The International Journal of Life Cycle Assessment (2023) 28:554–565
https://doi.org/10.1007/s11367-023-02154-0

LCA OF WASTE MANAGEMENT SYSTEMS

Use of life cycle assessment to evaluate circular economy business models in the case of Li-ion battery remanufacturing

Benedikte Wrålsen[1] · **Reyn O'Born**[2]

Received: 11 October 2022 / Accepted: 1 March 2023 / Published online: 15 March 2023

Abstract

Purpose The purpose of this study is to advance and illustrate how life cycle assessment (LCA) can assess circular economy business models for lithium-ion batteries to verify potential environmental benefits compared to linear business models. Scenarios for battery repurpose are assessed to support future decision-makers regarding the choice of new versus second life batteries for stationary energy storage. A procedure to determine the substitution coefficient for repurpose and reuse of batteries is proposed.

Methods Two different circular economy business models are assessed by applying primary data from two Norwegian companies for the development of a new life cycle inventory. With this new data, the authors compare second life battery (from first life in electric vehicle) scenarios and avoided production potential by performing a complete consequential LCA. Building on earlier work, a procedure to identify the substitution coefficient (i.e., potential for avoided production) for battery life cycle assessments is proposed. Interviews during factory visits were performed to identify a technical and a market factor affecting the substitution coefficient.

Results and discussion This study illustrates how life cycle assessment methodology can detect and thus enhance the potential environmental benefits and trade-offs of circular economy business models. Results show that the CBMs which use second life batteries correspond to 16% (for global warming potential) of manufacturing a new battery. This means that a second life battery must avoid > 16% production of a new battery to become the preferred alternative. Hence, circular economy business models with second life batteries can generate net environmental benefits while the remaining battery capacity and market price are identified factors that can alter the potential environmental benefits. The findings suggest that assumptions concerning the avoided production emissions are crucial for understanding the overall impacts of battery value chains.

Conclusions Circular economy business models which enable second life batteries show lower environmental impacts compared to a new battery when it can partly avoid production of a new battery. Based on the identified technical and market factor affecting this potential, a key message to industry and other organizations is that second life batteries should be chosen over new batteries. This depends on the remaining capacity being satisfactory for the new application, and the investment is not performed *because* of a low price compared to a new battery. Consequential LCA practitioners adopting a market approach while evaluating battery reuse and repurpose should model and account for the avoided production potential.

Keywords Circular economy · Life cycle assessment · Batteries · Substitution · Circular economy business models · Remanufacture

1 Introduction

Demand for stationary energy storage such as high-capacity batteries to support grids and store renewable energies is increasing (IEA 2020). Simultaneously, the electric vehicle (EV) market, powered by Li (lithium)-ion batteries (LIBs) is growing continuously (IEA 2021). This development in LIB demand increases the consumption of metals and other valuable materials used in battery production (BloombergNEF

Communicated by Xin Sun.

✉ Benedikte Wrålsen
benedikte.wralsen@uia.no

Reyn O'Born
reyn.oborn@uia.no

[1] School of Business and Law, University of Agder, Grimstad, Norway

[2] Faculty of Engineering and Science, University of Agder, Grimstad, Norway

2022) while used LIBs are increasingly seen as a future waste problem (Pehlken et al. 2017). These trends require intelligent management of used batteries and battery materials to ensure that EVs (and their LIBs) are sustainable in a life cycle perspective. Circular economy business models (CBMs) can contribute to tackle the upcoming wave of used batteries (Jiao and Evans 2016; Olsson et al. 2018). A CBM is a plan for how a business can operate profitably while ensuring decreased environmental impacts through closed-loop supply chains and reduced resource consumption (e.g., sharing models, energy efficiency, and applying recyclable materials in primary production) (Bocken et al. 2019; Geissdoerfer et al. 2020; Lüdeke-Freund et al. 2019). CBMs can be used to implement sustainable strategies to manage a product after its first life, such as repurposing in a second life application prior to recycling of the materials. However, current research questions the real advantages of such circular economy (CE) efforts and recognize trade-offs where further assessment is needed to understand how these CBMs affect the life cycle environmental impacts of product systems (Manninen et al. 2018; Rigamonti et al. 2017; Saidani et al. 2019; Zink and Geyer 2017). Life cycle assessment (LCA) is a useful methodology to assess CE efforts, where consequential LCA methods can be used to determine if CBMs should be implemented (Haupt and Hellweg 2019; Ncube et al. 2022; Peña et al. 2021; Rigamonti and Mancini 2021; Stucki et al. 2021; van Loon et al. 2021). Consequential LCA aims to detect environmental consequences of future decisions (Frischknecht et al. 2017; Schulz-Mönninghoff et al. 2021), such as a choice between new business models (Løkke et al. 2020). LCA can thus be a valuable tool to support sustainable, circular business opportunities (Murakami et al. 2019).

Earlier LCA studies (Ahmadi et al. 2017, 2014; Bobba et al. 2018; Commission et al. 2018; Cusenza et al. 2019; Ioakimidis et al. 2019; Kamath et al. 2020a, b; Philippot et al. 2022; Richa et al. 2017; Wang et al. 2022; Wilson et al. 2021; Xiong et al. 2020) found that second life batteries have lower environmental impacts compared to new batteries. However, these studies did not include primary, new inventory data for the remanufacturing processes required to form a second life battery from an EV battery pack to a larger battery for a stationary energy storage applications as most LCA studies of LIBs rely on secondary data (Aichberger and Jungmeier 2020). Schulz-Mönninghoff and colleagues (2021) assessed repurposing of a battery pack, however, only included testing, calibration, software updates, and shipment to assembly site for the reassembly life stage in Germany. The study included new inventory data for the installation, however, not from battery module level (i.e., not dismantling the battery pack and reassembly the module parts for a second life battery pack). Current research on LCA of second life batteries does not currently have focus on the disassembly and remanufacturing processes.

In consequential LCA (cLCA), determining a precise substitution coefficient (i.e., the amount of avoided production due to use of a second life product or material) is crucial for life cycle impact assessment results (Chalmers et al. 2015). Despite this, several consequential LCA studies on waste management assume one hundred percent avoided production (causing negative emissions) for second life products and recycled materials, which is seldom the case (Heijungs and Guinée 2007; Rigamonti et al. 2020; Zink et al. 2016; Zink and Geyer 2017). There is an ongoing discussion on how to determine the substitution coefficient in LCA studies (Vadenbo et al. 2017). Rigamonti and colleagues (2020) suggest a guideline to develop the technical substitution coefficient, representing degree of technical replacement potential. The researchers encourage LCA practitioners to develop coefficients for other secondary materials or products to advance and harmonize their work. Market-related factors also affect the substitution coefficient, such as price mechanisms (Zink et al. 2016). Increased emphasis is needed on considering market characteristics such as substitution, rebound, and price effects in cLCA (Yang and Heijungs 2018). The authors are not familiar with other LCA studies that propose a technique to combine a technical and market factor to identify the substitution coefficient for batteries.

This study assesses the consequential environmental impacts between two different circular economy business model alternatives for second life LIBs based on two companies in Norway. These two CBMs utilizing used EV batteries for energy storage are compared to the existing linear business model using new LIBs. The first CBM enables repurposing of used EV battery packs for a second life in stationary energy storage systems to obtain increased self-sufficiency (i.e., reduced grid dependence by local renewable energy generation). The second CBM enables repurposing by dismantling the pack into modules and thereafter reassembly of the modules to a second life battery pack. The origin of the batteries and the second life application for both CBMs are identical but differ in how these used batteries are dismantled and reassembled. A new life cycle inventory is introduced for the two CBM cases including the remanufacturing and installation processes required. Applying consequential LCA, this research investigates real environmental effects of CBMs where batteries are repurposed in a stationary energy system as identified in earlier work (Wrålsen et al. 2021). As part of the complete assessment, a procedure for practitioners to identify the substitution coefficient in battery reuse and repurpose cases is proposed, implementing both a market and a technical factor. The methodological advancements are illustrated within the two cases described in Sect. 3.

2 Li-ion battery repurpose

Previous research shows that remanufacturing and repurposing is identified as the CBM with the highest potential for LIBs (Wrålsen et al. 2021). Battery repurpose is when a used battery is applied in a different application than it was originally designed and manufactured for, for example, if a battery has a first life in an EV and a second life in a stationary energy storage system. LIBs have high energy density compared to other batteries and are recognized as interesting for repurpose when there is remaining capacity left after first life (Melin et al. 2021; Neubauer et al. 2015; Wind et al. 2021). If there is remaining capacity left depends on the case-specific use and application. Thus, the lifetime of second life batteries will vary (Wrålsen and Faessler 2022). A study testing the cycle lifetime of a used EV battery with unknown user history found that the battery could be charged and discharged 2033 cycles (Braco et al. 2020). In cases where repurposing is considered, the used batteries can be tested through characterization to assess remaining capacity and suitability for repurpose (Harper et al. 2019).

Current CBMs which enable a second life remanufacture EV batteries at different levels, primarily (1) remanufacturing of the complete battery pack or (2) remanufacturing by first dismantling the pack to several modules and then reassembling a new pack based on these modules. This is possible as an EV battery pack consists of several connected battery modules. These modules consist of several battery cells. Since the commercialization of LIBs in 1991, researchers have worked to increase the energy density of the battery cells by testing different materials and compositions (Zhao et al. 2021). Several LIB chemistries are now in use in EVs. The longest (real) driving range in a commercialized EV is currently (in 2023) almost 700 km, according to EVDB (EV database 2023).

Remanufacturing enabling repurpose will extend the battery lifetime before the materials are recycled at the final end-of-life. Recycling technologies for LIBs are underdeveloped and repurpose will enable more time for LIB recycling technologies to improve (Kotak et al. 2021). These technologies must be improved as battery packs consist of several valuable materials, for example, aluminum, steel, copper, nickel, cobalt, and lithium. The two latter are the most critical in terms of reserves and supply risks (to some extent also nickel) (Xu et al. 2020). High-nickel batteries such as the lithium nickel manganese cobalt oxide (NMC)811 chemistry is a growing trend, reducing market share of lower nickel content chemistries such as NMC 111. Chemistries without cobalt is also a growing trend (Wind et al. 2021).

Recognized battery repurpose applications can be grouped into (1) in-front-of-the-meter applications (i.e., the power passes through the meter before reaching the end-user), (2) behind-the-meter (i.e., the power can be used on-site), and (3) off-grid (i.e., battery systems not connected to the electricity grid). A second life battery can for example be used for energy arbitrage where the battery stores electrical energy when the electricity from the grid is cheap to purchase and uses this when the electricity price is high. This is an example of a repurpose application in-front-of-the-meter. The used battery with remaining capacity can alternatively be used for peak shaving to reduce the demand peaks which often cost more. This is an example of a repurpose application behind-the-meter (Faessler 2021). A disadvantage of second life batteries, and a potential challenge with repurpose practice, is that the batteries are designed for their first use application (e.g., an EV) and are therefore not technically optimal for the second life application (Rallo et al. 2020; Reinhardt et al. 2019).

3 Case studies

The life cycle inventory list in this study is based on two existing projects from two Norwegian companies working with different circular economy business models. Both projects apply used EV batteries for stationary energy storage systems for storing solar energy to increase self-sufficiency of electricity and decrease grid dependence.

3.1 Circular economy business model 1: Eco Stor

Eco Stor AS was established in 2018 in Norway to commercialize stationary energy storage solutions based on second life batteries from electric vehicles (Eco Stor AS 2022). The company offers solutions for applications such as solar energy storage (increased self-consumption), peak shaving, grid infrastructure support, and demand side grid trading. Their subsidiary company in Germany uses new batteries in large-scale systems for grid support applications (linear business model), and in Norway, second life battery packs from electric vehicles are used (circular economy business model). The used battery packs are sent from central Europe to Eco Stor in Norway by their vehicle manufacture business partners. This car manufacturer characterizes and sorts the used batteries to ensure only quality battery packs with sufficient remaining battery capacity are repurposed. Repurposing used battery packs from EVs can be challenging due to the lack of data sharing from the battery management system (BMS). The BMS programming code and historic consumer data is currently protected by the owner to hinder hacking and to secure business value. This hinders third-party firms like Eco Stor from having a history of battery cycling and battery state of health, which is critical to understanding how the used batteries can be repurposed (Faessler 2021). Therefore, cooperation with an electric vehicle manufacturer and

BMS owner is key to success for this CBM. The life cycle inventory list built for CBM 1 (repurposing battery packs) in this study reflects the required resources to build generic racks with battery packs applied for stationary energy storage projects. For this case, the energy storage system consisted of a 280 kWh battery system.

3.2 Circular economy business model 2: Batteriretur

Batteriretur is a Norwegian company approved to collect all types of used batteries in Norway, including high-capacity batteries such as lithium-ion batteries from EVs (Batteriretur 2022). The company is owned by several vehicle manufacturers and is responsible to treat the used batteries sustainably according to the European Union's Battery Directive from 2006 (European Union 2006). This directive states that the actors distributing the battery on the market are responsible for providing a collection (take-back) system and to recycle it to the full extent possible. The end-of-life collection, discharge of pack, characterization, dismantling of pack, and further distribution are Batteriretur's responsibility, and they do this on behalf of the battery market distributors. There are two options for the final distribution stage, as the batteries can either be sold to second life distributors or battery recyclers. Currently, most used batteries are sent for treatment and recycling in Europe. To analyze potential economic and environmental gains, Batteriretur developed a pilot project using second life battery modules (the main pack components) from EVs to store solar energy at their plant to reduce their dependency on the grid. The inventory built for CBM 2 (battery modules) in this study reflects the required resources for this pilot project. The case energy storage consisted of a 500 kWh battery system.

4 Material and methods

4.1 Goal and scope

The goal of this LCA study is to assess the environmental consequences of two CBMs which utilize used EV battery packs (CBM 1) and modules (CBM 2) for battery energy storage systems. A secondary goal of this study is to compare these two CBMs with a new NMC 811 battery pack used for the same purpose. The two CBMs are assessed as part of three different scenarios where avoided production (potential for a second life battery to replace new production) is included. The scope includes the resources required to remanufacture a used EV LIB for a new life in a stationary energy storage system and installation in this new application. The functional unit of this study is 1 kWh capacity (second life) NMC 811 battery pack. The inventory is modelled in mass, where 1 kWh capacity NMC 811 battery pack weights 6.7 kg (Crenna et al. 2021).

This study uses a consequential modeling approach that aims to achieve relevant information about environmental consequences to support prospective decisions and considers the consequences of decisions within the market (Ekvall and Weidema 2004; Yang and Heijungs 2018). The decision considered in this study is choosing a traditional, linear business model with a new LIB for stationary energy storage versus second life batteries based on two different CBMs. To account for the potential avoided production, substitution is included in the modelling. This method is preferred by the ISO 14044:2006 (ISO 2006) standard for LCA, where "negative" impacts from avoided production can be included (ISO 2006). CBM 1, CBM 2, and the new battery have the same function: 1 kWh of battery capacity ready for use in a stationary energy storage system application. It is crucial that these product systems are comparable to examine effects of substitution (Weidema 2000). Figure 1 shows the required processes for the two CBMs. Recycling of the materials is outside the scope of this study.

The complete, unmodified battery pack is used in CBM 1, and thus, dismantling, characterization, sorting, and reassembly are not part of the scope for CBM 1. Dismantling and reassembly are not necessary because the complete battery pack from the EV is used in the second life battery pack. Characterization and sorting, checking the state-of-health of the battery packs, and sorting them are done before the battery packs are received by the case company. CBM 2 requires characterization and sorting which are assessed within the scope. As this CBM builds second life battery packs based on battery modules from EVs, the dismantling of the battery packs and reassembly of the modules are required processes. The manufacturing of the machinery and tools at the remanufacturing plant are not included within the scope of either CBMs.

4.2 Life cycle inventory data

The inventory data for each CBM was collected from the two case companies. Both companies were visited following a digital interview. The company visits and the digital interviews followed the same semi-structured interview guide to secure the most crucial information for the inventory while being open to additional relevant information. Before and after the interview, the authors had e-mail correspondences with the case companies discussing relevant processes and developed a basic data collection procedure for collecting the inventory data at each company. Background data is from the consequential Ecoinvent database v.3.8 (Wernet et al. 2016) where a global approach on material production was adapted, except for production of new LIBs, which was assumed to come from China. The major upstream supply for new batteries comes from China; although Europe and the USA are expected to increase their market share (IEA

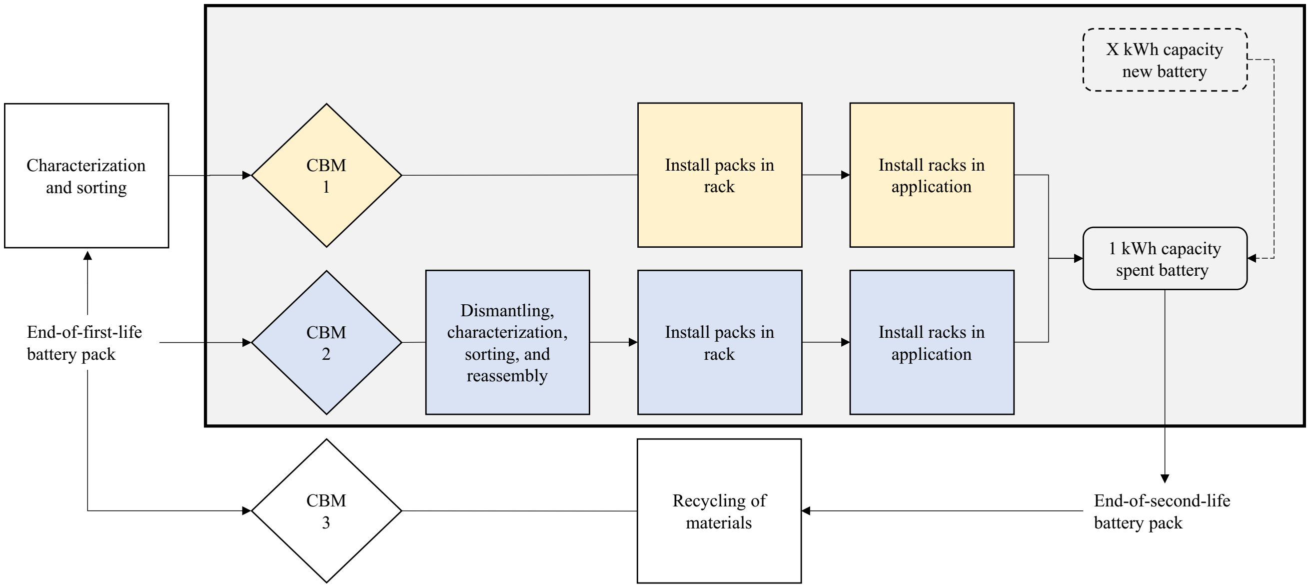

Fig. 1 Bold border and gray area represent system boundaries: the scope includes circular economy business model (CBM) 1 and 2 for lithium-ion batteries (LIBs). Stippled lines represent substitution potential

2022; Melin et al. 2021), it is assumed in this study that most new batteries will continue to be produced in the near future in China. When a new NMC 811 battery is displaced, it is therefore expected that the change in production (avoided) will occur in China as they are considered the main marginal supplier of batteries. All data sources for the inventory are listed in Table 1.

4.3 Impact assessment

SimaPro 9.3.0.2 (PRé Sustainability 2021) was used to build the inventory model and perform the impact assessment. ReCiPe 2016 Midpoint, Hierarchist (H) perspective, version 1.06 (Huijbregts et al. 2016) is the characterization method used in this analysis. It includes 18 impact categories which are assessed to avoid problem shifting between different environmental areas of protection. Global warming, mineral resource scarcity, and water consumption are the main impact categories highlighted in the "5.3" section as they have been identified as being important in previous battery assessments (Ahmadi et al. 2017).

4.4 Scenario analysis

In a market perspective, repurposing batteries can decrease the demand for new batteries and potentially avoid production of these (i.e., avoid impacts from the cradle-to-gate life stage: extraction of raw materials required for new batteries, the processing of the materials, and the battery cell manufacturing). To examine such consequences, three scenarios are assessed based on different substitution coefficients (i.e., degree of decreasing demand of battery due to repurpose of a used LIB). Rigamonti et al. (2020) proposed a procedure based on technical properties for practitioners applying consequential LCA modelling, which is applied in this study. According to the case companies in this study, the remaining battery capacity appears as a crucial technical factor for battery repurposing and is considered as the main

Table 1 Data and source

Data	Source	Specification
Circular economy business model 1 inventory	Case company 1	Resources required for the (foreground) processes
Circular economy business model 2 inventory	Case company 2	Resources required for the (foreground) processes
Background processes	Ecoinvent v3.8	Norwegian electricity mix for remanufacturing and testing
New battery inventory	Ecoinvent v3.8	Lithium-ion battery with chemistry NMC811
Technical factor determining substitution coefficient	Both case companies	Interview during visit, May 2022
Market factor determining substitution coefficient	Both case companies	Interview during visit, May 2022
Factors affecting battery market price	Both case companies	Illustrated in Fig. 2

factor for determining the technical substitution coefficient for second life LIBs. Battery charge–discharge cycles and calendar aging lead to reduced capacity (measured in kWh) while the second life LIB capacity can also be hindered if the battery was optimized for another application in the first life. Regardless, a battery should have > 60% of the original capacity remaining after end-of-first-life to be used in second life applications (Faessler 2021; Martinez-Laserna et al. 2018). Thus, if an EV battery has aged from 100 to 80% of its original capacity, roughly 50% of the total lifetime is used in its first life and 50% remains for second life. Equation 1 illustrates how to calculate the technical substitution coefficient and exemplifies a 50% capacity remaining. The procedure is based on Rigamonti et al. (2020).

$$\begin{aligned} TSC &= \frac{TP(SecP)}{TP(SubP)} \\ TSC &= \frac{kWh(SecP)}{kWh(SubP)} \\ TSC &= \frac{0.50(SecP)}{1(SubP)} = 50\% \end{aligned} \tag{1}$$

Equation 1 presents the proposed technical property for lithium-ion batteries and example of how the technical substitution coefficient is calculated (TSC, technical substitution coefficient; TP, technical property; SecP, secondary product; SubP, substituted product).

Market factors also affect the potential for avoided production as the flow of products and materials are integrated in market structures and mechanisms. A consequence of remanufacturing LIBs and selling these as second life batteries is increased supply of batteries. As a result, the price can be affected through price elasticity of demand. This price effect is present in the circular economy rebound concept by Zink and Geyer (2017) and frames the main market factor affecting the substitution coefficient for this study. If the second life LIB price is lower than a new LIB (often the case currently), the battery may be purchased *because* of the low price. The three business model characteristics affecting the LIB price illustrated in Fig. 2 were revealed during case company dialogues. Through identifying these characteristics, the assumed LIB price effect on the substitution coefficient becomes more robust.

Table 2 shows how the substitution coefficient is identified for the LCA based on the technical and market factors.

Equation 2 illustrates the final step to combine the technical and market factor to find the combined coefficient applied in this LCA study.

$$\begin{aligned} \frac{(TC + MC)}{2} &= CC \\ \frac{(0.5 + 0.5)}{2} &= 0.5 \end{aligned} \tag{2}$$

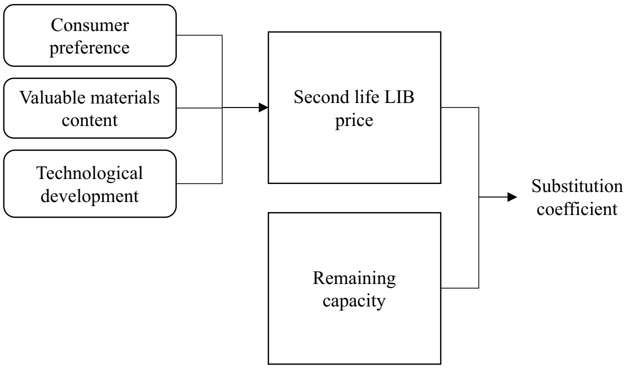

Fig. 2 Key market and technical factor affecting avoided production in battery reuse and repurpose cases. To the left, three business model characteristics affect the dynamic market price

Equation 2 presents the final step to calculate the combined coefficient to apply in the LCA (TC, technical coefficient; MC, market coefficient; CC, combined coefficient).

5 Results and discussion

5.1 Life cycle inventory

The inventory for CBM 1 represents the required resources to remanufacture and install second life battery *packs* in a 280 kWh stationary energy storage system. The inventory for CBM 2 represents the required resources to remanufacture and install second life battery *modules* in a 500 kWh stationary energy storage system. Porzio and Scown (2021) suggest phasing out use of battery mass as functional units in LCAs due to a large variation of chemistries and pack design. Hence, the inventory list in Table 3 is normalized to 1 kWh.

5.2 Life cycle impact assessment

The two CBMs are in different substitution scenarios compared with a new battery. The CBMs represent two different second life batteries remanufactured for stationary energy storage.

Table 2 How the remaining capacity and the second life battery price affect the substitution coefficient

Remaining capacity (%)	LIB price	Coefficient (%)
≤ 60	Second life < new	0
80	Second life < new	0.5
100	Second life ≥ new	1

Table 3 The resources required for circular economy business model (CBM 1 (Eco Stor); CBM 2 (Batteriretur); and a new battery, ready for (second life) stationary storage use per functional unit (1 kWh battery capacity))

Resource	CBM 1 (pack)	CBM 2 (module)	New (pack)	Unit
Steel rack (reusable one time)	1.250	0.700	1.250	kg
Battery interface unit	0.005	-	0.005	kg
Cables	0.288	0.288	0.288	kg
Circuit breakers and junction boxes	0.050	-	0.050	kg
Electricity, Norwegian	1.019	13.780	-	kWh
Inverter	0.058	0.058	0.058	p
Inverter rack	0.357	-	0.714	kg
Router	0.001	-	0.001	p
Electricity losses during startup test, Norwegian	0.014	0.008	0.014	kWh
Switch, power supply, e-stop, energy management system, extra controller	0.012	0.007	0.012	kg
New mini-BMS for modules	-	0.003	-	kg
Copper rail	-	0.083	-	kg
Electronics	-	0.050	-	kg
Main BMS (laptop)	-	0.02	-	p
Production of NMC811 (Ecoinvent)	−6.7	−6.7	6.7	kg

Table 4 shows the complete life cycle impact assessment (LCIA) results for all 18 categories. The two CBMs are in different substitution scenarios compared with a new battery. The CBMs represent two different second life batteries remanufactured for stationary energy storage.

The scenarios with 0% substitution show only impacts from the remanufacturing and installation processes required to transform a used EV battery to a functional second life battery. The scenarios with 50% substitution include negative impacts caused by 50% of the impacts from production of a new battery (−24.6 * 0.50). The scenarios with 100% substitution include negative impacts caused by 100% of the impacts from production of a new battery (−24.6 * 1). Thus, the two latter scenario groups show negative impacts in some of the categories. Mineral resource scarcity and terrestrial acidification show negative impacts, also for scenario i. with 0% substitution. This is mainly due to two by-products from copper processing for the inverter: firstly, the rare-earth metal palladium from electronics scrap in anode slime, and secondly, the rare-earth mineral molybdenite. As impacts associated with by-products are subtracted from the total in consequential LCA methodology, the net impacts can become negative. Smelting of copper concentrate is responsible for the majority of the terrestrial ecotoxicity impacts (553.1 kg 1,4-DCB with 0% substitution). The contribution analysis for the highlighted categories is shown in the supplementary information document.

The results show that the difference between the two CBMs is small (≤ 0.1) for all categories. As the CBM 1 case consisted of a 280 kWh sized system and CBM 2 was a 500 kWh system, the impacts from CBM 1 can be marginally lower as the resources required (Table 3) is divided by the total size of the system to obtain the functional unit of 1 kWh. Some, e.g., electronics are equal independent of this size range. Figure 3 compares the CBMs with a new battery for stationary energy storage and highlights three impact categories. The results are illustrated with three substitution scenarios (i. 0%, ii. 50%, and iii. 100%).

5.3 Discussion

The main results of this study show that the repurposing of used EV batteries for energy storage systems at both the pack and module level is environmentally advantageous compared to using new batteries. This confirms the findings in literature related to battery reuse and repurposing. The three substitution coefficient scenarios in Fig. 3 illustrate the significant effect assumptions on avoided production potential have on impact assessment results. Consequentially, if using the second life battery cannot avoid any production of new batteries, the resulting impacts are higher for choosing one of the battery solutions from the CBMs compared to a new battery. Thus, CBMs utilizing second life LIBs can lower environmental impacts in all categories if some production of a new battery is avoided.

This study developed a procedure for assessing the impacts of battery reuse and repurposing and emphasizes the importance of not neglecting substitution coefficients in LCA studies. In scenario iii., the second life batteries from the CBMs fully replace (substitute) a new battery and avoid production and thus environmental impacts, while in scenario i., where 0% substitution is assumed, the second life battery is consumed *in addition* to a new battery due to market expansion. The consumption of a second life battery will in this scenario not reduce the use of new batteries but increase the total number of batteries on the global market.

Table 4 LCIA results for CBM 1 (second life battery packs) and CMB 2 (second life battery modules) for all impact categories in three substitution scenarios and a new battery. Values per kilowatt-hour battery capacity

Impact category	Unit	CBM 1, 0% substitution	CBM 1, 50% substitution	CBM 1, 100% substitution	CBM 2, 0% substitution	CBM 2, 50% substitution	CBM 2, 100% substitution	New
Global warming	kg CO2 eq	4.04E+00	−6.26E+00	−1.66E+01	3.97E+00	−6.33E+00	−1.66E+01	2.46E+01
Stratospheric ozone depletion	kg CFC11 eq	2.76E-06	1.04E-07	−2.55E-06	3.03E-06	3.69E-07	−2.29E-06	8.07E-06
Ionizing radiation	kBq Co-60 eq	1.91E-01	−1.94E+00	−4.08E+00	1.91E-01	−1.95E+00	−4.08E+00	4.46E+00
Ozone formation, human health	kg NOx eq	2.11E-02	3.96E-02	5.81E-02	2.21E-02	4.07E-02	5.92E-02	−1.60E-02
Fine particulate matter formation	kg PM2.5 eq	−4.32E-02	−3.87E-02	−3.43E-02	−4.16E-02	−3.71E-02	−3.27E-02	−5.20E-02
Ozone formation, terrestrial ecosystems	kg NOx eq	2.18E-02	4.01E-02	5.84E-02	2.29E-02	4.12E-02	5.95E-02	−1.48E-02
Terrestrial acidification	kg SO2 eq	−1.60E-01	−8.86E-02	−1.76E-02	−1.53E-01	−8.21E-02	−1.11E-02	−3.02E-01
Freshwater eutrophication	kg P eq	5.22E-03	−4.25E-03	−1.37E-02	5.01E-03	−4.46E-03	−1.39E-02	2.41E-02
Marine eutrophication	kg N eq	1.69E-04	−2.09E-03	−4.36E-03	1.46E-04	−2.12E-03	−4.38E-03	4.70E-03
Terrestrial ecotoxicity	kg 1,4-DCB	5.53E+02	1.47E+03	2.38E+03	6.27E+02	1.54E+03	2.46E+03	−1.28E+03
Freshwater ecotoxicity	kg 1,4-DCB	2.26E+00	−1.45E+00	−5.17E+00	2.19E+00	−1.52E+00	−5.24E+00	9.69E+00
Marine ecotoxicity	kg 1,4-DCB	2.99E+00	−1.25E+00	−5.48E+00	2.93E+00	−1.30E+00	−5.54E+00	1.15E+01
Human carcinogenic toxicity	kg 1,4-DCB	7.82E-01	9.42E-01	1.10E+00	8.27E-01	9.87E-01	1.15E+00	4.63E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	5.69E+01	4.49E+01	3.28E+01	6.05E+01	4.84E+01	3.63E+01	8.10E+01
Land use	m2a crop eq	5.11E-01	1.95E+00	3.38E+00	5.85E-01	2.02E+00	3.45E+00	−2.36E+00
Mineral resource scarcity	kg Cu eq	−1.80E-01	−3.66E+00	−7.15E+00	−2.24E-01	−3.71E+00	−7.19E+00	6.79E+00
Fossil resource scarcity	kg oil eq	1.07E+00	−2.91E+00	−6.88E+00	1.05E+00	−2.93E+00	−6.91E+00	9.02E+00
Water consumption	m^3	5.25E-02	−1.85E+00	−3.76E+00	7.29E-02	−1.83E+00	−3.74E+00	3.86E+00

A lower battery price leads to a higher number of consumers willing to purchase a battery, which means more batteries in total according to the circular economy rebound concept (Zink and Geyer 2017).

The remaining battery capacity (technical factor) and battery price (market factor) were identified as important for the substitution coefficient for LCAs assessing reuse and repurpose of batteries. Building on work by Rigamonti and colleagues (2020) and Zink and colleagues (2016), the procedure for calculating the substitution coefficient proposes to account for both factors by combining them in the calculation. Although battery price is recognized as important, it is dynamic and regionally based and thus challenging to use as a parameter in LCA models. To increase predictability, three business model characteristics affecting the LIB price are identified (illustrated in Fig. 2):

1. Demand for second life batteries based on consumer preference (e.g., perception of quality and security).
2. Valuable materials affect economic value (e.g., older batteries can contain more cobalt).
3. Technological development integrated in new batteries can lower value of the older batteries (e.g., improved battery energy density).

These business model characteristics affect the battery price and thus the substitution potential of the second life batteries. By understanding the CBMs assessed, more realistic assumptions were made during the LCA modelling. Hence, CBM insights are valuable when calculating the substitution coefficient to understand the factors affecting the potential for avoided production.

By assessing the CBM for batteries proposed in Wrålsen et al. (2021), this study found the potential environmental benefits from this CBM compared to a linear business model. In percentage, the comparison shows that the remanufacturing process of the used batteries corresponds to 16% of the global warming impact of producing a new battery. A

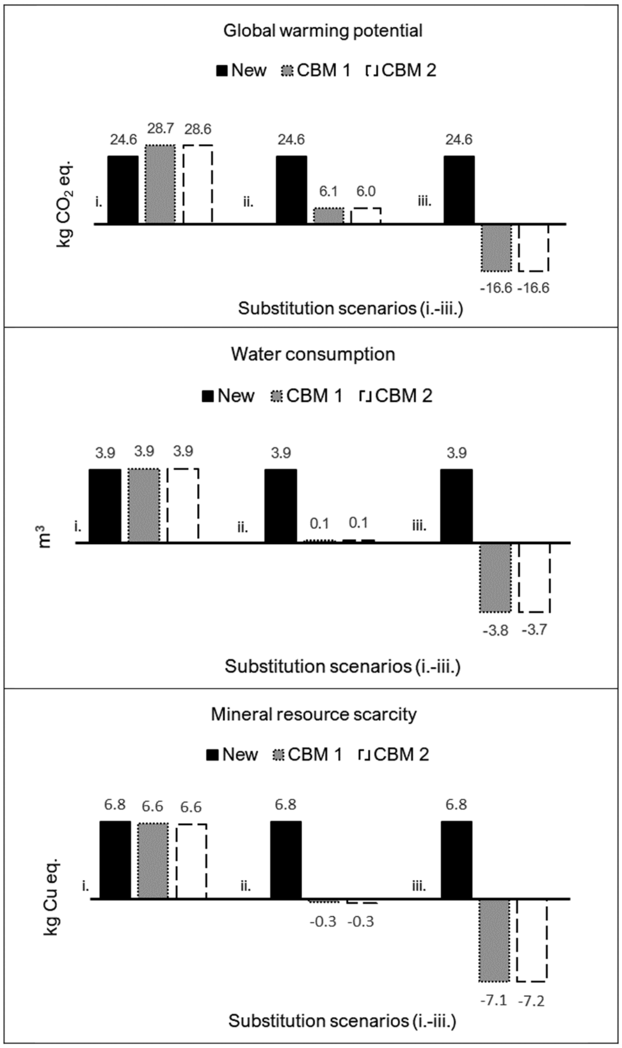

Fig. 3 Impacts of a second life battery from two different CBMs with no (scenario i.), 50% (ii. dotted line), and 100% (iii. stippled line) avoided production of a new NMC811 battery

minimum of 16% production needs to be avoided for second life batteries to contribute to climate change mitigation. For water consumption, this is valid when a used battery can replace 3% of a new battery. For mineral resource scarcity, this is valid even with 0% substitution. CBMs (which aim to gain environmental benefits) should be assessed for different environmental impact categories to quantify potential benefits and avoid problem shifting between different environmental areas of protection.

6 Conclusion

This study illustrates the possibilities and advantages of applying life cycle assessment to assess circular economy business models with the case of used lithium-ion batteries from electric vehicles. When comparing the impact of second life batteries facilitated by the circular economy business models with new batteries, results show that the latter has generally higher environmental impacts. Global warming potential results show that the remanufacturing of used batteries corresponded to 16% of emissions from manufacturing. The water consumption corresponded to 3% and mineral resource scarcity to 0%. Despite the relatively low impacts from the battery remanufacturing process, the results indicate that there is a relatively low threshold for environmental benefits by utilizing second life batteries to replace and avoid production of new batteries.

For organizations and individuals choosing between new and second life batteries, an investment in the latter is proposed if (1) the remaining technical capacity is sufficient for the new application and (2) the second life battery investment is not performed *because* of a lower price compared to a new battery but is acquired instead of a new battery. Hence, it should be able to replace a new battery with second life batteries to some extent. If these two technical and market factors are considered, the environmental advantages of the circular economy business models are validated through the results of this study.

For LCA practitioners working with consequential modelling, and particularly in circular economy contexts, the substitution coefficient is essential for improving the precision of the life cycle impact assessment results. It is recommended that the potential for avoided production should be identified for each specific study, preferably based on both technical and market factors. The proposed procedure can be applied to other products or product components. Furthermore, business model characteristics affecting market prices can be useful to understand the dynamics and thus improve the substitution coefficient in the model.

This study shows that life cycle assessment is valuable to examine if circular economy business models gain net environmental gain as pledged and to evaluate problem shifting to support decision-making. The substitution coefficient appears crucial for impact results, and future research should advance methodology for practitioners to calculate the avoided production potential, also for other second life products.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-023-02154-0.

Acknowledgements The authors gratefully acknowledge Mathias Winther Thorsen from Eco Stor AS and Batteriretur who provided the primary data and information from the case second life battery projects. The study is related to the 2^{ND} LIFE (The value of second life batteries in the future energy system) project funded by the Norwegian Research Council and partners (NFR: 2^{ND} LIFE–281005) and the BATMAN project (Lithium ion batteries—Norwegian opportunities within sustainable end-of-life management, reuse, and new material streams) funded by the Norwegian Research Council and partners (NFR: BATMAN—299334).

Funding Open access funding provided by University of Agder.

Data availability All data generated or analyzed during this study are included in this published article and its supplementary information file.

Declarations

Conflicts of interests The authors declare no competing interests.

References

Ahmadi L, Yip A, Fowler M, Young SB, Fraser RA (2014) Environmental feasibility of re-use of electric vehicle batteries. Sustain Energy Technol Assessments 6:64–74. https://doi.org/10.1016/j.seta.2014.01.006

Ahmadi L, Young SB, Fowler M, Fraser RA, Achachlouei MA (2017) A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems. Int J Life Cycle Assess 22. https://doi.org/10.1007/s11367-015-0959-7

Aichberger C, Jungmeier G (2020) Environmental life cycle impacts of automotive batteries based on a literature review. Energies. https://doi.org/10.3390/en13236345

Batteriretur (2022) Batteriretur.no [WWW Document]. https://batteriretur.no/

BloombergNEF (2022) Electric vehicle outlook [WWW Document]. https://about.bnef.com/electric-vehicle-outlook/

Bobba S, Mathieux F, Ardente F, Blengini GA, Cusenza MA, Podias A, Pfrang A (2018) Life cycle assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows. J Energy Storage 19:213–225. https://doi.org/10.1016/j.est.2018.07.008

Bocken N, Ritala P, Albareda L, Verburg R (2019) Innovation for sustainability: business transformations towards a better world. Palgrave Macmillan, Switzerland. https://doi.org/10.1007/978-3-319-97385-2

Braco E, San Martin I, Berrueta A, Sanchis P, Ursúa A (2020) Experimental assessment of cycling ageing of lithium-ion second-life batteries from electric vehicles. J Energy Storage 32:101695. https://doi.org/10.1016/j.est.2020.101695

Chalmers NG, Brander M, Revoredo-Giha C (2015) The implications of empirical and 1:1 substitution ratios for consequential LCA: using a 1 % tax on whole milk as an illustrative example. Int J Life Cycle Assess 20:1268–1276. https://doi.org/10.1007/s11367-015-0939-y

Commission E, Centre JR, Mathieux F, Di Persio F, Tecchio P, Pfrang A, Eynard U, Podias A, Cusenza M, Bobba S, Messagie M (2018) Sustainability assessment of second life application of automotive batteries (SASLAB): JRC exploratory research (2016–2017): final technical report. Publications Office. https://doi.org/10.2760/53624

Crenna E, Gauch M, Widmer R, Wäger P, Hischier R (2021) Towards more flexibility and transparency in life cycle inventories for lithium-ion batteries. Resour Conserv Recycl 170:105619. https://doi.org/10.1016/j.resconrec.2021.105619

Cusenza MA, Guarino F, Longo S, Ferraro M, Cellura M (2019) Energy and environmental benefits of circular economy strategies: the case study of reusing used batteries from electric vehicles. J Energy Storage 25. https://doi.org/10.1016/j.est.2019.100845

Eco Stor AS (2022) Company [WWW Document]. http://www.eco-stor.com/

Ekvall T, Weidema BP (2004) System boundaries and input data in consequential life cycle inventory analysis. Int J Life Cycle Assess 9:161–171. https://doi.org/10.1007/BF02994190

European Union (2006) Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC. Off J Eur Union L 266:1–14

EV database (2023) Logest electric range [WWW Document]. http://ev-database.org/

Faessler B (2021) Stationary, second use battery energy storage systems and their applications: a research review. Energies 14. https://doi.org/10.3390/en14082335

Frischknecht R, Benetto E, Dandres T, Heijungs R, Roux C, Schrijvers D, Wernet G, Yang Y, Messmer A, Tschuemperlin L (2017) LCA and decision making: when and how to use consequential LCA; 62nd LCA forum, Swiss Federal Institute of Technology, Zürich, 9 September 2016. Int J Life Cycle Assess 22:296–301. https://doi.org/10.1007/s11367-016-1248-9

Geissdoerfer M, Pieroni MPP, Pigosso DCA, Soufani K (2020) Circular business models: a review. J Clean Prod 277:123741. https://doi.org/10.1016/j.jclepro.2020.123741

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

Haupt M, Hellweg S (2019) Measuring the environmental sustainability of a circular economy. Environ. Sustain Indic 1–2:100005. https://doi.org/10.1016/j.indic.2019.100005

Heijungs R, Guinée JB (2007) Allocation and 'what-if' scenarios in life cycle assessment of waste management systems. Waste Manag 27:997–1005. https://doi.org/10.1016/j.wasman.2007.02.013

Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira MDM, Hollander A, Zijp M, van Zelm R (2016) ReCiPe 2016: a harmonized life cycle impact assessment method at midpoint and endpoint level report I: characterization.

IEA (2022) Global supply chains of EV batteries. International Energy Agency. France. Available at https://iea.blob.core.windows.net/assets/4eb8c252-76b1-4710-8f5e-867e751c8dda/GlobalSupplyChainsofEVBatteries.pdf

IEA (2021) Global EV outlook 2021 - accelerating ambitions despite the pandemic. Glob EV Outlook 2021:101

IEA (2020) Renewables. Paris

Ioakimidis CS, Murillo-Marrodán A, Bagheri A, Thomas D, Genikomsakis KN (2019) Life cycle assessment of a lithium iron phosphate (LFP) electric vehicle battery in second life application scenarios. Sustain 11. https://doi.org/10.3390/su11092527

ISO (2006) ISO 14044:2006 Environmental management - life cycle assessment - requirements and guidelines. The International Organization for Standardization. Available at https://www.iso.org/standard/38498.html

Jiao N, Evans S (2016) Secondary use of electric vehicle batteries and potential impacts on business models. J Ind Prod Eng 33:348–354. https://doi.org/10.1080/21681015.2016.1172125

Kamath D, Arsenault R, Kim HC, Anctil A (2020a) Economic and environmental feasibility of second-life lithium-ion batteries as fast-charging energy storage. Environ Sci Technol 54:6878–6887. https://doi.org/10.1021/acs.est.9b05883

Kamath D, Shukla S, Arsenault R, Kim HC, Anctil A (2020b) Evaluating the cost and carbon footprint of second-life electric vehicle batteries in residential and utility-level applications. Waste Manag 113:497–507. https://doi.org/10.1016/j.wasman.2020.05.034

Kotak Y, Fernández CM, Casals LC, Kotak BS, Koch D, Geisbauer C, Trilla L, Gómez-Núñez A, Schweiger HG (2021) End of electric vehicle batteries: Reuse vs. recycle. Energies. https://doi.org/10.3390/en14082217

Løkke S, Schmidt JH, Lyhne I, Kørnøv L, Revsbeck R (2020) How green are supported 'green' business models? Time for the life cycle approach to enter public support programmes. Int J Life Cycle Assess 25:2086–2092. https://doi.org/10.1007/s11367-020-01806-9

Lüdeke-Freund F, Gold S, Bocken NMP (2019) A review and typology of circular economy business model patterns. J Ind Ecol 23:36–61. https://doi.org/10.1111/jiec.12763

Manninen K, Koskela S, Antikainen R, Bocken N, Dahlbo H, Aminoff A (2018) Do circular economy business models capture intended environmental value propositions? J Clean Prod 171:413–422. https://doi.org/10.1016/j.jclepro.2017.10.003

Martinez-Laserna E, Gandiaga I, Sarasketa-Zabala E, Badeda J, Stroe DI, Swierczynski M, Goikoetxea A (2018) Battery second life: hype, hope or reality? A critical review of the state of the art. Rene Sustain Energy Rev 93:701–718. https://doi.org/10.1016/j.rser.2018.04.035

Melin HE, Rajaeifar MA, Ku AY, Kendall A, Harper G, Heidrich O (2021) Global implications of the EU battery regulation. Science 373(80):384–387.

Murakami S, Nakatani J, Nakajima K, Amasawa E, Ii R, Hayashi K, Yoshikawa N, Daigo I, Kishita Y, Ihara T, Shobatake K, Kudoh Y, Motoshita M, Kanemoto K, Hara M, Kashiwagi A, Hashimoto S, Shigetomi Y, Kanzaki M, Kikuchi Y, Ohno H, Fukushima Y (2019) EcoBalance 2018—nexus of ideas: innovation by linking through life cycle thinking (9–12 October 2018, Tokyo, Japan). Int J Life Cycle Assess 24:1544–1552. https://doi.org/10.1007/s11367-019-01641-7

Ncube A, Fiorentino G, Panfilo C, De Falco M, Ulgiati S (2022) Circular economy paths in the olive oil industry: a life cycle assessment look into environmental performance and benefits. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-022-02031-2

Neubauer J, Smith K, Wood E, Pesaran A (2015) Identifying and overcoming critical barriers to widespread second use of PEV batteries. National Renewable Energy Laboratory (NREL)

Olsson L, Fallahi S, Schnurr M, Diener D, Van Loon P (2018) Circular business models for extended EV battery life. Batteries 4:57

Pehlken A, Albach S, Vogt T (2017) Is there a resource constraint related to lithium ion batteries in cars? Int J Life Cycle Assess 22:40–53. https://doi.org/10.1007/s11367-015-0925-4

Peña C, Civit B, Gallego-Schmid A, Druckman A, Pires AC, Weidema B, Mieras E, Wang F, Fava J, Canals LMI, Cordella M, Arbuckle P, Valdivia S, Fallaha S, Motta W (2021) Using life cycle assessment to achieve a circular economy. Int J Life Cycle Assess 26:215–220. https://doi.org/10.1007/s11367-020-01856-z

Philippot M, Costa D, Hosen MS, Senécat A, Brouwers E, Nanini-Maury E, Van Mierlo J, Messagie M (2022) Environmental impact of the second life of an automotive battery: reuse and repurpose based on ageing tests. J Clean Prod 366:132872. https://doi.org/10.1016/j.jclepro.2022.132872

Porzio J, Scown CD (2021) Life-cycle assessment considerations for batteries and battery materials. Adv Energy Mater. https://doi.org/10.1002/aenm.202100771

PRé Sustainability (2021) SimaPro. Amersfoort. Available at https://simapro.com/licences/faculty/

Rallo H, Benveniste G, Gestoso I, Amante B (2020) Economic analysis of the disassembling activities to the reuse of electric vehicles Li-ion batteries. Resour Conserv Recycl 159:104785. https://doi.org/10.1016/j.resconrec.2020.104785

Reinhardt R, Christodoulou I, Gassó-Domingo S, Amante García B (2019) Towards sustainable business models for electric vehicle battery second use: a critical review. J Environ Manage 245:432–446. https://doi.org/10.1016/j.jenvman.2019.05.095

Richa K, Babbitt CW, Nenadic NG, Gaustad G (2017) Environmental trade-offs across cascading lithium-ion battery life cycles. Int J Life Cycle Assess 22:66–81. https://doi.org/10.1007/s11367-015-0942-3

Rigamonti L, Falbo A, Zampori L, Sala S (2017) Supporting a transition towards sustainable circular economy: sensitivity analysis for the interpretation of LCA for the recovery of electric and electronic waste. Int J Life Cycle Assess 22:1278–1287. https://doi.org/10.1007/s11367-016-1231-5

Rigamonti L, Mancini E (2021) Life cycle assessment and circularity indicators. Int J Life Cycle Assess 26:1937–1942. https://doi.org/10.1007/s11367-021-01966-2

Rigamonti L, Taelman SE, Huysveld S, Sfez S, Ragaert K, Dewulf J (2020) A step forward in quantifying the substitutability of secondary materials in waste management life cycle assessment studies. Waste Manag 114:331–340. https://doi.org/10.1016/j.wasman.2020.07.015

Saidani M, Yannou B, Leroy Y, Cluzel F, Kendall A (2019) A taxonomy of circular economy indicators. J Clean Prod 207:542–559. https://doi.org/10.1016/j.jclepro.2018.10.014

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

Stucki M, Jattke M, Berr M, Desing H, Green A, Hellweg S, Laurenti R, Meglin R, Muir K, Pedolin D, Shinde R, Welz T, Keller RL (2021) How life cycle–based science and practice support the transition towards a sustainable economy. Int J Life Cycle Assess 26:1062–1069. https://doi.org/10.1007/s11367-021-01894-1

Vadenbo C, Hellweg S, Astrup TF (2017) Let's be clear(er) about substitution: a reporting framework to account for product displacement in life cycle assessment. J Ind Ecol 21:1078–1089. https://doi.org/10.1111/jiec.12519

van Loon P, Diener D, Harris S (2021) Circular products and business models and environmental impact reductions: current knowledge and knowledge gaps. J Clean Prod 288:125627. https://doi.org/10.1016/j.jclepro.2020.125627

Wang Y, Tang B, Shen M, Wu Y, Qu S, Hu Y, Feng Y (2022) Environmental impact assessment of second life and recycling for LiFePO4 power batteries in China. J Environ Manage 314:115083. https://doi.org/10.1016/j.jenvman.2022.115083

Weidema B (2000) Avoiding co-product allocation in life-cycle assessment. J Ind Ecol 4:11–33

Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B (2016) The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21:1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Wilson N, Meiklejohn E, Overton B, Robinson F, Farjana SH, Li W, Staines J (2021) A physical allocation method for comparative life cycle assessment: a case study of repurposing Australian electric vehicle batteries. Resour Conserv Recycl 174:105759. https://doi.org/10.1016/j.resconrec.2021.105759

Wind J, Foss CEL, Andersen HF (2021) LIB technology mapping. Kjeller, Norway. Available at https://ife.no/wp-content/uploads/2023/02/batman-technology-mapping-report-update-2021.pdf

Wrålsen B, Faessler B (2022) Multiple scenario analysis of battery energy storage system investment: measuring economic and circular viability. Batter. https://doi.org/10.3390/batteries8020007

Wrålsen B, Prieto-Sandoval V, Mejia-Villa A, O'Born R, Hellström M, Faessler B (2021) Circular business models for lithium-ion batteries -

stakeholders, barriers, and drivers. J Clean Prod 317:128393. https://doi.org/10.1016/j.jclepro.2021.128393

Xiong S, Ji J, Ma X (2020) Environmental and economic evaluation of remanufacturing lithium-ion batteries from electric vehicles. Waste Manag 102:579–586. https://doi.org/10.1016/j.wasman.2019.11.013

Xu C, Dai Q, Gaines L, Hu M, Tukker A, Steubing B (2020) Future material demand for automotive lithium-based batteries. Commun Mater 1:99. https://doi.org/10.1038/s43246-020-00095-x

Yang Y, Heijungs R (2018) On the use of different models for consequential life cycle assessment. Int J Life Cycle Assess 23:751–758. https://doi.org/10.1007/s11367-017-1337-4

Zhao S, Guo Z, Yan K, Wan S, He F, Sun B, Wang G (2021) Towards high-energy-density lithium-ion batteries: strategies for developing high-capacity lithium-rich cathode materials. Energy Storage Mater 34:716–734. https://doi.org/10.1016/j.ensm.2020.11.008

Zink T, Geyer R (2017) Circular economy rebound. J Ind Ecol 21:593–602. https://doi.org/10.1111/jiec.12545

Zink T, Geyer R, Startz R (2016) A market-based framework for quantifying displaced production from recycling or reuse. J Ind Ecol 20:719–729. https://doi.org/10.1111/jiec.12317