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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

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ABSTRACT

In their efforts to implement a circular economy (CE) for lithium-ion batteries (LIB) in electric vehicles, automotive manufacturers need to take into account the perspective of energy consumers when assessing the environmental benefits of LIB repurposing in life cycle assessment (LCA). In response to this issue, this study presents a novel LCA framework, which allows manufacturers to assess different cases of LIB repurposing in an energy system and interpret the results in a CE context. The framework firstly uses energy flow modelling to enable the assessment of combining different battery storage applications in multi-use cases. Secondly, it includes a comparison of repurposing with alternative circular business models options for LIB. The framework is applied to an automotive manufacturer, seeking to assess a real-world project of LIB repurposing in different combinations of behind-the-meter applications at an industrial production site in Germany. As a key outcome, results reveal that from the perspective of the energy consumer, climate change benefits in multi-use cases are 10–22% lower than in single applications. Furthermore, from the perspective of the automotive manufacturer, repurposing is identified as the most beneficial option of circular business models available for LIB, taking into account additional recycling benefits resulting from the delay of end-of-life. Based on these findings, the study contributes to the application of LCA for decision-making in a CE and highlights pitfalls and potentials for a sustainable implementation of LIB repurposing in the future.

1. Introduction

For most automotive manufacturers, e-mobility stands at the core of their strategy to reach zero-emission mobility in the upcoming years (EC, 2019, IEA, 2019; T&E, 2018). With the increasing deployment of electric vehicles (EV) in the near future (Bobba et al., 2019; WEF, 2019), there comes the challenge of implementing the concept of a Circular Economy (CE) for Lithium-Ion batteries (LIB) in order to establish sustainable management of resources (CEID, 2020; EC, 2020).

To implement a CE, which can be defined as a "regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops" (Geissdoerfer et al., 2017), Circular Business Models (CBM) are presented as one of the key concepts (De Angelis, 2018). Among the different CBM patterns identified in literature (Lüdeke-Freund et al., 2019), the main examples for the case of LIB include "remanufacturing", "repurposing" and "recycling" (Olsson et al., 2018; Richa et al., 2017). Choosing among these options requires manufacturers to assess the contribution to the CE goals of the company alongside technical and economic considerations for each CBM (Becker et al., 2019; Beverungen et al., 2017).

In this context, repurposing describes the further use of LIB in second life battery energy storage systems (SLBESS) at the end of their useful life in the EV (Jiao and Evans, 2017; Olsson et al., 2018). In this way,

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repurposing extends the useful life of LIB by up to 10 years, thereby postponing LIB end-of-life (EoL) and delaying costly and energy-intensive recycling processes used today (Richa et al., 2017).

Besides this, repurposed LIB can serve a variety of applications in SLBESS, which has been demonstrated in multiple pilot projects implemented until today (Reinhardt et al., 2019). Given that each application leads to specific benefits, literature points towards the potential of combining and simultaneously providing different BESS applications in so-called multi-use-cases in order to maximize economic returns and optimally exploit the available capacity (Lombardi and Schwabe, 2017; Müller, 2018; Tepe et al., 2021). Therefore, understanding the benefits of multi-use cases for specific SLBESS customers can be seen as a pre-requisite for the assessment of LIB repurposing as a CBM in the future.

For automotive manufacturers the challenge is thus twofold. On the one hand, new business models for LIB repurposing, such as multi-use cases, require further investigation of the use stage of SLBESS from the perspective of energy consumers. On the other hand, they need to position repurposing in relation to other CBM options for LIB in terms of the contribution to a sustainable deployment of a CE.

In this regard, the reduction of environmental impacts is stated as one of the key motivations of pursuing LIB repurposing (CEID, 2020, WEF, 2019). In a CE context, Life Cycle Assessment (LCA) is described as a key method for assessing CE strategies (Elia et al., 2017). In order to address the use stage of the SLBESS in LCA, recent studies focus on the energy-related benefits of LIB repurposing, e.g. by taking into account the additional use of renewable energy (RE) consumed when using SLBESS (Bobba et al., 2018; Cusenza et al., 2019b; Podias et al., 2018). However, despite market potentials and growing numbers of LIB available in the future (Bobba et al., 2019; Gur et al., 2018; Jiao and Evans, 2016), there is still a lack of LCA frameworks that integrate the assessment of SLBESS applications from the perspective of energy consumers in the CE decision-making of automotive manufacturers.

Given these premises the objective of this study is to address this gap by answering the following two research questions:

1) From the perspective of an energy consumer, what are the effects on the environmental benefits of LIB repurposing when combining different SLBESS applications in multi-use-cases?
2) From the perspective of an automotive manufacturer, what is the contribution of repurposing to the reduction of environmental impacts of LIB life cycles in relation to other CBM?

To address both questions, we use a case study on implementing a SLBESS at an industrial production site in Germany to develop an LCA framework based on energy flow modelling (Section 2). The presentation and discussion of results is structured as follows: firstly, we review the results obtained from the energy flow model for the energy system under investigation (Section 3.1). Secondly, we present LCA results from the perspective of the energy consumer (Section 3.2), followed by results from the perspective of an automotive manufacturer (Section 3.3). Thirdly, we test and discuss key parameters in a sensitivity analysis in order to validate the results (Section 3.4). Lastly, we identify implications for decision-making on LIB repurposing in a CE context (Section 4).

2. Materials and method

A case study method is chosen, which aims at deriving knowledge from a real-life phenomenon (Ridder, 2020). Given that indeed both research questions require in-depth knowledge of the relevant decision-making requirements for LIB repurposing, a case study offers the opportunity of framing the problem in a particular setting. While LCA is confirmed as a key assessment method to address environmental impacts in a CE (Elia et al., 2017; Niero and Rivera, 2018; Peña et al., 2020), we claim that the implications for decision-making are complex and not well understood when it comes to implementing LIB repurposing from both the perspective of energy consumers and automotive manufacturers. This is supported by previous research, which discusses the numerous methodological options of assessing LIB repurposing in LCA in a CE context (Schulz et al., 2020). By choosing a case study method, we aim at advancing knowledge on both practical implications for the case of LIB repurposing and the role of LCA for environmental decision-making across sectors in a CE.

2.1. Introduction to the case study

In the case study, we take the perspective of an automotive manufacturer, seeking to implement a pilot project for LIB repurposing at industrial scale to evaluate the environmental benefits for the CE strategy of the company. In terms of the general business model, literature states that repurposed LIB can be provided at a price of less than 50€/ kWh in the future (Madlener and Kirmas, 2017; Neubauer et al., 2012; Rallo et al., 2020). Despite ongoing price reductions for fresh batteries in the stationary sector to around 120–400 €/kWh depending on the battery chemistry by 2030 (IRENA, 2017), repurposed LIB are seen as an attractive alternative to reduce the cost of BESS investments in the upcoming years (Assunção et al., 2016; Debnath et al., 2014; Gur et al., 2018; Heymans et al., 2014).

The implementation of the SLBESS takes place at an industrial production facility in Germany, which is considered a representative example of a large-scale energy consumer, using the SLBESS for behind-the-meter applications such as the optimization of local RE integration, peak shaving, as well as uninterrupted power supply (UPS) (Tepe et al., 2021). As such, energy consumers must be delimited from distribution- and transmission system operators, who apply SLBESS at utility scale in so-called front-of-the-meter applications. These include the provision of ancillary services to power grids, deferring grid infrastructure investments and supporting the readiness for an increasing feed-in of RE (Tepe et al., 2021).

Within the production facility, the energy system under investigation is a real-world pilot installation of a 650 V industrial direct current (DC) micro-grid. The included consumers are DC lighting, a ventilation system as well as four DC fast charging points for EVs. The total annual electricity consumption amounts to 2.281 MWh with a maximum peak power of 1135 MW. The load profile of the energy system is based on primary data obtained from the operator of the facility. Furthermore, a photovoltaic (PV) system delivers 1 MW peak power. Further information on the DC grid are provided in the supplementary materials (SM) Section 2.2.

In order to evaluate the potential of multi-use cases, the SLBESS applications are combined in four different use cases:

- Single-use case: PV
- Dual-use case 1: PV + PS
- Dual-use case 2: PV + UPS
- Multi-use case: PV + PS + UPS

Further details on modelling the use cases are provided in SM Table 2. The SLBESS under investigation is based on a modular container architecture. A battery container unit includes 112 retired plug-in hybrid electric vehicle (PHEV) batteries with lithium nickel manganese cobalt oxide (NMC) cells. New batteries of this type are characterized by a nominal capacity of 13,8 kWh and a total maximum of 3.500 full charging cycles, which is aligned with average assumptions in literature, taking into account the time of production (Cano et al., 2018). For repurposing, the remaining number of charging cycles is determined based on Fischhaber et al. (2015), who assume a usable range of the state-of-health between 40 and 80% for the SLBESS. From the total nominal capacity of 1545 MWh for the 112 LIB in scope, it thereby follows an initial capacity for the SLBESS of 1236 MWh and a maximum of 1.400 charging cycles. Additionally, a second container unit includes the power electronics such as power converters and distributers.

2.2. Development of the LCA framework and energy flow modelling

To address the specific methodological challenges of each research question in LCA, we adopt the approach taken in Richa et al. (2015), who carry out the assessment of LIB repurposing from both LIB producer and utility perspective in two steps. For each step, the authors then define functional unit and system boundaries according to the respective decision-context.

In the first step, we use energy flow modelling to determine the reduction of energy consumption of the DC grid when applying the SLBESS. Similar approaches are suggested in previous studies (Bobba et al., 2018; Cusenza et al., 2019b; Podias et al., 2018). In response to research question 1, this includes modelling the relevant applications in single- dual- and multi-use cases. Contrary to the dominant approach in previous studies to use the avoided production of new LIB for quantifying environmental benefits on LIB repurposing (Schulz et al., 2020), we focus on the use stage of the SLBESS and the additional use of RE consumed in the grid (Cusenza et al., 2019b; Faria et al., 2014; Sathre et al., 2015). Step 1 thereby seeks to establish a link between LIB repurposing and the environmental impact reduction targets of energy consumers (IRENA, 2017). Moreover, by focusing on energy-related emissions, the risk of increasing grid impacts by applying storages is prevented, which can occur depending on the displaced grid mix and SLBESS efficiency losses (Casals et al., 2019; Hittinger and Azevedo, 2015; Lin et al., 2016).

In the second step, we compare the LCA results for repurposing with those for other CBM options available for LIB, namely remanufacturing, i.e. the repair and reuse of LIB in the EV, and direct recycling. In this way, the framework enables automotive manufacturers to consider LCA results in the choice of preferred CBM. Furthermore, we adopt the approach presented in Richa et al. (2017) and take into account the delay of recycling caused by repurposing and remanufacturing. Thereby, in addressing research question 2, we consider all alternatives in a CE when assessing the role of repurposing for the LIB life cycle (Bobba et al., 2019; Kurdve et al., 2019; Olsson et al., 2018).

Based on these premises, the proposed LCA framework is presented in Fig. 1. The recovery of LIB from the EV is assumed to take place today, i.e. at the time of conducting the study. At that point, LIB have mostly been in use for the duration of an average EV lifetime, e.g. 8–10 years. This implies the necessity to investigate which production processes and cell technology have formerly been used for that LIB. Similarly, the effects caused by the delay of LIB EoL by up to 10 years require assumptions on future recycling processes (Velázquez-Martínez et al., 2019).

In order to simulate the effects of implementing a SLBESS, the system is modelled in the energy simulation software TOP Energy (GFAI, 2017) (see Fig. 2). The software uses economic parameters to optimize the energy-related cost and revenues of the system. Additionally, the simulation also uses the cost of degradation of the SLBESS to determine the optimal number of charging cycles. Further information is reported in the SM and includes a description of the simulation method (SM Sections 2.1 and 2.2), data on energy consumers (SM Table 3), technical specification of the SLBESS (SM Tables 4 and 5), economic parameters (SM Tables 6 and 7) and application-specific data (SM Table 8).

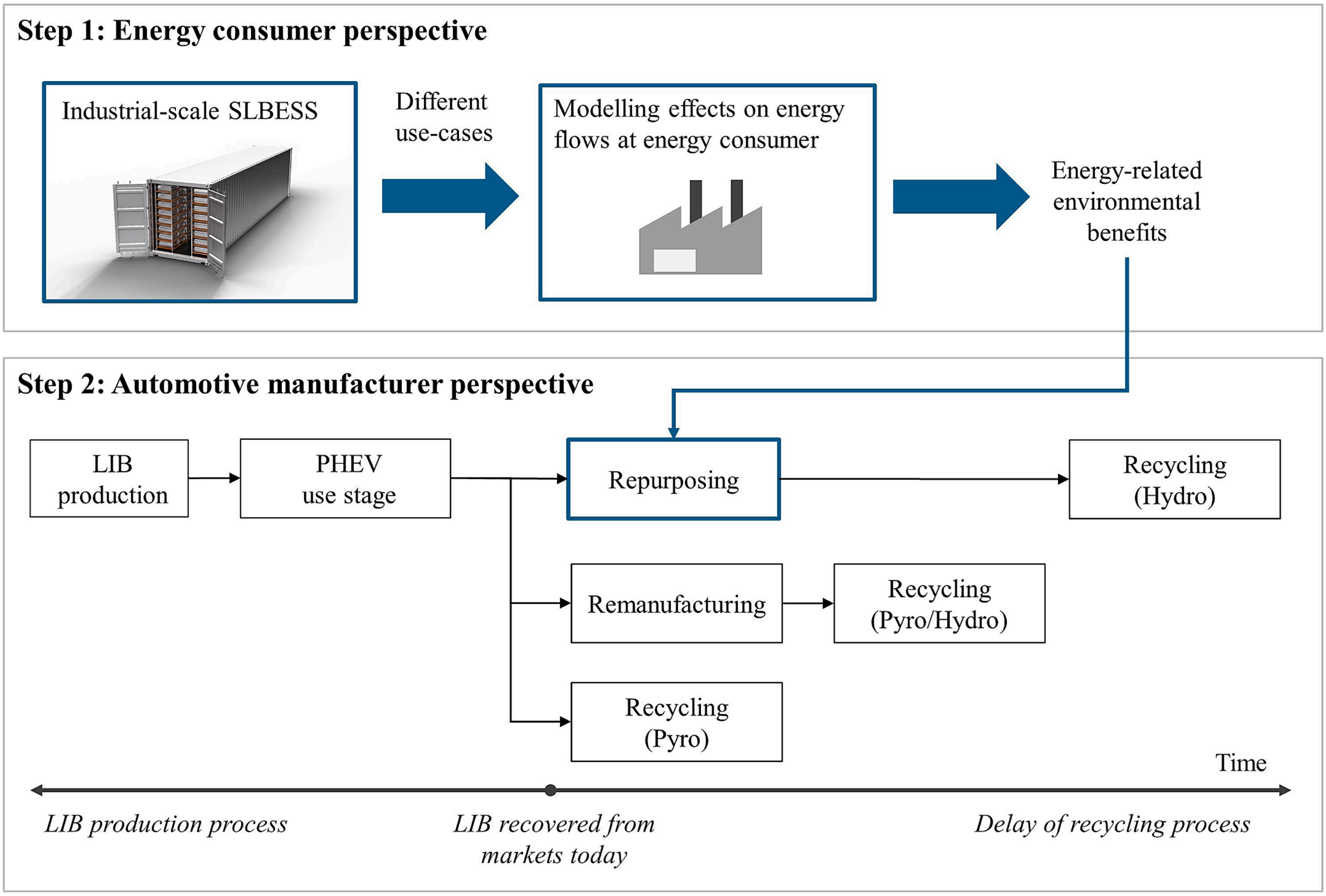


Fig. 1. Proposed LCA framework for assessing lithium-ion battery (LIB) repurposing in response to the research questions, including the modelling of energy flows for the use of the second life battery energy storage system (SLBESS) (step 1), and comparison to alternative options of circular business models (step 2).

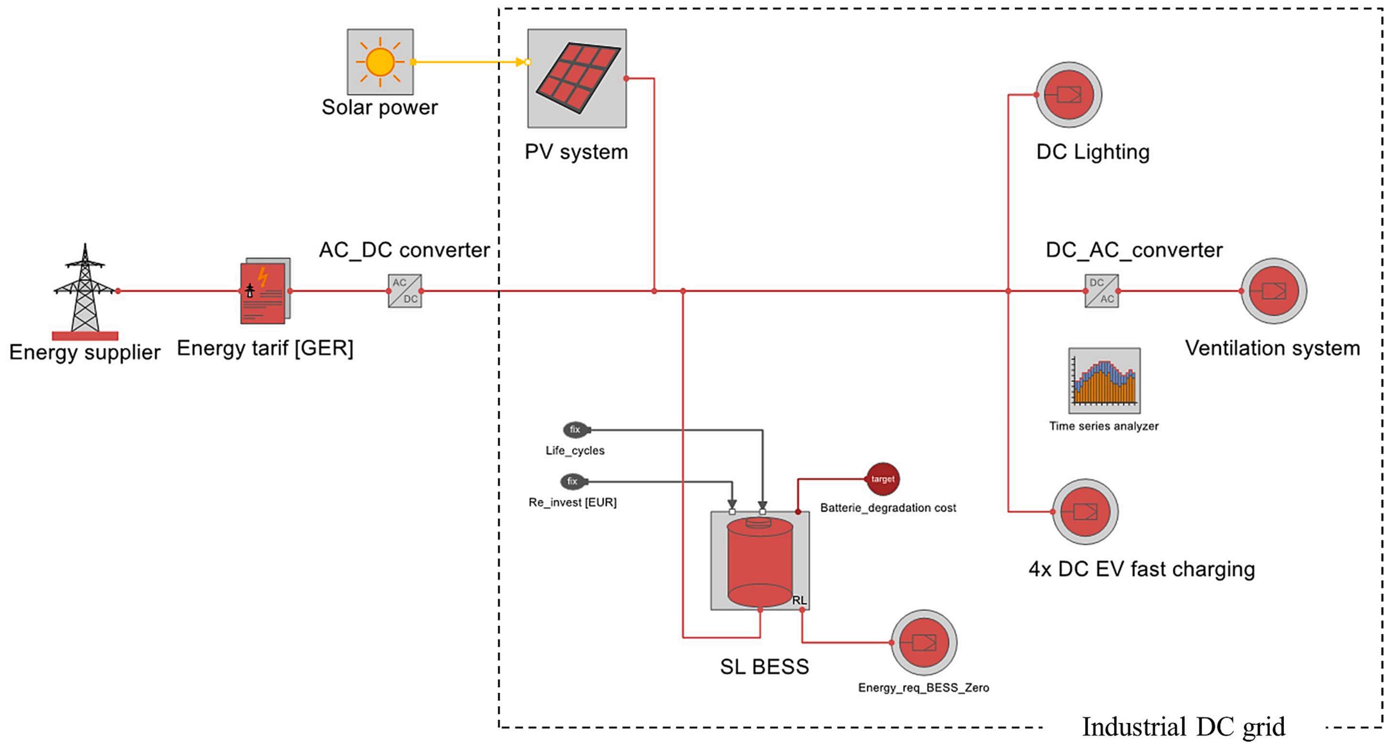


Fig. 2. Schematic representation of the model in TOP Energy, including converters, the photovoltaic (PV) system, the direct-current (DC) lighting, the ventilation system, the electric vehicle (EV) fast charging points and the second life battery energy storage system (SLBESS).

2.3. LCA framework for step 1 – energy consumer perspective

2.3.1. Functional unit

Based on the definitions in Section 2.1, the energy consumer perspective of the LCA focuses on the energy-related effects of the SLBESS application in multi-use cases. Therefore, the functional unit (FU) is defined as the energy consumption of the DC grid in the production facility over a period of 10 years. This choice of FU is not dependent on the size of the SLBESS and corresponds to the approach taken in previous studies (Bobba et al., 2018; Cusenza et al., 2019b).

2.3.2. System boundary and definition of use cases

To address the multi-functionality problem between LIB first use in the PHEV and the second use in the SLBESS, we apply a cut-off approach, meaning that both production- and recycling-related impacts are fully allocated to the use of the LIB in the PHEV (Bobba et al., 2018; Cusenza et al., 2019a; Richa et al., 2015). Consequently, the SLBESS does not take the burden of LIB production or disposal. Other options to deal with the multi-functionality issue such as market- or quality-based allocation are discussed in Schulz et al. (2020), but not considered here due to the still early stage of SLBESS deployment. The cut-off approach only delimits LIB repurposing from the PHEV life cycle. It does not apply to the handling of LIB recycling, which is later specified in step 2 of the framework (see Section 2.4).

Following the approach in Bobba et al. (2018), the system boundary in step 1 thus only includes all processes and production and disposal of those parts, which are additionally required for further using the LIB in the SLBESS. For the repurposing process, i.e. the qualification of LIB for integration in the SLBESS, this comprises testing and production of added parts. The disposal of replaced parts is allocated to the PHEV. Furthermore, step 1 includes the SLBESS production and the implementation at the site of use, as well as the SLBESS use stage and the SLBESS disposal. Since LIB recycling impacts are allocated to the PHEV, the SLBESS disposal only includes the recycling of added parts such as container case, power electronics, connectors, cables etc. (see Fig. 3). Referring to the definitions in Section 2.1, the benefits of the SLBESS application are determined based on the reduced energy demand of the DC grid compared to the business-as-usual (BaU) scenario, which is the operation of the grid without the SLBESS.

The BaU scenario is characterized by the use of German grid mix, taking into account the expected decarbonization by 2030 (IEA, 2017) (see SM Section 3.3). The grid furthermore delivers peak power for peak consumers, e.g. the DC charging stations. The supply of the baseload is partly supported by the local production of RE from the PV system, which amounts to 1.012 MWh annually. Lastly, UPS is not provided in the BaU scenario, meaning that potential short-term grid failures and the corresponding economic cost are accepted.

In the SLBESS scenario, the SLBESS supports the integration of RE in the DC micro-grid (single-use case). Furthermore, we investigate how the additional provision of peak shaving (dual-use case 1), UPS (dual-use case 2) or peak shaving and UPS (multi-use case) affect the energy flows in the system. The required capacity for UPS is based on providing peak power demand for 15 min and amounts to 284,5 kWh (Fischhaber et al., 2015). For peak-shaving applications, other studies assume the displacement of natural gas power plants (Ahmadi et al., 2017; Sathre et al., 2015). However, given that these benefits occur outside of the scope of the system under investigation, they are not included in the model. Thus, both UPS and peak shaving are included only as a measure to improve economic profitability but do not lead to environmental benefits. Detailed information on determining the maximum peak power for peak shaving and the UPS requirements are described in SM Section 2.6.

2.3.3. Life cycle inventory

All modelling and calculations are carried out in Simapro software version v9.0.0.48 (PRé, 2016). Following the recommendation for micro-level decision support in LCA stated in the ILCD handbook (EC-JRC, 2010), we apply allocation at point of substitution (unit) processes provided in ecoinvent 3.4. database (Wernet et al., 2016).

The repurposing process takes place at battery pack level and thus

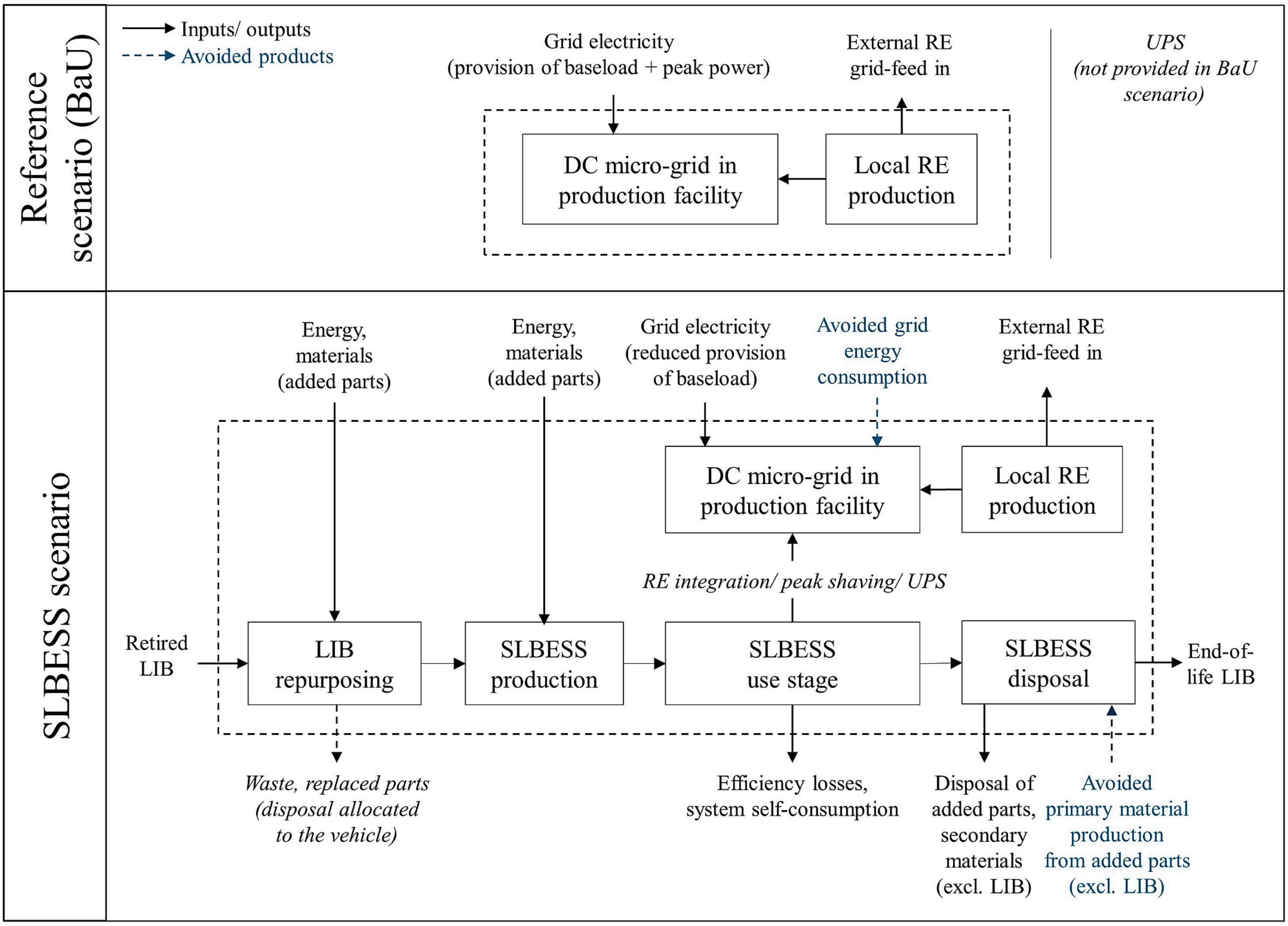


Fig. 3. System boundaries for step 1; Top: Direct current (DC) grid in business-as-usual (BaU), supported by local renewable energy (RE) production, uninterrupted power supply (UPS) not provided in BaU. Bottom: Second life battery energy storage system (SLBESS) scenario; note that the SLBESS disposal only covers added parts, not the lithium-ion battery (LIB) treatment.

only includes testing, calibration, software updates and shipment to the assembly site. Based on Casals et al. (2017), impacts associated with replacement of connectors and cables are considered negligible (see SM Table 10). For the production of the SLBESS, the study builds on a detailed inventory, which has been developed as part of preliminary report for this case study and has mostly used primary data (Shaarawy, 2019). The SLBESS production includes manufacturing of added parts such as case, balance of plant components, as well as shipment and setup at the location of use for each of the two container units included in one SLBESS (see SM Tables 11–13).

For modelling the use stage, the reduced primary energy demand is determined in the energy flow simulation for the specific use case and included in the model as avoided impacts. We take into account the degree of the expected decarbonization of the German grid mix by 2030 (IEA, 2017) (see SM Section 3.3). Furthermore, the use stage includes corresponding efficiency losses, which are obtained based on the number of charging cycles performed and the charge- and discharge efficiency, which is assumed to be constant at 95% throughout the SLBESS use stage. This leads to a total roundtrip efficiency of 90,3% (see SM Table 4). Additionally, we include a constant system self-consumption of the SLBESS of appr. 34 MWh per year, which covers the energy demand for lighting, cooling and battery management system based on Shaarawy (2019) (see SM Tables 14–17). While other studies provide detailed methods for considering battery ageing (Casals et al., 2017; Podias et al., 2018), this study takes a simplified approach and assumes a linear degradation of LIB based on Fischhaber et al. (2015) as described in section 2.1. Since this represents a limitation of the study, we monitor the charge-and discharge rate of the SLBESS to exclude risks of excessive ageing. Finally, the SLBESS disposal stage assumes industrial recycling processes for all SLBESS components (see SM Table 18-19).

2.4. LCA framework for step 2 - automotive manufacturer perspective

2.4.1. Functional unit

The FU is defined as a the production of 1 kWh of LIB with a capacity of 13,8 kWh and a weight of 110 kg for use in a PHEV over 200.000 km of driving distance, with the LIB being subsequently used for repurposing, remanufacturing or recycling. Such choice is consistent with previous studies, e.g. Richa et al. (2015). In order to produce 1 kWh of LIB capacity, the required reference flow is calculated based on the capacity and weight of the LIB and amounts to 7,97 kg/kWh. This factor is applied to convert mass-based calculations, e.g. for LIB recycling processes, into the kWh-based FU.

2.4.2. System boundary

The system boundary in step 2 firstly includes the LIB production and the PHEV use stage. Furthermore, we include all three CBM options, i.e. remanufacturing, repurposing and recycling in the system boundaries (see Fig. 4). In addition, we use system expansion to include the avoided products caused by each CBM, which is an approach chosen in previous

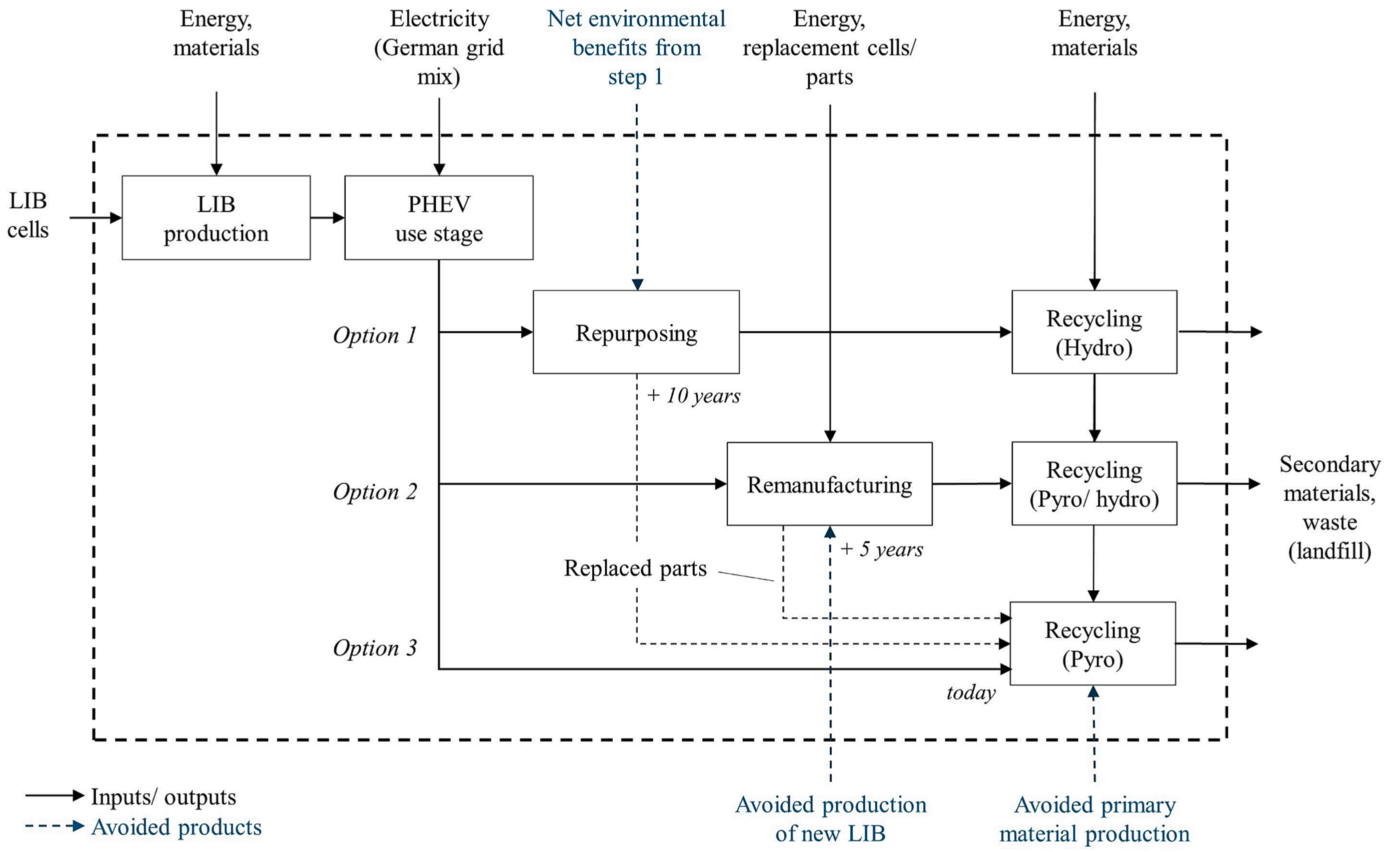


Fig. 4. System boundaries for step 2, including lithium-ion battery (LIB) production and plugin-hybrid electric vehicle (PHEV) use stage, followed by the different circular business model (CBM) options.

studies (Ahmadi et al., 2017; Cicconi et al., 2012; Genikomsakis et al., 2014; Richa et al., 2015). This includes the avoided production of a new LIB for remanufacturing and the avoided primary material production for recycling. For repurposing, the net impacts from the perspective of the energy consumer, which have been determined as part of step 1 of the framework (see Section 2.3), are now included to assess repurposing as a CBM option from the automotive manufacturer perspective. Replaced parts during the repurposing and remanufacturing process are assumed to enter the same process as directly recycled LIB today. Other parameters which affect material flows, e.g. the overall cell conversion rate and market recovery losses as mentioned in Richa et al. (2015), are excluded from the scope of this study.

Furthermore, as described in Section 2.1, the delay of the recycling processes in the case of remanufacturing and repurposing causes that EoL LIB enter different recycling processes. Literature shows that the choice of recycling processes can lead to different results in LCA of LIB (Ellingsen et al., 2017; Richa et al., 2017; Romare and Dahllöf, 2017). Moreover it is stated that a pyrometallurgical process is the most common process used today, whereas a combination of mechanical pre-treatment and hydrometallurgical recycling will be the preferred option in relation to CE targets in the future (Velázquez-Martínez et al., 2019). Therefore, we assume a pyrometallurgical recycling process in case a LIB is directly recycled today (see Figure 4). Furthermore, we assume that LIB enter a hydro-metallurgical process with mechanical pre-treatment after repurposing, i.e. 10 years later. In case of remanufacturing, we assume a 50/50 mix of pyro-and hydrometallurgical treatment after a delay by 5 years.

2.4.3. Life cycle inventory

Detailed information on the life cycle inventory in step 2, which is modelled based on Ecoinvent database 3.4 (Wernet et al., 2016), is provided in the SM Section 4.1. The manufacturing process of the LIB is modelled based on Ellingsen et al. (2014) without any alterations in terms of material composition. The only change in the inventory concerns the electricity used for the cell production. Opposed to the self-defined grid mix used in Ellingsen et al. (2014), we use an average mix, which is computed based on a full RE supply as a best case, as well as a carbon-intense Chinese grid mix. Additionally, the LIB use stage in the PHEV is modelled based on Helms et al. (2015) and includes the charging efficiency losses, assuming a roundtrip efficiency of 95% for fresh LIB based on Kamath et al. (2020).

Furthermore, the remanufacturing process assumes a 10% replacement of individual cells as well as replacement of housing and connectors, which avoids the production of a new LIB of the same kind, i.e. NMC111 (Kampker et al., 2016; Richa et al., 2017) (see SM Table 21). In terms of the recycling processes, the cell technology of the LIB under investigation is a decisive factor (Harper et al., 2019). Due to a lack of recent studies with a detailed inventory for NMC recycling, we use the inventory for both pyro- and hydrometallurgical recycling provided in Fisher et al. (2006). Yet, in terms of the recycling efficiency, we deviate from the assumptions in that source and instead use the assumptions stated in Lebedeva et al. (2016). Lastly, we assume a current German grid mix for recycling processes today while taking into account the expected future decarbonization of the German grid mix by 2030 for future recycling processes (see SM Tables 22 and 23).

2.5. Life cycle impact assessment

The Life Cycle Impact Assessment (LCIA) is carried out using the ILCD 2011 Midpoint+ methodology (EC-JRC, 2011), focusing on two impact categories: climate change (CC) and mineral, fossil and renewable resource depletion (hereafter referred to as RD). While the former is included due to its political relevance for both EVs and the energy sector (WEF, 2019), the latter addresses the resource perspective, which is of particular relevance in the field of CE (Ghisellini et al., 2016). The results in the remaining impact categories are reported in SM Tables 24–27.

2.6. Sensitivity analysis

In terms of relevant parameters for the sensitivity analysis, research points towards the importance of determining an adequate SLBESS system size (Cusenza et al., 2019b). In the case study, the size of the SLBESS of 1235 MWh is pre-determined. However, using a rule of thumb of 1 kWh storage capacity per MWh consumption (Weniger et al., 2015), the optimal system size is estimated at 2281 MWh (see SM Section 2.4). Consequently, the SLBESS is potentially undersized in relation to the load profile of the energy system, thus affecting the results of the study. Therefore, the first sensitivity analysis assumes to double the SLBESS size, which is a technically feasible option due to the modular architecture of the system.

Secondly, a central aspect regarding the time delay of the recycling process is the improvement of the electricity grid mix due to increasing integration of RE on the grid (Cusenza et al., 2020; EEA, 2021). Given the relevance for the energy-intensive pyro-metallurgical recycling process (Velázquez-Martínez et al., 2019), the second sensitivity analysis assumes that energy for this process is provided by wind power today.

3. Results and discussion

3.1. Results of the energy flow simulation

A summary of the key parameters is provided in Table 1. An exemplary result for the charge profile of the SLBESS is included in SM Section 5.1.

The results show how applying the SLBESS in the DC grid leads to an increase of the local RE-integration rate to 77,7% compared to 64% in the BaU. The storage here performs 123 charging cycles per year. In dual-use case 1, the same amount of RE is consumed in the DC grid while simultaneously reducing the required peak power from the grid to 680 kW compared to 1.135 kW in the BaU. In dual-use case 2, permanently reserving 285 kWh capacity for UPS reduces the storage capacity, which is available for optimizing energy flows to 828 kWh. This leads to a reduction in the RE integration to 75,6% compared to 77,7% in the single-use- and dual-use case. Lastly, the SLBESS performs 140 charging cycles per year in the multi-use case. Here, the local RE integration rate lies at 75,6% while simultaneously reducing peak power to 710 kW and reserving the required capacity for UPS.

The results of the energy flow modelling show how applying the SLBESS to additionally reduce the peak power demand caused by the DC fast charging stations does not compromise the benefits of RE integration. As suggested in previous studies, this potentially enables the management of joint use of SLBESS among different consumers (Tang et al., 2019). By observing the change in the maximum discharge rate of the storage, the risk of excessive ageing can be monitored (Casals et al., 2017; Podias et al., 2018). In the case study, the discharge rate increases from 785 kW to 820 kW, which represents a c-rate below 1 and can thus be considered non-critical (Martinez-Laserna et al., 2018). As discussed in Casals et al. (2019), the reduction of peak power demand can furthermore potentially reduce the need for power generation infrastructure. However, the quantification of such benefits lies outside the scope of the present study and requires further validation together with local energy producers.

Lastly, reserving capacity of the storage for other applications such as UPS effectively represents a decrease of the available SLBESS size, which reduces the additional integration of RE in the local grid. This confirms the relevance of the SLBESS size as a key parameter regarding the environmental benefits of LIB repurposing (Cusenza et al., 2019b). Consequently, using energy flow modelling enables decision-makers to allocate storage capacity to specific applications in order to achieve desired targets (Tepe et al., 2021).

3.2. Step 1 - LCA results from the energy consumer perspective

The results of the LCIA from the energy consumer perspective in terms of CC and RD are presented in Fig. 5A. Results for other impact categories can be found in SM Tables 24–26.

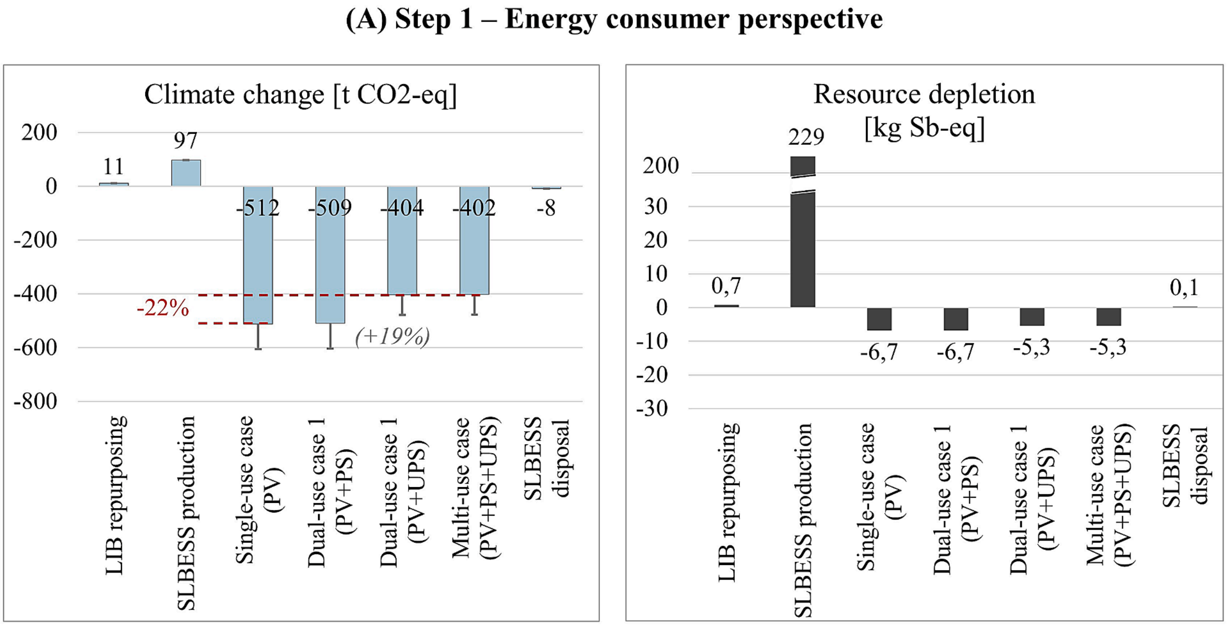
Firstly, the repurposing process leads to minor contributions in both impact categories. Taking into account that LIB are repurposed on battery pack level, i.e. without replacement or re-grouping of cells or modules, this confirms the findings of other studies with similar assumptions (Bobba et al., 2018).

In contrast, the SLBESS production leads to impacts of 97t CO2-eq in the CC impact category and to 229 kg Sb-eq in the RD category. While the contribution to CC is largely driven by the high amount of steel and copper needed for container case, cables and power conductor rails, the contribution to RD results from the extensive requirements for power electronics such as power converters, distributers and battery management system. In this regard, most studies reviewed in Schulz et al. (2020) only include the LIB repurposing processes, but exclude SLBESS production in the LCA, owing to the assumption of identical processes when comparing repurposing to the production of a new LIB, e.g. in Kim et al. (2015). We implement a detailed inventory of the modular SLBESS container architecture in the case study to show that such approaches potentially neglect the negative impacts of additional parts needed for a CBM in terms of both CO2-eq and of Sb-eq. Furthermore, only -8t CO2-eq and -0,1 kg Sb-eq can be recovered from the SLBESS recycling owing to low recycling efficiency for power electronics.

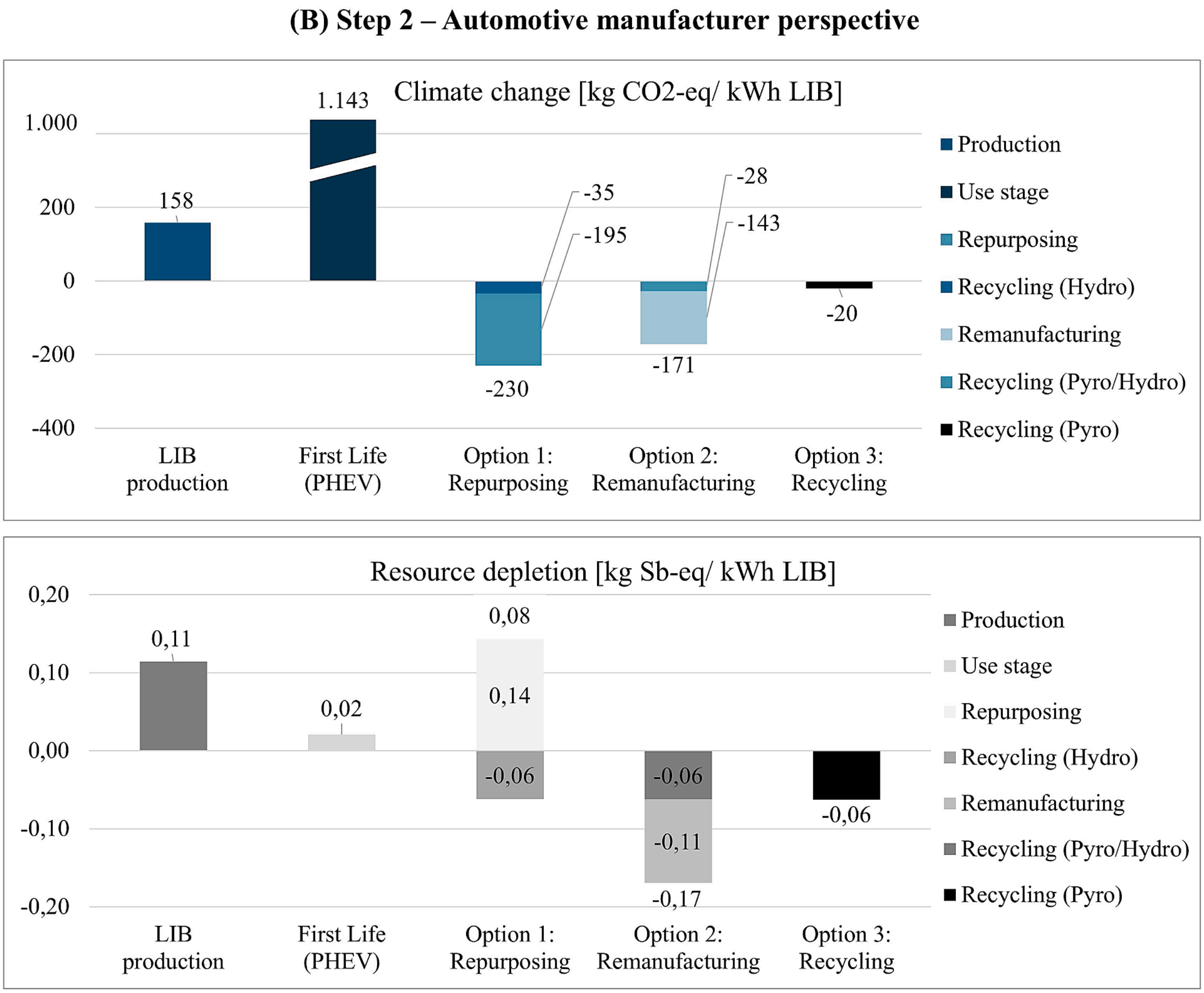
Moreover, results indicate that the SLBESS use stage is the dominant phase in the CC impact category whereas impacts in the RD impact category in the use phase are negligible. All the use cases considered lead to environmental benefits of repurposing while showing potential increase of results by around 19% depending on the decarbonization of the German grid mix achieved by 2030. Based on the average values presented in Fig. 5A, the comparison reveals that the single-use case,

Table 1
Results of the energy flow simulation. Use of the second life battery energy storage system (SLBESS) for local renewable energy (RE) integration from photovoltaic (PV), maximum peak power after peak shaving (PS) and reduced available capacity due to provision of uninterrupted power supply (UPS).

Use case	Available SLBESS capacity [kWh]	SLBESS charging Cycles [per year]	Efficiency losses [MWh per year]	Local RE-integration [MWh per year]	Local RE-integration rate [%]	Max peak power required from grid [kW]	Max discharge power of SLBESS [kW]
BaU	–	–	–	648	64%	1.135	–
Single-use (PV)	1.113	123	13,36	786	77,7%	1.089	785
Dual-use 1 (PV+PS)	1.113	125	13,59	786	77,7%	680	820
Dual-use 2 (PV+UPS)	828	139	11,28	765	75,6%	1.135	721
Multi-use (PV+PS+UPS)	828	140	11,37	765	75,6%	710	811



(A) Step 1 – Energy consumer perspective



(B) Step 2 – Automotive manufacturer perspective

Fig. 5A. A (top): Results for step 1 in climate change (left) and resource depletion impact category (right) for the DC grid over a period of 10 years; including lithium-ion battery (LIB) repurposing; second life battery energy storage system (SLBESS) production; different use cases of photovoltaic (PV) optimization, peak shaving (PS) and uninterrupted power supply (UPS). Fig. 5B (bottom): Results for step 2 in impact category climate change (top) and resource depletion (bottom) per kWh LIB for different options of circular business models.

which focuses only on RE integration, leads to the highest impact reductions with -512t CO2-eq for the FU, followed by the dual-use case 1 with only slightly lower benefits of -509t CO2-eq. In line with the findings stated in Section 3.1, this shows how the additional provision of peak shaving by SLBESS does not significantly affect the environmental benefits of repurposing. Meanwhile, the provision of UPS leads to a lower amount of RE integrated locally in the DC grid and thus to a reduction of the environmental benefits to -404t CO2-eq in dual-use case 2 and to -402t CO2-eq in the multi-use case. For the multi-use case, this corresponds to a relative reduction compared to the most beneficial case by 110t CO2-eq or approximately 22% (see Fig. 5A). Consequently, reducing the available SLBESS capacity for RE integration leads to a reduction of potential environmental benefits in the CC impact category.

From these findings, it follows that repurposing leads to net impact reductions for CC from the perspective of the energy consumer whereas additional net impacts are concluded for RD. Specifically in response to research question 1, the results suggest that climate change benefits in multi-use cases are 22% lower than in single applications.

In light of previous research, the innovative contributions are twofold. Firstly, our study confirms potential net benefits of LIB repurposing for energy consumers when supporting the local integration of RE at industrial scale, for which no studies exist (to our knowledge) so far. Based on the dependency on the displaced grid mix, we show how LIB repurposing can be expected to be particularly beneficial in countries with low shares of RE today. For countries with ambitious RE targets, the net benefits can be expected to decrease together with the ongoing decarbonization of electricity grids. Our results thereby confirm findings of previous studies, stating that the environmental benefits of applying BESS are closely linked to the displaced grid mix (Casals et al., 2019; Hittinger and Azevedo, 2015; Lin et al., 2016).

Secondly, the results reveal environmental pitfalls in endeavors for improving economic feasibility of SLBESS through multi-use cases. Our results thereby underline the necessity for automotive manufacturers to integrate energy flow modelling in their environmental decision-making in order to exploit the full potential of LIB repurposing (Bobba et al., 2018; Cusenza et al., 2019b). Given that results are likely to be case-specific, future studies should test and compare different energy systems with varying consumption characteristics and validate the findings for other segments such as home storages (Tang et al., 2019) or in grid-scale front-of-the-meter applications (Podias et al., 2018). Additionally, a limitation of this study is given by the simplified approach to LIB ageing. Future studies could hence implement non-linear ageing in order to better describe the effects of multi-use cases on LIB degradation (Casals et al., 2017).

3.3. Step 2 – LCA results from the automotive manufacturer perspective

The results from the automotive manufacturer perspective for the two chosen impact categories are presented in Fig. 5B. Detailed results for other impact categories are reported in SM Table 27.

In this context, the LCIA firstly shows results for LIB production of 158 kg CO2-eq per kWh. Based on values between 120–250 kg CO2-eq / kWh obtained for NMC batteries in literature, our result is in line with median values in previous studies (Ellingsen et al., 2017; Temporelli et al., 2020). The corresponding impact in the RD impact category amount to 0,11 kg Sb-eq/ kWh. Furthermore, the use stage of the PHEV clearly dominates the CC impact category when using a German grid mix while showing the lowest impacts in the RD impact category.

In terms of the CBM options investigated, repurposing provides total benefits of -230 kg CO2-eq, thereby offering the highest impact reductions among the CBM options assessed for CC. Out of these, -195 kg CO2-eq are the net benefits resulting from the multi-use case of the SLBESS, as determined previously in the step 1. Additionally, the hydrometallurgical recycling process that is assumed to take place after repurposing contributes with benefits of -35 kg CO2-eq, which is slightly above potential values of -32 kg CO2-eq per kWh of LIB reported in previous studies (Ellingsen et al., 2017). This can be explained by both the advantageous future grid mix used, as well as the high recovery rates on most cell materials such as cobalt, lithium, manganese, nickel and copper (Lebedeva et al., 2016). In total, repurposing yields benefits in the magnitude of 1,5 times the impacts of LIB production and thus considerably improves life cycle impacts of LIB as a whole. Meanwhile, the results in the RD impact category are dominated by the net impacts obtained for repurposing in step 1. Despite benefits from LIB recycling, the resource consumption associated with the SLBESS production leads to additional net impacts for repurposing of 0,08 kg Sb-eq. This lies in the magnitude of the impacts related to LIB production and can thus be considered substantial.

Furthermore, remanufacturing leads to total benefits of -171 kg CO2-eq / kWh, of which -143 kg CO2-eq result from remanufacturing and the avoided production of a new LIB. At the same time, -28 kg CO2-eq result from the mixed recycling process of pyro-and hydrometallurgical process and the avoided production of primary materials. The displaced products additionally lead to benefits of -0,17 kg Sb-eq in the RD impact category.

Lastly, the results for direct recycling show that a pyro-metallurgical processes today yields net benefits of -20 kg CO-eq in the CC impact category, as well as -0,06 kg Sb-eq in the RD impact category.

Consequently, in response to research question 2, a novel finding of this study is that repurposing shows the highest net contribution to the CC impact category among the three CBM investigated. Furthermore, the delay of LIB recycling increases benefits by 73% from pyrometallurgical recycling (-20 kg CO2-eq) to the hydrometallurgical recycling (-35 kg CO2-eq) when assuming a decarbonization of the grid mix in Germany between today and 2030. In contrast, additional impacts occur in terms of Sb-eq. In relation to previous research, our results thus confirm previous findings, stating the relevance of repurposing in relation to the overall impacts of the EV life cycle (Faria et al., 2014). Moreover, our results build upon previous findings in Richa et al. (2017), showing the inter-dependency between repurposing and recycling as CBM in terms of environmental impacts in different impact categories.

From the perspective of an automotive manufacturer, the results suggest that repurposing is the preferred CE strategy for LIB compared to recycling, which is generally in line with the waste hierarchy and other frameworks suggesting the preference of tighter material loops (Bocken et al., 2016; EU, 2008) . Most importantly, unlike for the case of remanufacturing, the benefits of repurposing are not directly related to the production impacts of LIB, but depend on the use case selected for the SLBESS. Hence, an overall contribution of this study is to emphasize how automotive manufacturers need to look beyond the LIB production stage in order to exploit the potential of LIB repurposing in a CE context.

By providing a quantification of the additional environmental benefits of postponing recycling processes, our results advance the sustainable management of LIB EoL streams (Olsson et al., 2018). However, given the dependency on the LIB cell chemistry, considering temporal aspects in future material flows is crucial and requires further investigation. Thus, while our results emphasized the role of LCA as a complementary method for conceptualizing and implementing LIB repurposing as CBM, more work is needed to fully capture the implications of the different CBM options from a CE perspective of a company. As an example, future studies should validate the results by assessing each CBM in terms of material circularity, thereby taking into account future LIB cell technologies as well as recycling yields in relation to future material flows and stocks (Bobba et al., 2019). In this regards, our results in the RD impact category highlight the need for jointly assessing both CC and resource-perspectives for LIB.

3.4. Results from the sensitivity analysis

In the sensitivity analysis, we assess the effects of doubling the SLBESS size in order to match the load profile of the DC grid in the case study. For that, the configuration defined in Section 2.1 serves as a base case. The data obtained from the energy flow simulation based on a SLBESS capacity of 2,473 MWh are reported in SM Table 29. Fig. 6 shows the corresponding LCA results for the CC impact category, which we previously identify as the relevant category for energy-related impacts. Detailed results are provided in SM Tables 30–33.

The sensitivity analysis reveals that additional reductions of energy-related emissions of 57 (single-use case), 41 (dual-use case 1), 119 (dual-use case 2) and 109t CO2-eq (multi-use case) can be achieved compared to the base case by increasing SLBESS size and increasing local RE integration in the DC grid. These correspond to relative increases by 11%, 8%, 29% and 27% respectively. Impacts associated with LIB repurposing, SLBESS production and SLBESS disposal simply double compared to the base case.

The results show that effects of increasing the SLBESS size are larger for dual-use 2 and multi-use case. This can be expected since in those cases, the increase in size compensates for the reduced available capacity for RE integration in the base case. Additionally, the reductions from single-use case 1 to multi-use case in the sensitivity case only amount to 58t CO2-eq, which corresponds to 10%, compared to 22% in the base case (see Fig. 6). This shows that the risk of environmental pitfalls in multi-use cases can be reduced by increasing the SLBESS size.

Practically, this means that optimizing the SLBESS size according to the energy system under investigation is crucial for the full exploitation of environmental benefits of LIB repurposing. While this aspect is mentioned in Cusenza et al. (2019a), our results provide additional, quantified evidence for the sensitivity of environmental benefits to the chosen SLBESS size.

In terms of the effects of the grid mix on recycling impacts, detailed results are provided in SM Tables 34 and 35. Changing the grid mix for pyrometallurgical recycling to wind energy improves benefits to -24,4 kg CO2-eq compared to -20 kg CO2-eq in the base case. It follows from this that LIB repurposing increases the benefits of recycling by 44 – 73% depending on the grid mix. The results of the sensitivity analysis thereby highlight the relevance of the electricity mix used in LIB recycling and thus confirm the decarbonization of electricity grids as a crucial parameter in a CE for LIB.

4. Conclusion

In this study, we showed how integrating energy flow modelling in LCA enabled an automotive manufacturer to determine the potential benefits of different cases of LIB repurposing from the perspective of an energy consumer. In addition, we illustrated how to implement the LCA results in environmental decision-making by interpreting the results in the context of a CE.

As a key contribution, the framework presented in this study allows manufacturers to address the use stage of SLBESS, understand the conditions under which repurposed LIB can create sustainable value in energy systems and to compare repurposing to alternative options of CBM for LIB. For this, we used a case study based on primary data from a real-world project of an industrial energy consumer in Germany, which served to assess the effects on the environmental benefits of LIB repurposing yielded by combining different SLBESS applications in multi-use-cases. Our results emphasize the importance of applying SLBESS for local RE integration, taking into account the displaced grid mix and its development over time. Moreover, a novel finding is that implementing multi-use cases for SLBESS in the pursuit of economic goals can imply the risk of compromising potential environmental benefits of LIB repurposing by 10–22% depending on the system size.

Automotive manufacturers seeking to minimize the environmental impacts of LIB life cycles thus need to go beyond production-related impacts of LIB and further engage with use scenarios for SLBESS in order to exploit the full potential of LIB repurposing in a CE. As a key outcome, our results suggest that repurposing has the highest potential contribution to reduction of greenhouse gas emissions compared to other CBM options for LIB such as remanufacturing and recycling. However, our study illustrates how the results depend on the energy-system under investigation, as well as on the recycling processes and temporal aspects of when a LIB reaches its EoL. In this regard, we find that by postponing EoL by appr. 10 years in the case investigated, LIB repurposing leads to additional CO2 benefits of LIB recycling by 44–73% compared to commonly applied processes today and depending on the electricity grid mix used.

In summary, our results suggest that automotive manufacturers should systematically carry out case-by-case assessments of CBM options as part of their environmental decision-making in a CE context in order

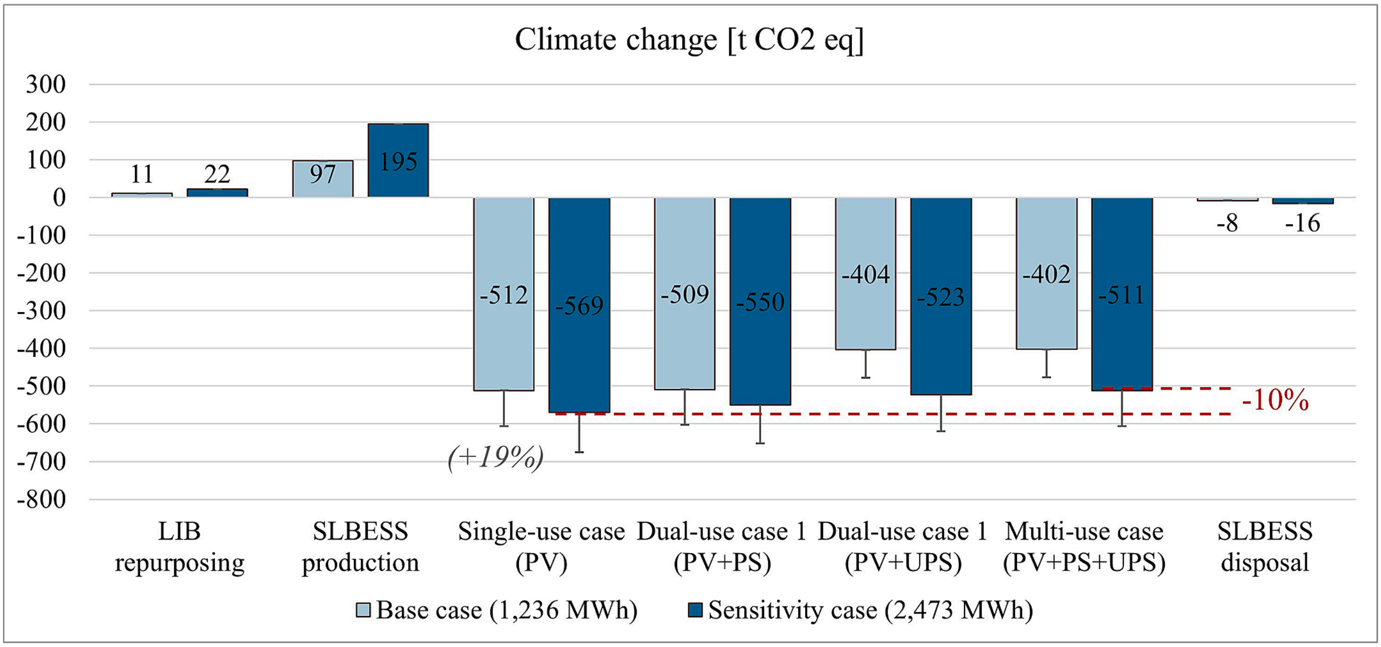


Fig. 6. Sensitivity analysis of doubling the second life battery energy storage system (SLBESS) size.

to ensure maximum environmental impact reduction benefits. For that, our study addresses key challenges on LIB repurposing from both energy consumer and automotive manufacturer perspective and integrates them in an original manner. While further work is needed to define what constitutes success factors of LIB repurposing as a CBM, e.g. from an economic perspective, our results highlight the need for engaging with different methods in combination, such as energy flow modelling and LCA, to implement a CE for LIB in the future. Future studies should expand on the energy-flow based approach provided in our study and investigate the applicability for cases of implementing SLBESS in front-of-the meter applications at distribution-grid level, e.g. the avoidance of RE curtailment and provision of ancillary services. Furthermore, both the novel results obtained for LIB repurposing in the RD impact category and the inter-relationship with EoL material flows point towards the necessity of developing dedicated approaches for managing resource consumption of CBM for LIB. Coupling LCA with material circularity assessments seems to be a promising avenue in research in order to ensure a sustainable deployment of LIB repurposing in the future.

CRediT authorship contribution statement

Magnus Schulz-Mönninghoff: Conceptualization, Methodology, Software, Writing - original draft, Writing - review & editing, Formal analysis, Visualization, Project administration. **Niki Bey:** Conceptualization, Supervision, Validation, Resources, Writing - review & editing. **Patrick Uldall Nørregaard:** Investigation, Data curation, Software. **Monia Niero:** Methodology, Writing - review & editing, Validation, Supervision.

Declaration of Competing Interest

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

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Supplementary materials

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