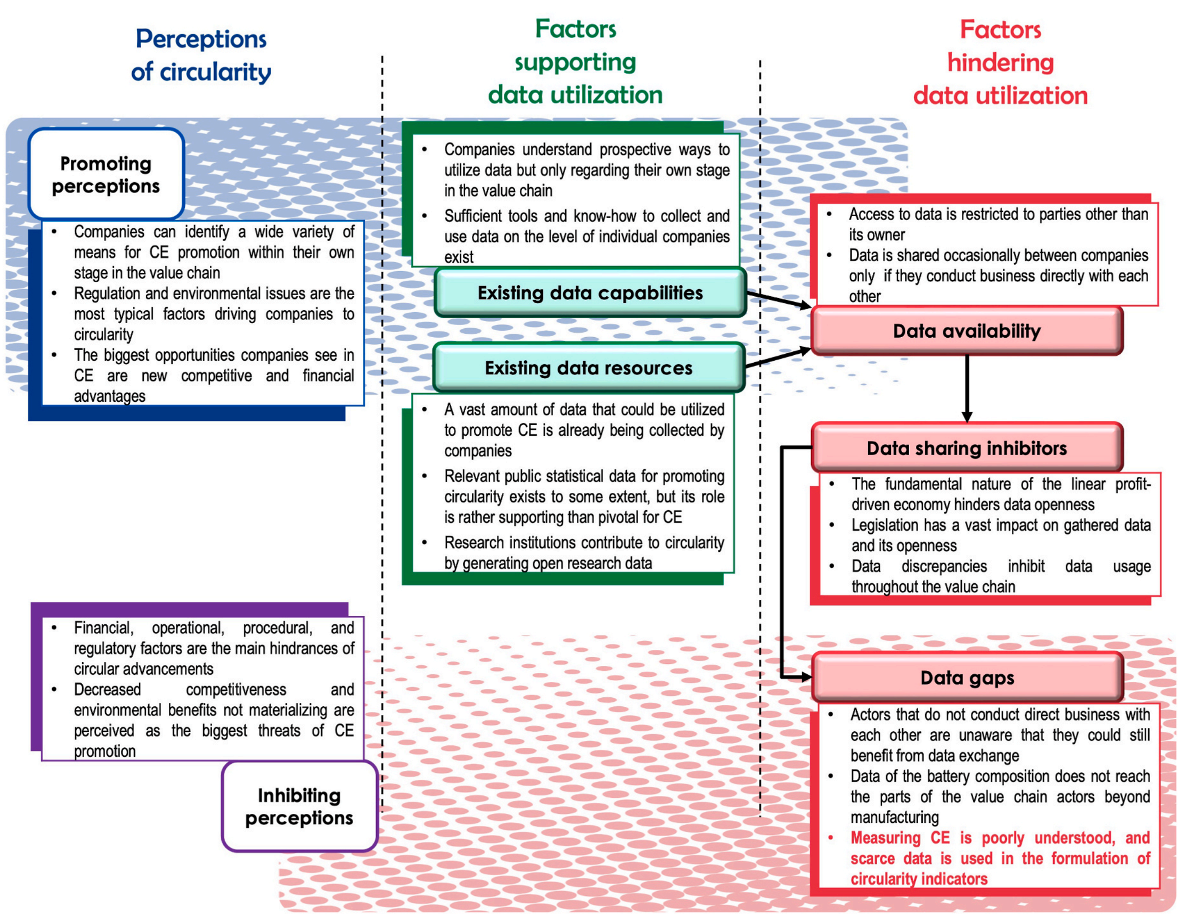

Fig. 2. Visual grounded theory model on data gaps for the CE of batteries.

guiding interview questions are found in the Supplementary Information section (Tables S1 and S2, respectively).

The data analysis followed the principles for inductive coding suggested by Gioia et al. (2013). The purpose of this work was to provide a transparent and logical representation of the empirical evidence to support the systematic combining within abductive analysis (Dubois and Gadde, 2002) and the work on theory elaboration (Ketokivi and Choi, 2014). A threefold data structure – 1st and 2nd order codes and aggregate themes – was constructed to articulate the progression from the empirical data to codes, themes, categories, and constructs (Gioia et al., 2013). The 1st order codes were derived directly from the interview materials, producing 18 categories that summarized the most relevant viewpoints of the informants regarding the value of data for CE. Next, these 1st order codes were structured under seven 2nd order codes to indicate common aspects behind the findings, e.g., related to 'data availability' or 'existing data capabilities.' Lastly, three aggregate themes were defined to summarize the different perspectives, labeled as 'factors supporting data utilization,' 'factors hindering data utilization,' and 'perceptions of circularity.' These results will be elaborated next.

4. Results

The first research question in this work considered how data gaps are currently hindering advancements of circular economy in the rechargeable batteries industry, while the second question is why these data gaps exist. Based on the data collected through interviews, the visual grounded theory model presented in Fig. 2 was created. The main findings on each of the grounded theory categories identified are detailed in the next Subsections.

4.1. Perceptions of circularity

In the first place, it was found that data gaps are influenced by the perceptions and corporate culture of the CE actors. Understandably, the interviewees have subjective perceptions that influence their answers. However, the collected answers can be used to identify company-wide perceptions and general trends.

For instance, while companies foresee potential strategic and financial opportunities related to new circular models, decreased competitiveness is perceived as one of the main threats of circularity. From the financial perspective, this clearly impacts their strategic decision-making, as presently, the assumed financial opportunities of CE remain uncertain. In other words, the current perceptions of financial gain and confidentiality are maintaining the *status quo* where open data sharing is not encouraged.

Instead, companies claim to be driven towards CE mainly by regulation and public demands on environmental issues. The environmental benefits of circularity are not perceived to have enough value to be pursued without external pressure. Looking at the combination of regulation and public image as the main drivers towards CE, it can be established that companies still perceive that top-down strategies are needed to motivate circularity advancements.

The second apparent threat of CE is whether the expected environmental benefits will be realized after modifications in the stakeholders operations. Based on existing literature, this is a valid concern as several authors consider that environmental sustainability is not embedded by definition in the circular economy (Allwood, 2014; Murray et al., 2017; Geissdoerfer et al., 2017; Zink and Geyer, 2017; Korhonen et al., 2018). As will be further discussed in Section 3.4, due to the absence of standardized circularity indicators, the prevailing notion is that companies cannot measure their progress towards environmental impact reduction through circularity strategies.

The study found that hindrances to circular advancements are perceived to result from financial, operational, procedural, and regulatory factors. Surprisingly, the interviewees did not consider data gaps as one of the main obstacles of their circularity strategies. Instead, companies see data has a supporting role by which these aspects can be improved, with data collection considered an enabler with low priority, similarly as De Mattos and de Albuquerque (2018) and Frishammar and Parida (2019) suggest. This is already problematic since the importance of data related to promoting CE might be overlooked, leading to a low motivation to promote data sharing.

4.2. Factors supporting data utilization

The interviews also shed some light regarding practices that support data utilization. Firstly, it was pointed out that some institutes in the public sector have generated openly available data that can be used in circularity promotion. However, the general feeling among the interviewees was that this freely accessible data is not sufficient to fill all data gaps in the ecosystem. This was admittedly considered unrealistic since the required data is in many cases too case specific for any public institutions to offer. Thus, while the publicly generated data is not solving the existing data gaps, its insufficiency is rather related to the widely varying needs of the different actors in the value chain.

Considering the means in which data can promote circularity identified in the existing literature, most were addressed during the interviews (see Table 1). Comparing the various R-level strategies, actions related to recycling and recovery were more commonly mentioned than means related to reducing or reusing. Such bias reflects a stronger association by the general public between circularity and recycling compared with other Rs. Another prejudice was also found in the increased emphasis that companies had on the "inward-focused approach" proposed by Luoma et al. (2021), where data is used to optimize the circularity within the value chain stages, as opposed to the "outward-focused approach," where the focus is on data utilization to promote consumption of more circular products.

It was also found that some of the data considered missing by some actors, was collected at some part of the value chain, as exemplified in Fig. 3. In other words, the data required for circularity promotion based on the practical experience of companies may already exist at various levels. Accordingly, data collection cannot be considered as the primary reason behind the data gaps.

Several capabilities are crucial for companies to efficiently utilize data in circularity promotion. Certainly, companies gain value from data only if they can exploit it to generate insights that lead to better decisions (Grover et al., 2018). In this respect, the interviewees claimed to have the tools and know-how to collect and use data, with the caveat that this should be directly related to their business. These tools allow them to transform data into useful knowledge with the potential to support CE. Companies also considered to have a good understanding on the type of data that could be utilized to improve the circularity of their own business. According to Rajala et al. (2018), this understanding is necessary for companies to apply data in their ecosystem-wide CE promotion. However, the perception of companies related to technology implementation in the metals and mining industry, including data utilization, might differ from their actual capabilities (Gao and Hakanen, 2021). Indeed, there may be a biased perception on the competence of companies, particularly when dealing with vague concepts such as sustainability or circular economy. The interview answers showed that the perceived capabilities become insufficient when dealing with data processed by third parties.

One of the main challenges identified is a lack of understanding on how other actors in the value chain could utilize data to promote circularity. Research considering how third-party data utilization can impact systemic-level circularity implementation is sorely needed. However, based on the extensive consensus in the existing literature on the importance of collaboration, it can be assumed that this lack of understanding and the absence of data sharing platforms are a real contribution to the data gaps. As will be discussed in the next subsection, difficulties in utilizing data collected by other actors were commonly mentioned.

Table 1
Examples of data needs to promote the various R-levels of circular economy.

R-level	Promotion means	Type of data needed (Luoma et al. (2021) categorization)	Identified in interviews (Section 3.2)	Reference
Reduce	Design products that people get attached to	Customer behavior data Product/service lifetime data	No	Bressanelli et al. (2018) Luoma et al. (2021)
Reduce	Optimize use phase	Customer behavior data Product/service lifetime data	Yes	Bressanelli et al. (2018) Rajala et al. (2018)
Reduce	Optimize maintenance	Product/service lifetime data	Yes	Alcayaga et al. (2019) Bressanelli et al. (2018) Gupta et al. (2019) Spring and Araujo (2017)
Reduce	Reduce demand for excess capacity	Customer behavior data Product/service lifetime data	No	Bressanelli et al. (2018) Spring and Araujo (2017)
Reduce	Optimize production process	System performance data Material flows data	Yes	Acerbi and Taisch (2020) Nascimento et al. (2019) Rajala et al. (2018)
Reduce	Simulate the production process	System performance data Material flows data	Yes	Lieder et al. (2017) Nascimento et al. (2019)
Reduce	Integrating processes or sharing resources within the value chain	System performance data Material flows data	No	Gupta et al. (2019) Hakanen and Rajala (2018)
Reduce	Supply chain optimization	Material flows data	Yes	Hakanen et al. (2017) Rajala et al. (2018)
Reduce, Reuse	Design products with better durability	Customer behavior data Product/service lifetime data	Yes	Bressanelli et al. (2018) Luoma et al. (2021)
Reuse	Promote second-hand sales	Customer behavior data	No	Alcayaga et al. (2019)
Reuse	Promote upgrades	Product/service lifetime data	No	Pialot et al. (2017) Khan et al. (2018)
Reuse	Identify new reuse innovations	Product/service lifetime data	Yes	Rajala et al. (2018)
Recycle	Improve recycling process efficiency	Material flows data	Yes	Nascimento et al. (2019)
Recycle, Recover	Increase material recovery rates	Material flows data	Yes	Nascimento et al. (2019)
Recycle	Capture value in the recycled assets	Material flows data	Yes	Hakanen et al. (2017) Mishra et al. (2018)
Recycle	Design products that are easily recyclable	Material flows data	Yes	Favi et al. (2019)
Recycle, Recover	Identify the right time to recycle	Product/service lifetime data	No	Li et al. (2015)
Recycle, Recover	Optimize end-of-life activities	Product/service lifetime data	Yes	Bressanelli et al. (2018) Khan et al. (2018) Li et al. (2015) Go et al. (2015)

4.3. Factors hindering data utilization

The study results indicate that the data gaps exist primarily due to limitations in data accessibility, with minimal data sharing to third parties. Data is shared only between companies that conduct business with each other, and even then, it is occasional and heavily controlled by strict specifications and rules. In fact, some interviewees stated that their company would unlikely collaborate with another solely for data sharing purposes. Consequently, data from one actor in the value chain never reaches actors beyond those in the immediate stages of the life cycle. Based on the existing practices, this behavior is understandable, as data is typically equated with valuable know-how and confidentiality practices encourage this behavior. The inherent challenge is that there is no natural way to build trust for companies that do not otherwise conduct business with each other. On the other hand, customer-supplier dynamics are capable of building relationships of trust, hence facilitating data exchange. One of our interviewees (Process engineer, Manufacturing) stated for example: "*with customers, we share quite a lot of data because, [if] we get to develop our products together with the customer, [it] brings value to both.*" Perhaps it is necessary to promote a vision in which, due to the cyclic nature of the circular economy, all actors in the value chain are at some point customers and suppliers. As mentioned in the work by Gupta et al. (2019) trust, commitment, and accountability are prerequisites for information exchange, an aspect vital to implementation of circular supply chains.

Companies also named several factors hindering data openness that can be related to the dominant linear economy models. Understandably, all actors are accustomed to operating in an economy prioritizing profits over environmental impact. According to our findings, companies regard data as a strategic resource and the focus on economic gains makes circularity implementation challenging (Sauvé et al., 2015). Data is considered a mean to generate competitive advantages and a factor that could sabotage the financial gains of companies if revealed to competitors. These comments are in line with previously published research claiming that confidentiality is one of the main issues currently hindering data collaboration in CE promotion (Tseng et al., 2018).

Due to the perceived strategic importance, the risks are considered too high in comparison with the financial benefits of data sharing. In the linear economic system, it is understandable that companies want to avoid the strategic and financial risk directly associated with data sharing. The societal and environmental risks posed to the entire value chain by hindering circularity implementation are thus given a lower priority. To overcome the financial risk, many companies report strict policies for data sharing, leading to the current situation where only a minimal amount of data is accessible. These practices are standard in all companies and across all data, although it is likely that only a fraction of

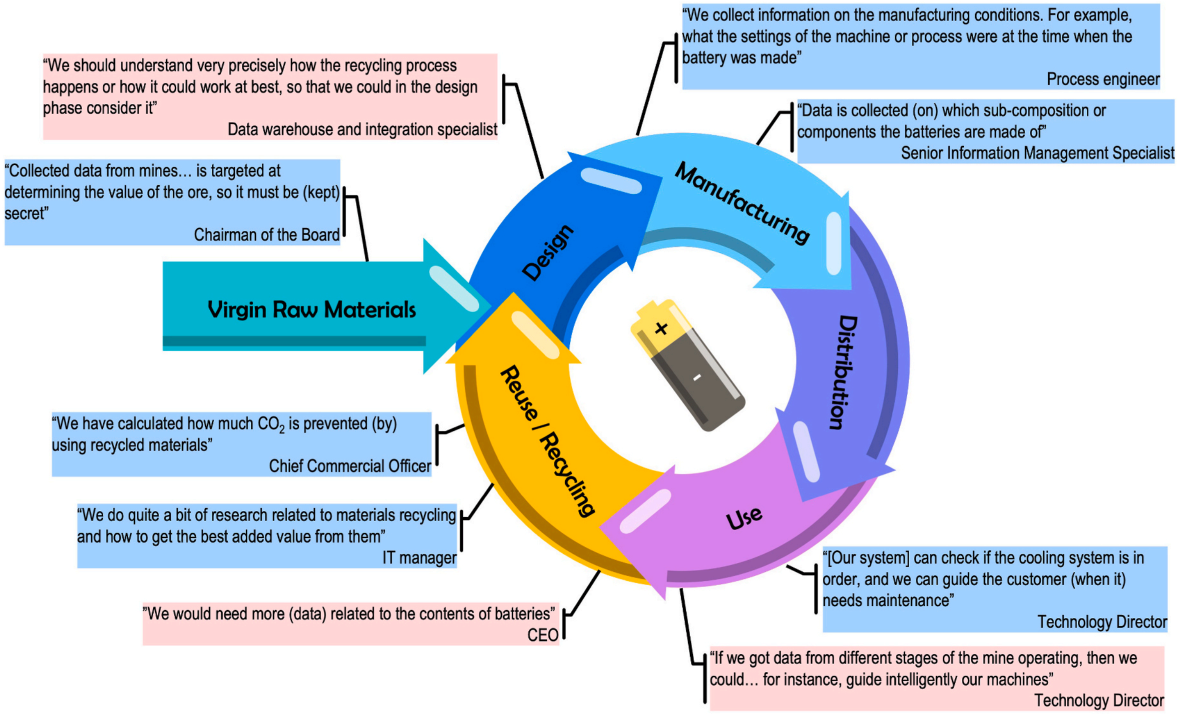

Fig. 3. Example statements on data collection practices (light blue) and perceived data needs (light red) throughout the battery materials industrial ecosystem.

it is strategically critical. In practice, data with various degrees of sensitivity are treated similarly for the sake of simplicity. Yet, there also seems to be an emotional component related to the perception that all data is valuable and giving it away is unequivocally a disadvantage.

Overall, companies seemed to take a similar attitude towards data ownership as with any other resource and thus, they expect compensation if some other actor uses this resource. However, Shapiro and Varian (1999) famously stated that the nature of data is vastly different compared to physical goods and proposed that maximizing data protection rather hurts than benefits capturing its full value. Accordingly, value maximization for data happens through different means than concrete physical resources. And according to Barbrook (1998), companies get the full value of their data most likely by making it available for others, enabling so-called "hi-tech gift economy." As mentioned in the introduction, it is data transfer and not its collection that determines the most efficient systems. Findings supporting this claim have also been made by other researchers. For instance, Turunen et al. (2018) found that in industrial service networks, mere data ownership or exclusive access do not provide strategic advantages. Instead, they suggest companies succeed when they can utilize and steer vast information flows. This differing nature of data compared to physical resources was overlooked by the interviewees, reflecting a mindset in which data should be protected from other actors in the value chain. From a systemic perspective, the actions that companies take to protect their data in pursuit of gaining strategic advantage might even be doing the opposite. Admittedly, it may be challenging to identify which of the large amounts of data gathered is relevant for the CE to begin with. It is thus necessary to find a vehicle by which data can be shared without the fear of revealing strategic and confidential information.

Another common perception among the interviewees is that current legislation is not optimal in encouraging companies to share data in pursuit of circularity. The European Union General Data Protection Regulation (GDPR, European Union, 2016) for instance, limits what data companies can gather, store, and share, especially related to the consumption phase of batteries. The GDPR affects the handling of data on customer behavior, and product and system lifetime data. All such data can only be collected and shared in a limited fashion, under the threat of strict financial penalties. Although this is understandably aimed at privacy protection, this could be a significant hindrance for circularity, as research has shown that understanding customer behavior is integral for CE (Lieder and Rashid, 2016). On the other hand, legislation could be especially useful in overcoming some of the issues posed by the linear economy and its financial objectives. For example, Sauvé et al. (2016) noted the potential for authorities to intervene in the challenges promoted by the current economic system. Incentives are instruments that could make sharing data sensible from the financial perspective of a company. Andersen (2007) suggested that circularity could become attractive to business managers if legislators forced companies to cover the actual environmental costs for their actions.

Finally, data discrepancies hinder the utilization of data from and by other actors. Each company within the value chain currently has its own data systems, formats, and structures, leading to data not being commensurate across the value chain. As stated by one of our interviewees (Technology Director, Applications): *"If we want [data] from some customer's background system or from some other device manufacturer's system … there are many, many types of standards and the data [are] in different formats and there are different information systems, data sources, and it is quite some mishmash (sic) in the end. So, if that data [is transferred] to our servers … then it might be that it needs nine months of software development before one gets computers to send [the data]."*

Utilizing combined data from several sources would require transforming it into a standardized format, which was considered laborious, time-consuming and costly by the interviewees. Data discrepancies thus hinder data sharing from the perspective of the receiver and user of the data. Both Rajput and Singh (2019) and Tseng et al. (2018) noted that data discrepancies hinder the application of tools necessary to advance CE strategies. Evidently, this is a practical gap that could be overcome by proper standardization of data, although this is not currently promoted by neither legislation nor professional associations.

Data discrepancies also indicate the absence of data-sharing structures throughout the value chain. While companies did claim to have sufficient resources and capabilities for collecting and utilizing their own data, these capabilities do not yet exist at a system-level perspective. Companies do not have protocols to successfully transform data collected by other actors into a useable format since no standard exists. Interestingly, interviewees considered this as an inhibitor for data sharing on which their companies have little influence.

5. Discussion

Based on the results presented above, the following general trends were identified:

1. Companies gather information on a regular basis to carry out their operations
2. It is unlikely that companies will open the access to all their information, as this is considered a valuable asset, unless pressured through strict legislation
3. Even if companies were forced to share information, it is unclear which of it is relevant for circularity strategies and what would be the right format to allow a seamless flow of data between actors
4. There are no means to measure circularity being implemented by companies to corroborate the impact and potential success of new operating strategies or business models

Taking all these points into consideration, there is a clear need to find a channel that allows the exchange of data in a manner that does not affect the internal know-how of the companies and that is specifically relevant to trace the effectiveness of operational strategies from the perspective of circularity. Our subsequent argument is that these conditions would be met by using relevant parameters developed for the circularity of systems. Indeed, parametrization for the circular economy is needed, as the current operations continue to be evaluated using traditional metrics based on the paradigms of the linear economic. As seen in the answers compiled in Table 2, various interviewees identify the absence of circularity indicators as a shortcoming. Parametrization is thus an untapped opportunity to enable the flow of data between companies if the proper indicators and targets are widely implemented.

The search for quantitative and qualitative parameters to evaluate circularity is an endeavor that has caught the attention of researchers in the field, as exemplified by recently published reviews on the matter (Kristensen and Mosgaard, 2020; De Pascale et al., 2021). The obvious need for these indicators is the evaluation of materials circulation efficiency and their social or environmental impact, but their utility as means to promote data exchange has been overlooked so far (to the best of the authors' knowledge).

As an illustrative example, one can consider the use of statistical entropy (SE), a parameter that has been recently studied to trace material flows in recycling processes for batteries (Velazquez Martinez et al., 2019b) or automotive materials (Roithner et al., 2022). Due to space limitations, a detailed description of the SE methodology is not included in the present work, but the interested reader is referred to the above-mentioned works, and the texts by Brunner and Rechberger (2011) and Velázquez-Martínez et al. (2019c). Briefly, SE can be defined as a mathematical analogy of thermodynamic entropy used in information theory to trace information gains or losses in a system. When applied in combination with material flow analysis, SE can provide a measure of materials concentration (information gain) or dilution (information loss) at a systemic level, i.e., taking into account all existing streams, be it product, byproduct, or waste. Applied as a circularity indicator, SE has been used to trace the impact of transformative stages in the value chain on materials flows. In such context, lower entropy levels are favored, as they reflect the effective minimization of material losses. In other words, this parameter helps decision makers to identify technologies and managerial strategies that prevent material losses, thus reducing the associated environmental impact. Furthermore, SE and material flow analysis are independent to the size of the ecosystem and can thus be implemented at micro-, meso- or macroscopic-levels.

In the hypothetical scenario illustrated in Fig. 4, the actors in the value chain could be exchanging data in the form of SE values at the end of their transformation stages. As the circularity parameter has embedded the data specifically relevant to evaluate the circularity of the system (in this case, materials preservation), the detailed operational data could remain the sole property of the companies. The collective actions would be focused on minimizing the entropic levels, considering for instance the concentration of raw materials before manufacturing as a target point of minimum SE. In this scenario, the impact of design/manufacturing strategies on the ease of collection or the recycling efficiency would be reflected in values of SE further down the battery lifecycle (i.e., SE_0 or SE_1, respectively). In turn, SE analysis can be a tool for the evaluation of new recycling processes, but also fosters cooperation for the optimization of products and materials formulations that ease their recovery. The role of extractive activities could also be redesigned as a mean to replenish materials flow, with processes being designed strictly to maintain SE_3 at a target value. The latter would evidently minimize the resource depletion associated to mining activities. Discussions and subsequent decisions at the system level would then be carried out based on their impact on the SE value at any given point in the life cycle, maintaining the internal operations as "black boxes" from the other actors. Circularity indicators, such as SE, thus become the vehicle by which the necessary data is transmitted without interference on the strategies and competitive advantage of companies. Also, by not representing a mean imposed by legislation, the resistance of companies to implement them may be alleviated. Admittedly, the challenge remains on identifying relevant parameters and reaching a consensus on which should be used across the entire value chain. Nevertheless, this work offers a strong argument to support further research on the development and testing of circularity parameters.

This research extends the views on the collaborative benefits of sharing data and information in the implementation of a CE model. The general trends identified in this study corroborate the views that embracing CE and data sharing among companies is not merely a strategic challenge (Acerbi and Taisch, 2020), but may require a complete restructuring of operations and practices across the industry (Hakanen and Rajala, 2018). The social aspects behind data sharing must not be

Table 2
Selected quotes from interviews on parametrization needs.

"If we think about things related to … improving the circularity rate (of a product) … then that is not only in our hands, it requires a common playbook throughout the entire value chain. So, how things are done and how [the product] was thought through already in the design phase from the cradle to the grave. If we envision it like this … then we would need quite a lot of data that we could utilize in the design - how we could do this optimally from the perspective of circularity."	Data warehouse and integration specialist, Manufacturing (Cells and batteries)
"As we have this producer responsibility for batteries, you can get (data on) ***how many*** *non-rechargeable* ***batteries, rechargeable batteries*** *and* ***lead-acid batteries*** *there are,* ***but there it actually stops****. What if we had much more in much more detail?"*	Specialist, Consulting
*"****Measuring*** *overall is quite a* ***very important*** *thing because according to old truths, you get what you measure, but it can be that* ***one indicator can be difficult to determine directly****."*	Technology manager, Applications
"But as these [regulatory] requirements [for circularity] come, in order for them to be fulfilled then it requires tracking, so ***[indicators]*** *are the* ***core and the key aspect****."*	Specialist, Consulting
"We go reporting technicalities so (regulatory targets) are met, which ***everyone for sure meets as long as they are creative enough****."*	Chief Executive Officer, Recycling

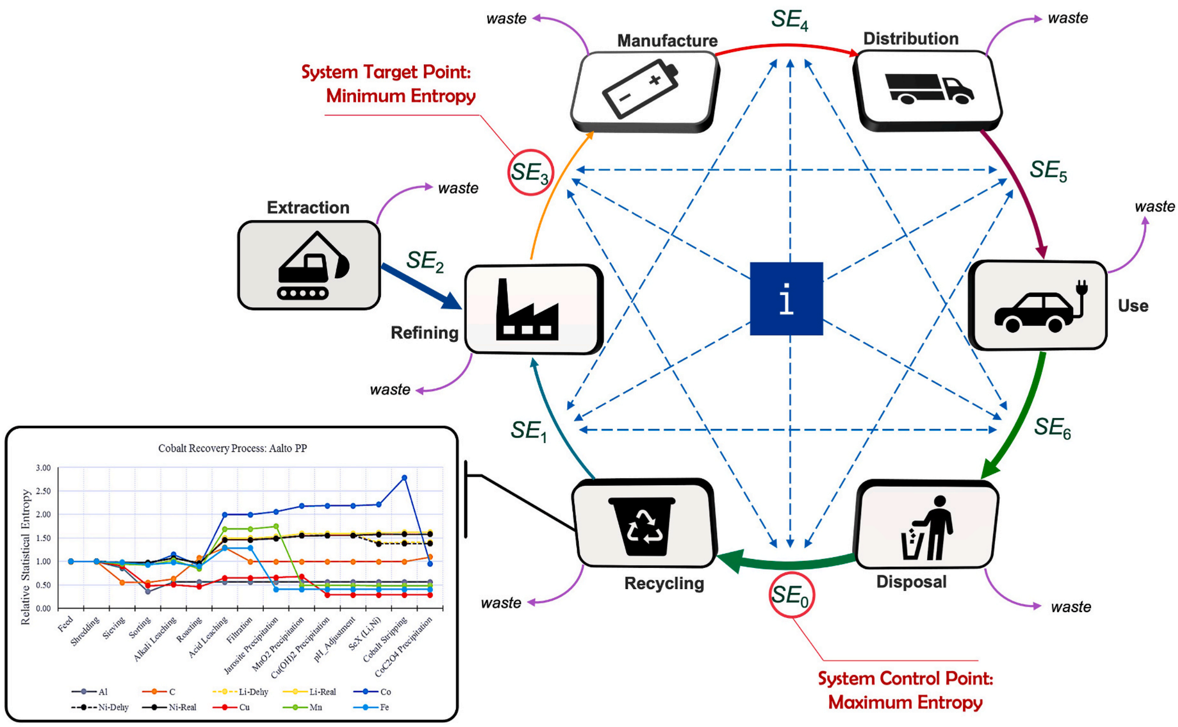

Fig. 4. A visual concept in which statistical entropy (SE) is used as a system-level circularity indicator: SE values can be exchanged at the interface levels while keeping internal data within a black box and system-level targets accordingly set; the inset example shows the SE analysis of a recycling process published by Velazquez Martinez et al., (2019a)

overlooked (Acerbi and Taisch, 2020) as, while political frameworks have been identified as potential enablers of the CE (Rajput and Singh, 2019), enforcing data sharing through legislation is effective only if the data is utilized properly. It is likely that an important part of the value of data for CE derives from an “inward-focused” approach, involving real-time and historical material-flow data (Luoma et al., 2021), highlighting the role of collaboration across industry to form a shared meaning for the accumulated item-level data, also referred to as “material intelligence” (Hakanen et al., 2017). Overall, the findings of this study support the views arguing the need for more trust, interaction, and collaboration among the ecosystem stakeholders (Gupta et al., 2019; Rajala et al., 2018).

6. Conclusions

The current data gaps hinder advancements of the CE by limiting the optimization of strategical actions to isolated stages of the value chain and only to the extent that is possible without data collected by other actors. Clearly, optimal and efficient circularity implementation is not happening for individual companies, let alone value-chain wide. With the existing data gaps, innovations on data utilization are not pursued and its value is not fully captured. This is problematic in all ecosystems but is particularly relevant in the context of products such as the rechargeable batteries, where governments worldwide have placed ambitious circularity targets due to the criticality of its raw materials.

This study shows that companies within the recyclable batteries value chain have limited knowledge related to circularity indicators and are not actively pursuing their use, although parametrization is acknowledged as a vital concept. Utilizing circularity indicators requires vast data inputs, but they can provide clear guidance on which information is relevant to trace the impact of circularity strategies. Indeed, parametrization is a prerequisite for the effective cooperation and promotion of CE ecosystems, including management decisions, policies, and new technologies. Circularity indicators may also serve as a practical vehicle by which relevant data is exchanged without compromising sensitive data of companies. In the absence of system-wide indicators, companies are at risk of making uninformed decisions related to circularity without fully understanding the impacts and ramifications of their actions. This work is thus a call for action to experts and decision makers worldwide and sets the basis for further research on circularity indicators and implementation strategies to facilitate data exchange in circular economy systems.

CRediT authorship contribution statement

Rodrigo Serna-Guerrero: Writing, Visualization, Supervision. **Sara Ikonen:** Writing – original draft, Investigation, Formal analysis. **Oona Kallela:** Investigation, Formal analysis. **Esko Hakanen:** Methodology, Conceptualization, 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.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2022.133984.

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