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# Circular economy considerations in choices of LCA methodology: How to handle EV battery repurposing?

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A B S T R A C T

Growing Electric Vehicle (EV) markets and increasing focus on Circular Economy (CE) strategies have stimulated research in the modelling of EV battery repurposing as a special case of product re-use in Life Cycle Assessment (LCA). This paper reviews the methods suggested in literature. Based on the results, the study proposes three types of LCA approaches on EV battery repurposing, taking the perspective of an automotive manufacturer in a CE context. Furthermore, the paper suggests a classification of EV battery repurposing cases depending on the chosen reference scenario and derives directions for future research.

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## 1. Introduction

Since the EU Circular Economy Action Plan has come into play in 2015 (EC, 2015), all stakeholders involved from industry, as well as governmental and non-governmental institutions are now facing challenges of implementing the concept in practice and identifying ways to establish business models, which "keep products, components, and materials at their highest utility and value at all times" (EMF, 2015). For companies, "the partly conditional, beneficial and trade-off relationships between CE and sustainability" (Pauliuk, 2018) imposes on CE the challenges of sustainability in general. Academic research thus calls for a systems perspective on the role of businesses in the wider system of stakeholders and the environment (Murray et al., 2017; Geissdoerfer et al., 2017). In order to support CE decisions, methods for assessing and quantifying the environmental benefits of CE strategies are thus increasingly challenged by the need to reflect the systemic context of an organization.

Meanwhile, with the recent growth of EV markets and the concept of battery 2$^{nd}$ use (B2U), several studies examine the potentials of re-using EV batteries in battery energy storage systems (BESS). Besides economic aspirations, research on the environmental benefits of repurposing Li-ion batteries (LIB) in BESS as an asset to overcome flexibility challenges in future energy markets has received growing attention. In this respect, automotive original equipment manufacturers (OEM) who have entered the B2U market today face the challenge of implementing metrics for measuring the environmental implications of B2U in order to take meaningful decisions.

The present paper reviews the methods available for assessing the environmental implications of EV battery repurposing and presents relevant CE considerations to guide methodological choices from an OEM's perspective.

| | |
|---|---|
| B1U | Battery First Use |
| B2U | Battery Second Use |
| BaU | Business as Usual |
| BESS | Battery Energy Storage System |
| CE | Circular Economy |
| EoL | End-of-Life |
| EPR | Extended Producer Responsibility |
| EV | Electric Vehicle |
| LCA | Life Cycle Assessment |
| LIB | Lithium-ion Battery |
| OEM | Original Equipment Manufacturer |
| PSS | Product Service System |

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## 2. EV battery repurposing in a CE context

Product repurposing is defined as "utilizing a product or its components in a role that it was not originally designed to perform" (BS 8887–2, 2009). Whereas other forms of re-use such as remanufacturing and refurbishing can be differentiated based on the associated degree of rework, repurposing is considered a special case with no further classification (Ardente et al., 2018). Studies on the characteristic enablers and barriers for re-use in general refer to repurposing as cascading reuse and emphasize the importance of taking into account the reduced efficiency of reused products and the relevant amount of new products displaced (Cooper and Gutowski, 2017; Bobba et al., 2016; Thomas, 2011; Sandin and Peters, 2018; Cooper and Allwood, 2012; James, 2011). As stated by Zink et al. (2014), repurposing can displace other product technologies and should therefore target applications with the highest avoidance potential.

Furthermore, the definition and prioritization of CE strategies provided by the waste hierarchy (EU, 2008) is challenged by repurposing cases (Richa et al., 2017), given that repurposing does not by definition preserve the original value of a product. Instead, changing the context of applying a product leads to blurred demarcations of inter-dependent first- and second life product systems. In this sense, the findings of Korhonen et al. (2018), stating that spatial system boundaries and inter-organizational collaboration among others represent typical challenges in CE hence seem to be particularly relevant to product repurposing. This extends further into issues regarding the applicability of the concept of Extended Producer Responsibility (EPR) in legislation on product repurposing.

For the case of EV battery repurposing, this is confirmed by studies stating that B2U requires close collaboration between OEMs and potential users of B2U solutions in the energy sector such as utility operators (Jiao and Evans, 2017; Jiao and Evans, 2016). Besides market development affecting the evolution of EPR networks (Richa et al., 2015), both sectors affect the environmental performance of B2U through their decisions on B2U system configuration and target applications (Cusenza et al., 2019; Ahmadi et al., 2017). For OEMs, B2U consequently implies to engage with the energy sector in order to analyse and optimize the technological and environmental characteristics of B2U.

## 3. Methodological choices in LCA on LIB repurposing

### 3.1. General LCA provisions for re-use and CE strategies

The role of LCA to measure the environmental benefits of implementing CE strategies has been confirmed recently (Niero and Rivera, 2018). Although several attempts exist in literature to ensure consensus and standardized application of LCA for the case of re-use, a lack of guidelines for the specific case of product repurposing is concluded in several studies (Ardente et al., 2018; Cooper and Gutowski, 2017; Richa et al., 2015).

Repurposing is generally identified as a cascaded multi-functionality problem in LCA, which arises from a product serving additional functions after its' original primary function in the first life cycle (Richa et al., 2015). The issue therefore lies in the rules applied for splitting manufacturing and End-of-Life (EoL) impacts among multiple life cycles and is part of the goal and scope definition phase in LCA according to the ILCD handbook (European Commission, 2010).

Allacker et al. (2017) generally distinguish between a product level approach, using allocation formulas (i.e. 50/50, physical, market-based) to allocate impacts among multiple life cycles, and an overall system approach, using system boundary expansion to include additional life cycles in the original product system. In this respect, Pelletier et al. (2015) find feasibility issues in the ISO 14040 decision hierarchy on resolving multi-functionality. Elsewhere, Allacker et al. (2014) highlight the differences among available methods and illustrate preferences for specific contexts such as product policy support. In contrast to that, a method by James (James, 2011) defines that all impacts before the re-use should be allocated to the initial product's first life, given the uncertainty over the number of potential life cycles.

To guide LCA practitioners in assessing CE strategies, a novel approach is presented by Kjaer et al. (2016), suggesting that methodologies can be classified based on the reference system, being either the existing Product/Service-System (PSS) ("PSS optimization"), a comparable alternative ("PSS comparison") or a baseline scenario without the PSS ("PSS consequence"). The applicability in other CE contexts such as product repurposing has however not been investigated.

### 3.2. Specific findings regarding modelling B2U in LCA

Generally, the life cycle of an EV battery, i.e. the battery first life (B1U), includes LIB manufacturing, the impacts associated with the EV use phase, as well as EoL processes such as recycling and disposal (Ahmadi et al., 2017). For the specific case of B2U, additional impacts result from repurposing processes, i.e. the energy and material requirements of enabling an EV LIB to be applied in B2U (Cusenza et al., 2019). These typically include transport, testing, and BESS hardware requirements such as inverters for grid connection. Additionally, the B2U use phase is included through the BESS application, considering efficiency losses and internal energy consumption (Ahmadi et al., 2017).

In this respect, recent studies on EV battery repurposing present several methodological differences in assessing B2U. A review by Bobba et al. (2018) highlights case-specific differences such as assessment scope (e.g. different B2U applications and product systems), system boundaries (life cycle stages included in the assessment) and the definition of the functional unit. The study emphasizes the wide range of applications for B2U, causing trouble in determining suitable reference scenarios and obtaining comparable results across studies. Furthermore, Richa et al. (2015) state that on the one hand, a system expansion approach corresponds to an OEMs perspective, in which the goal is to examine the extent to which B2U can reduce the net environmental impacts across the battery life cycle. On the other hand, different allocation approaches represent an energy sector perspective, which assesses B2U in comparison to alternative battery technologies in BESS applications.

Overall, both general LCA methods for product repurposing and specific approaches to B2U indicate that a lack of methodological guidance for repurposing LCAs leaves practitioners with the task to make case-specific choices in modelling B2U.

## 4. Findings of the literature review of LCA studies on B2U

The review focuses on two main LIB application fields, namely LIB in EV battery life cycles on the one hand, and in BESS systems on the other hand. Using the scientific literature database DTU findit, a gross list of approx. 36 LCA studies on LIB in either EV or a BESS system is concluded. Afterwards, different terms applied for B2U such as "Second Life", "Second Use", "Reuse" and "Repurposing" have served to identify 11 cases of B2U from both fields.

Based on the findings stated previously, the key aspects assessed in the review firstly include the study focus and the corresponding approach to handling multi-functionality. Secondly, the definition of the reference scenario is reviewed in each study, focusing on the assumptions regarding alternative products or technologies for the BESS application. The summary of the literature review is reported in Table 1. The following approaches to handling multi-functionality are identified in literature:

- **Cut-off allocation**, fully assigning manufacturing and EoL impacts to the B1U, and exclusively assessing the positive and negative impacts of B2U;
- **Allocation based on allocation factors**, focusing on BESS and B2U application, considering to partly allocate LIB manufacturing and EoL impacts to B2U according to different criteria: a) quality-based (e.g. battery capacity), b) market-based (e.g. market value), c) equally divided (50/50);
- **System expansion**, expanding system boundaries of B1U to include repurposing, BESS and B2U application;

The review finds that four out of 11 studies focus on the full life cycle, applying system expansion to determine the benefits of B2U (Ahmadi et al., 2017; Cicconi et al., 2012; Genikomsakis et al., 2014; Casals et al., 2017). Out of the remaining six studies, four apply cut-off allocation (Faria et al., 2014; Sathre et al., 2015; Kim et al., 2015; Fischhaber et al., 2016), whereas two studies apply allocation factors (Cusenza et al., 2019; Bobba et al., 2018). Among the latter, Bobba et al. (2018) use market-based allocation while assuming full allocation to B1U based on the fact that batteries are considered waste at the end of B1U in legislation today (EU, 2006). Cusenza et al. (2019) apply quality-based allocation based on energy delivered during each application. Lastly, Richa et al. (2015) apply cut-off, market-based, quality-based and 50/50 allocation, finding major implications of the chosen approach for the amounts of LIB cells required to enter B2U in order to be environmentally beneficial.

In terms of the chosen reference scenario definition, three approaches can be identified:

- Displacement of new batteries, i.e. scenarios in which a BESS would otherwise be implemented using new batteries (of either the same or a different technology);
- Displacement of alternative technologies, i.e. scenarios in which BESS serve applications which are usually provided by other technologies;
- Business as Usual (BaU), i.e. scenarios in which entirely or partly new functions are added through B2U

In summary, most published studies assume the displacement of newly produced batteries (Richa et al., 2015; Cicconi et al., 2012; Genikomsakis et al., 2014; Kim et al., 2015; Fischhaber et al., 2016). Other studies either assume alternative technologies to fulfil BESS functions (Ahmadi et al., 2017; Sathre et al., 2015), or choose a BaU reference scenario without any storage at all (Cusenza et al., 2019; Faria et al., 2014). Two studies apply all three approaches and compare the results, showing that each approach affects different life cycle stages and impact categories (Bobba et al., 2018; Casals et al., 2017).

## 5. Mapping methodological choices with CE context

### *5.1. B2U scope definition and sector collaboration*

Based on the findings of the literature review, a relationship between the approach to handling multi-functionality in LCA and typical CE considerations relating to product repurposing can be established.

Firstly, a cut-off allocation approach in LCA does not allow OEMs to jointly measure the environmental benefits of B2U in relation to B1U. Following the definitions in (Richa et al., 2015), it represents an energy market perspective, given that no credits for displaced products or other life cycle effects can be drawn for the EV life cycle. From a CE perspective, the approach corresponds to OEMs taking the role of a supplier of repurposed EV batteries on

**Table 1**
Literature review of methodologies applied in LCA studies on B2U

| Author/study | Year | Study focus | Handling of multi-functionality | B2U reference scenario |
|---|---|---|---|---|
| Cicconi et al. (2012) | 2012 | Full life cycle | System expansion | Production of new LFP battery |
| Genikomsakis et al. (2014) | 2014 | Full life cycle | System expansion | Production of new LFP battery |
| Faria et al. (2014) | 2014 | B2U | Cut-off | BaU, energy requirements satisfied from grid |
| Sathre et al. (2015) | 2015 | B2U | Cut-off | Peak power delivered by fossil fuel power plant |
| Richa et. al. (2015) | 2015 | Full life cycle | System expansion | Production of new PbA battery |
| | | B2U | Allocation (div.) | Production of new PbA battery |
| | | B2U | Cut-off | Production of new PbA battery |
| Kim et al. (2015) | 2015 | B2U | Cut-off | Production of new LMO battery |
| Fischhaber et al. (2016) | 2016 | B2U | Cut-off | Production of new LMO battery |
| Casals et al. (2017) | 2017 | Full life cycle | System expansion | a) BaU, energy requirements satisfied from grid/RES b) Energy is obtained from a diesel generator c) Production of new PbA battery |
| Ahmadi et al. (2017) | 2017 | Full life cycle | System expansion | ICE vehicle + natural gas peak power |
| Bobba et. al. (2018) | 2018 | B2U | Allocation (market-based) | a) PV system + production of new LMO/NMC battery b) PV system, no storage c) PV system + operation of diesel generator |
| Cusenza et al. (2019) | 2019 | B2U | Allocation (quality-based) | BaU, energy requirements satisfied from the grid |

**Table 2**
Proposed categorization of B2U cases based on reference scenario and displaced products

| CE perspective | Reference scenario | Affected life cycle stage and impact categories |
|---|---|---|
| Optimize existing BESS | Production of new battery (same or different technology) | Battery manufacturing/ resource consumption (e.g. ADP-res.) |
| Compare B2U to other technologies | Apply alternative technology for BESS application | BESS use phase (e.g. GWP for natural gas peak power) |
| Introduce new functions through B2U | Business as Usual (BaU, no BESS technology implemented) | BESS use phase (e.g. GWP, depending on grid mix) |

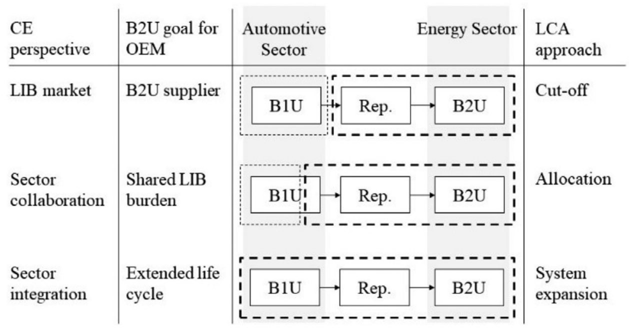


**Figure 1.** Proposed link between LCA approaches and OEM perspectives on B2U in a CE context.

the LIB market (see Fig. 1). Secondly, the review of allocation approaches indicates that in order to determine allocation factors for sharing LIB manufacturing and EoL burden through B2U, OEMs are required to track B2U performance in terms of market potential or system performance in relation to B1U. For that, collaboration and continuous data exchange with energy market players is necessary to share LIB production impacts among automotive and energy sector, taking into account the wide range of B2U applications and markets. With 50/50 allocation representing a theoretical case, market- or quality-based allocation hence corresponds to a sector collaboration approach in a CE context.

Lastly, a system expansion approach in LCA to measure the performance of B2U as part of the overall LIB life cycle expands the decision context of OEMs to the B2U application. In order for OEMs to optimize the full LIB life cycle, a high level of integration with the energy sector is required. System expansion thus represents a sector integration approach from a CE perspective.

Consequently, an OEM's CE perspective on product repurposing can thus be classified as either a LIB market approach, a sector collaboration approach or a sector integration approach, in order to guide methodological choices in LCA. Besides requiring further validation through application examples, an analysis of which approach is suited best for which stakeholder group within the EV battery life cycle should be carried out.

### 5.2. Classification of B2U cases based on reference scenario

Furthermore, the results of the literature review indicate that repurposing cases can be differentiated based on the chosen reference scenario. Following the approach suggested by Kjaer et al. in (2016), repurposing in the case of B2U can either i) displace new batteries and optimize an existing BESS solution, ii) fulfill grid services and functions in comparison to other technologies, or iii) can introduce new functions to an existing non-storage (BaU) system. Additionally, existing studies show that the displacement of new batteries affects impact categories related to resource consumption and battery manufacturing (e.g. ADP-res.) whereas comparisons with alternative technologies or BaU scenarios mostly affect impact categories associated with the use phase of the BESS (e.g. GWP, depending on the share of fossil energy sources) (Bobba et al., 2018; Casals et al., 2017) (see Table 2).

As stated earlier, the differences in the reference scenario definition results from the variety of possible BESS application scenarios. Although different options can thus be justified from the context of the assessment, the categorization presented serves to guide practitioners towards assumptions consistent with the B2U business model in a CE. Furthermore, the categorization is explicitly derived from the case of B2U. Therefore, the applicability for repurposing cases in general requires further validation. However, it implies the potential of expanding the classification of types of re-use offered by Ardente et al. (2018). Furthermore, the classification establishes a relationship between the CE perspective and the impact categories in which environmental benefits occur. It thus offers practitioners to choose preferable B2U strategies, e.g. to target the optimization of existing BESS when seeking to improve in impact categories related to resource consumption. In this respect, future research should include the definition of specific goals, which OEMs pursue through CE.

## 6. Summary of results and outlook

The ongoing efforts to implement CE in industry challenge methods to assess the environmental benefits of CE strategies viewed in the systemic context of an organization. As concluded in previous studies, clear guidance on methods for repurposing LCAs are lacking today, leaving practitioners with two main tasks to determine their LCA approach: firstly, deriving suitable approach to handle multi-functionality based on the study focus in the respective context, and secondly, determining the adequate reference scenario in order to quantify the environmental benefits associated with B2U.

Based on existing LCA literature, this study presents three types of CE contexts for B2U from an automotive manufacturer's perspective, which determine the corresponding LCA approach: a LIB market perspective, a sector collaboration perspective and a sector integration perspective. Furthermore, the paper suggests a classification of B2U cases based on the reference scenario and business model in a CE, being either the production of a new battery, an alternative technology, or a BaU scenario.

For future studies, the next step is to implement the findings and thus validate the integration of CE principles in LCA based on actual B2U case study. Besides the definition of system boundaries and reference scenario, this also includes the implementation of a corresponding functional unit. Building on the existing body of literature, future work should include a critical review of the different organizational entities involved in the LIB life cycle, including their role and the corresponding decision context and specific goals in a CE. Here, the ability of applying LCA results in automotive industry to support sector collaboration and to mitigate risks of rebound effects and burden shifting for B2U seem to be potential future research fields. From a holistic view, linking LCA approaches with different stakeholder perspectives on CE carries the potential to enable the development of generic frameworks for implementing CE strategies within organizations.

Lastly, further research is needed to validate the classification product repurposing cases. While the terminology of optimization, comparison and consequence-cases proposed by Kjaer et al. seems to correspond well with the findings of the present study, the novelty of the approach requires further investigation. It could however represent the basis for defining environmentally beneficial B2U business models for each of the cases, considering stakeholder networks between automotive OEMs and e.g. utility operators.

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