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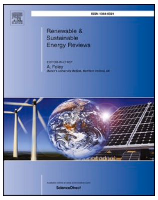

Circularity and life cycle environmental impact assessment of batteries for electric vehicles: Industrial challenges, best practices and research guidelines

Aitor Picatoste [a,*], Daniel Justel [a], Joan Manuel F. Mendoza [a,b,**]

[a] Mondragon Unibertsitatea, Faculty of Engineering, Mechanics and Industrial Production, Loramendi 4, Mondragon 20500, Gipuzkoa, Spain
[b] Ikerbasque, Basque Foundation for Science, Plaza Euskadi 5, Bilbao 48009 Bizkaia, Spain

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ABSTRACT

Circular economy (CE) strategies, aimed at reducing resource consumption and waste generation, can help mitigate the environmental impacts of battery electric vehicles (BEV), thereby providing a more efficient alternative to petrol-fuelled vehicles. Lithium-ion batteries (LIB) are commonly used in BEV because of their higher performance than that of the benchmarks. However, how to analyse the CE innovations through life-cycle assessment (LCA) and how environmental savings relate to different CE strategies remain unclear. Therefore, the purpose of this study was to i) identify and characterise the CE strategies most studied thus far in LCA studies on electric vehicle batteries, ii) evaluate the reasons behind the variability in the environmental impacts and savings between LIB with different chemistries, and iii) provide guidelines for the development of robust LCA studies for LIB by integrating CE management scenarios. The results showed that LCA-supported CE strategies have not been sufficiently explored in the literature, causing variability in methodological choices and research outcomes. While battery recycling was a dominant topic contemplated in 80% of the analysed LCA studies, other CE strategies, such as battery upgrading or remanufacturing, received little attention. The normalised impacts for LIB varied from 4400 kg CO_2 eq. to 55,000 kg CO_2 eq. based on several factors subject to the practitioners' choices, such as the battery chemistry considered, impact assessment method applied, available inventories used, and the CE scenario analysed. LCA methodological guidelines for determining the environmental sustainability of the CE strategies for electric vehicle batteries were provided based on the findings.

1. Introduction

The transportation sector is one of the largest contributors to greenhouse gas (GHG) emissions [1], representing 33% of the total carbon emissions globally [2]. In the European Union (EU), passenger vehicles represent approximately 80% of the GHG emissions in the transportation sector [3], accounting for more than 828 Mt CO_2 eq., which could increase to 1500 Mt CO_2 eq. (>81%) by 2050 under business-*as*-usual scenarios [4].

The use of cleaner vehicles is a potential solution for mitigating the environmental impacts of road transportation [5] and, therefore, the environmental footprint of cities. Battery electric vehicles (BEV) use electricity for propulsion using rechargeable batteries and do not produce tailpipe GHG emissions during operations [6]. Accordingly, their emissions are dependent on the electric mix of the region in which they operate [7]. Thus, considering the increase of renewable energy sources (RES) in the electricity mix by 2030, the use of BEV could reduce the GHG emissions approximately by half compared with that from an equivalent fleet of internal combustion engine vehicles (ICEV) [8].

However, the reduction of GHG emissions in the use phase of BEV is not sufficient to demonstrate their improved environmental performance compared to that of the ICEV. For example, the battery is an important component of BEV from an environmental perspective. Approximately 80% of the life-cycle environmental impacts of BEV are determined by both the battery and energy consumption during

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[*] Corresponding author. Mondragon Unibertsitatea, Faculty of Engineering, Mechanics and Industrial Production, Loramendi 4, Mondragon 20500 Gipuzkoa, Spain.
[**] Corresponding author. Mondragon Unibertsitatea, Faculty of Engineering, Mechanics and Industrial Production, Loramendi 4, Mondragon 20500 Gipuzkoa, Spain.

E-mail addresses: apicatoste@mondragon.edu (A. Picatoste), jmfernandez@mondragon.edu (J.M.F. Mendoza).

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Abbreviations

BEV	Battery electric vehicles
C2G	Cradle to gate
C2Gr	Cradle to grave
CE	Circular economy
CED	Cumulative energy demand
EC	European commission
EOL	End of life
EU	European Union
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
ICEV	Internal combustion engine vehicles
ISO	International organization for standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCO	Lithium cobalt
LCP	Lithium cobalt phosphate
LFP	Lithium Iron Phosphate
LIB	Lithium-ion batteries
LiO_2	Lithium oxygen
LMO	Lithium Manganese Oxide
LVP	Lithium vanadium phosphate
MJ eq.	Megajoules equivalent
NCA	Nickel Cobalt Aluminium
NMC	Lithium Nickel Manganese Cobalt Oxide
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PHEV	Plug-in hybrid energy vehicles
PV	Photovoltaic
RES	Renewable energy source
SESS	Stationary energy storage system
SI	Supporting information

operation [9], with the battery representing 40–50% of the total GHG emissions [10].

High-autonomy and electrical power electric vehicle batteries have different chemistries and undergo complex manufacturing processes [11], which greatly influence their environmental performance. For example, the impact of producing an Li-based battery can vary from 40 kg to 350 kg CO_2 per kWh battery capacity depending upon the battery chemistry [12]. The end-of-life (EOL) management of the batteries also show high variability, both in terms of recycling techniques and related environmental impacts [13].

The implementation of circular economy (CE) strategies focused on resource efficiency by narrowing (reducing overall resource consumption), slowing (prolonging the use cycle of raw materials and products), and closing (facilitating closed-loop recycling) resource loops [14–16], are critical for the development of sustainable BEV [17]. For example, reducing dependence on virgin raw materials through the development of secondary supply chains for critical and/or special metals in the automotive industry is an important environmental strategy [18] that facilitates battery lifetime extension and repurposing [19].

However, resource efficiency improvements may have rebound effects if the CE strategies are not properly planned and deployed [20]. For example, developing electric vehicle batteries with high shares of recycled inputs without considering other life-cycle aspects, such as use performance, could reduce the lifetime and energy efficiency of the batteries, thereby increasing the total environmental impact of vehicles in the long term [21]. Similarly, although the recycling of batteries could decrease the total impact by 1.5 kg CO_2 eq./kg (depending on the battery chemistry and recycling process considered), there are scenarios in which the recycling process can add 2 kg of CO_2 eq./kg [13] owing to the high energy consumption and low recovery rates of some recycling processes [22].

Additionally, the CE innovations focused solely on mitigating the GHG emissions could potentially lead to environmental burden shifting, implying the resolution of one environmental issue by creating a negative impact on different environmental dimensions and/or product life-cycle stages [23].

Accordingly, the environmental analysis of the CE strategies applied in the design and life-cycle management of electric vehicle batteries requires system thinking supported by robust holistic science-based tools, such as life-cycle assessment (LCA) [24,25]. Although several literature reviews have been conducted on the LCA of BEV, the implementation of the CE strategies supported by them is scarce.

Hawkins et al. [26], who reviewed 51 LCA studies focusing on global warming potential (GWP) of BEV and ICEV, highlighted the lack of standardisation between the studies and the high variability in the assumptions applied in operations, such as electricity consumption, ranging from 0.10 to 0.24 kWh/km.

Nordelöf et al. [27], who examined 79 LCA studies on BEV, indicated that the absence of future time perspective in the applied LCA methodologies constraints the long-term environmental performance analysis of BEV because their market penetration and electric mixes change constantly, which is a concern also shared by Marmiroli et al. [28].

The quality and disaggregation level of the primary data is another relevant challenge highlighted by Dillman et al. [5], who reviewed 25 articles to set a framework for the development of prospective LCA calculations. Moreover, although Dolganova et al. [29] reviewed 103 articles on the resource efficiency of BEV and D'Adamo and Rosa [18] analysed the EOL procedures of BEV by reviewing 171 articles, they found that these studies failed to address the holistic view of the CE.

The published literature suggests a high concern regarding the variability of the LCA results of BEV and their batteries and calls for the development of standards and guidelines to harmonise CE assessment and LCA methodologies. However, the literature reviews on the LCA studies of BEV are usually focused on EOL management [18] and lead to partial analyses of life-cycle impacts and misguide sustainability-oriented decisions [30] owing to their narrow scopes.

Accordingly, this study had three main research goals. Goal 1 was to identify and characterise the CE strategies studied thus far in the LCA of electric vehicle batteries and analyse why other CE strategies have not yet been properly addressed in the literature. Goal 2 was to evaluate the reasons behind the variability in the environmental impacts and savings of the Lithium-ion batteries (LIB) in the LCA studies addressing the CE strategies. Goal 3 was to propose best practices and guidelines for the development of additional robust LCA studies of electric vehicle batteries by integrating the CE criteria.

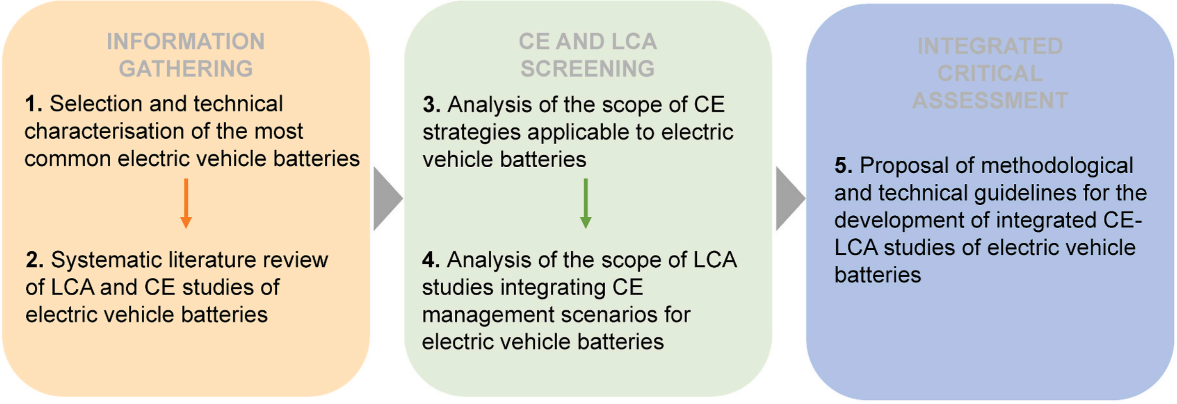
2. Materials and methods

Fig. 1 presents an illustration of the methodology used to perform the research, comprising five methodological steps grouped into three analytical blocks.

2.1. Information gathering

2.1.1. Selection and technical characterisation of the most common electric vehicle batteries

Different chemistries and battery structures are utilised in BEV, such as sodium-nickel chloride, nickel metal hydride, and Li-ion [31].



1. Selection and technical characterisation of the most common electric vehicle batteries

2. Systematic literature review of LCA and CE studies of electric vehicle batteries

3. Analysis of the scope of CE strategies applicable to electric vehicle batteries

4. Analysis of the scope of LCA studies integrating CE management scenarios for electric vehicle batteries

5. Proposal of methodological and technical guidelines for the development of integrated CE-LCA studies of electric vehicle batteries

Fig. 1. Research methodology. Acronyms: BEV (battery electric vehicles), CE (circular economy), LCA (life cycle assessment).

However, the evolution of battery technologies and market opportunities indicate that the technological maturity and manufacturing costs of LIB make them a more suitable candidate for the development of the BEV market [32].

Furthermore, LIB with higher energy density provide longer performance and greater mobility on a single charge, which is a critical aspect of BEV [33]. Importantly, LIB do not have a single battery chemistry; rather, they have a family of battery chemistries based on Li-ion as will be presented and discussed in Section 3.1. Therefore, Li-ion batteries were included in the scope of our study.

2.1.2. Systematic literature review of LCA and CE studies of electric vehicle batteries

A systematic literature review was performed to identify the relevant LCA studies on electric vehicle batteries in which the CE strategies were analysed by using SCOPUS search engine through a combination of three search streams comprising synonyms for BEV, CE, and LCA, as presented in Table S1 of the Supporting Information (SI).

The search was temporally restricted from 2010 to 2021 to i) analyse a decade of research and ii) only examine research performed within the current notion of the CE, which has been actively driven from the 2010s, mostly owing to the role played by the Ellen MacArthur Foundation [34] and the European Commission (EC) [35].

Only peer-reviewed journal articles and reviews written in English were considered, resulting in 177 hits (September 2021). The titles, keywords, and abstracts of the articles were screened to determine their relevance to the research topic based on the following criteria:

- The articles focused only on electric vehicle batteries. Accordingly, the articles that focused on plug-in hybrid, hybrid, and hydrogen fuel-cell vehicles were not evaluated.
- The articles focused only on four-wheeled passenger vehicles. Accordingly, motorcycles, e-bikes, and heavy-duty vehicles were not evaluated.
- One of the technologies analysed must be a passenger BEV when comparing different technologies or vehicle categories in an article.
- The articles must provide an explicit LCA study of BEV [24,25].
- The articles must address one or several CE strategies for BEV.

By applying the above cut-off criteria, the number of articles for comprehensive evaluation was reduced to 39.

2.2. CE and LCA screening

2.2.1. Analysis of the scope of the CE strategies applicable to electric vehicle batteries

A circular strategy scanner developed by Blomsma et al. [36] was used to identify and characterise the CE strategies addressed in the reviewed literature, including reinvent, rethink, reduce, upgrade, repair, reuse, refurbish, remanufacture, repurpose, recycle, cascade, and recover. These CE strategies offer different perspectives for increasing the circularity of products, which are considered pathways for reducing the environmental impacts of BEV [18].

Nevertheless, many researchers rely on concepts, considerations, definitions, and meanings different from those compiled by Blomsma et al. [36]. For example, 'cascade' is used by Ahmadi et al. [19], Richa et al. [37], Tao and You [38], and Yang et al. [39] as a synonym for 'repurpose', which means the adaptation of the battery for a second lower-quality life cycle [40]. This does not match the definition of the 'cascade' provided by Blomsma et al. [36], which refers to 'a subsequent use that significantly transforms the chemical or physical nature of the material'.

Another term that has different interpretations within the reviewed literature is 'reuse'. Hendrickson et al. [41] defined 'reuse' as the use of materials after recycling, while Ahmadi et al. [19] considered it as a second-life use of electric vehicle batteries, such as a stationary energy storage system (SESS), which in practice is an example of battery repurposing as highlighted by Bobba et al. [40] in concordance with the results of Blomsma et al. [36]. This is a relevant finding because if researchers misinterpret the CE concepts and indicators, the results can be misleading (e.g. Kurucz et al. [30]).

To avoid misinterpretation of concepts, the definitions provided by Blomsma et al. [36] were used to evaluate the scope of the CE strategies, including commonly used synonyms, which were built by relying on both a literature analysis and industrial stakeholder consultations.

2.2.2. Analysis of the scope of the LCA studies integrating the CE management scenarios for electric vehicle batteries

The LCA methodology was standardised by the ISO [24,25] and further developed by the EC through the Product Environmental Footprint (PEF) guide [42]. Additionally, the EC has published the 'PEF Category Rules (PEFCR) for high specific energy rechargeable batteries for mobile applications' [43], which are also applicable to electric vehicle batteries. The PEFCR increase the consistency of LCA studies by adapting the PEF to the studied product and providing standardised procedures to be replicated by LCA practitioners.

We selected the PEFCR as a reference for the analysis of different methodological choices made in the reviewed articles, identifying the best choices for the analysis of the CE strategies for electric vehicle batteries. Likewise, the variability of the LCA studies was analysed for different impact categories and correlated to the CE strategies for electric vehicle battery management.

For comparison, the data from the articles were normalised by linear scaling (Table S5 in the SI) to a standard LIB with the following characteristics: 150,000 km lifetime, 30,000 kWh energy provided during its lifetime, 30 kWh capacity, and 250 kg weight, which are the most frequent or average values for electric vehicle batteries as observed in the reviewed literature (Table 1). These assumptions also provided sensible values when calculating the energy efficiency of BEV (0.2 kWh/km) and energy density of the battery (0.12 kWh/kg).

2.3. Critical assessment to propose methodological and technical guidelines for the development of integrated CE–LCA studies of electric vehicle batteries

The integrated critical assessment of the key findings, best practices, and guidelines for the development of robust LCA studies of electric vehicle batteries by using the CE criteria and considerations are provided in this study. This includes recommendations to overcome both the technical (industrial) and methodological challenges.

3. Results and discussion

Table 1 presents an overview of the scope of the 39 reviewed LCA articles, including the methodology and primary CE strategies addressed.

As shown in Table 1, there is a wide range of LCA approaches to study the environmental performance of electric vehicle batteries with different functional units (FU), system boundaries, and battery lifetime assumptions.

Additionally, certain factors have been highly consistent in the literature. For example, the analysis of Li–Ni–Mn–CoO_2 (NMC) batteries was present in 61% of the reviewed articles. Similarly, the recycling of LIB was addressed in 80% of the studies. However, various methodological choices were applied to evaluate these aspects, which greatly influenced the results as will be demonstrated and further discussed in the following sections.

Next, the technical characteristics of electric vehicle batteries are analysed (Section 3.1), followed by an assessment of the CE strategies addressed in the reviewed articles (Section 3.2). Subsequently, the integration of these CE strategies in the LCA studies is evaluated to determine the reasons behind the variability in environmental impacts (Section 3.3). Finally, these findings are used to provide guidelines for performing the LCA studies to analyse the CE innovations in the battery design and development of BEV (Section 3.4).

3.1. Technical characteristics of electric vehicle batteries

The battery chemistry, lifetime, driving distance, and size of the batteries varied substantially among the reviewed articles (Table 1).

LIB are typically classified on the basis of their cathode chemistry [73]. As the battery chemistry changes, several key variables affecting the environmental performance of BEV, such as capacity, energy density, manufacturing process, and recycling possibilities, also change [57].

Eight LIB chemistries were identified in the literature (Table 1), although three received more attention, namely, NMC (61%), Li iron phosphate (LFP) (38%), and lithium manganese oxide (LMO) (23%). Nevertheless, approximately 41% of the reviewed articles analysed more than one battery chemistry.

Our findings revealed that the total driving distance considered by the authors ranged from 150,000 to 200,000 km (76% of the articles), greatly affecting the impact per kilometre and resource consumption, as will be described in Section 3.3.

Importantly, many articles (33%) considered a battery capacity of 25–35 kWh. A larger battery capacity results in a higher material and energy consumption during the manufacturing phase [70]. However, Tao and You [38] demonstrated that life extension and second-life cycles are very effective in higher-capacity batteries and can help in reducing the environmental impacts by 50%, which is analysed in detail in Section 3.3. The effect of battery design variability, in terms of battery chemistry, size, and lifetime (both temporal and total mileage) on the resource consumption and environmental performance of batteries is also analysed in Section 3.3.

3.2. CE strategies for the life-cycle management of electric vehicle batteries

In the following sections, we have provided an overview of how the major CE strategies defined by Blomsma et al. [36] (Section 2.2.1) are addressed in the reviewed articles.

3.2.1. Reinvent and rethink

These two CE solutions are related to dematerialisation [74]. Reinvent seeks to render physical products redundant by striving for full resource decoupling through disruptive innovations, whereas rethink refers to increasing the value of the product and material through the development of sustainable business models [36].

The vehicle-to-grid technologies mentioned by Dranka and Ferreira [47] can be considered as a rethink approach because they mention using the battery of vehicles as an energy delivery device for homes. Car sharing [10,44,47] and servitisation of batteries [13] are discussed as promising reinvent resource-efficient solutions. Nevertheless, quantitative results regarding the environmental benefits of these CE strategies have not been reported in the literature.

3.2.2. Reduce

Reduction is based on the efficient use of materials and energy throughout the product life cycle. As shown in Table 1, the reduction strategies focus primarily on the energy efficiency during battery operation [54,55] or manufacturing [60,61]. Lowering the weight of the battery has also been discussed by Iturrondobeitia et al. [51] and Li et al. [53] to achieve environmental savings. Similarly, Ajanovic and Haas [44] and Lander [52] elucidated the effect of longer lifetimes of electric vehicle batteries in reducing the energy use. As the environmental benefits of this CE strategy were analysed using LCA in the reviewed literature, the key findings are described in Section 3.3.

3.2.3. Repair and maintenance

Repair strategies allow the extension of the lifetime of products, countering wear and tear through substitution of faulty components [36]. Repair costs and environmental impacts are usually analysed at the vehicle level [7,46,52,70], not at the battery level. Thus, the environmental benefits of repairing electric vehicle batteries are yet to be determined.

3.2.4. Reuse

Reuse is defined as the extension of the lifetime of a discarded product by other customers through a new use cycle [36]. Wewer et al. [68] is the only reviewed article that analysed the reuse of discarded batteries in other BEV. According to them, the need for reconditioning the batteries was minimal and could extend their lifetime by approximately 6 years [68], leading to 14% energy savings compared to that when recycling the battery after the first-use cycle [68].

3.2.5. Refurbish and remanufacture

Refurbishment involves returning an out of use product to a satisfactory working condition, although of inferior quality compared to that of the original specification [36], whereas remanufacturing entails reconditioning a product to its original manufacturer's performance and quality specifications [36]. However, these strategies have not yet been addressed in the literature for electric vehicle batteries.

3.2.6. Repurpose

Repurpose entails using a product or its parts for different uses and applications other than the original purpose [36]. The material and energy consumption during the second production phase is considered very small in repurposing the battery for communication base stations

Table 1

Scope of the LCA studies for electric vehicle batteries, integrating CE considerations. Acronyms: C2G (cradle to gate), C2Gr (cradle to grave), CBS (communication base system), ECQFD (Environmentally conscious quality function deployment, FCHEV (fuel cell hybrid energy vehicles), FU (functional unit), ICEV (internal combustion energy vehicles), LCO (Lithium cobalt), LCP (Lithium cobalt phosphate), LFP (Lithium Iron Phosphate), LIB (Lithium-ion batteries), LMO (Lithium Manganese Oxide), LiO_2 (Lithium oxygen), LVP (Lithium vanadium phosphate), NCA (Nickel Cobalt Aluminium), NMC (Lithium Nickel Manganese Cobalt Oxide), PHEV (plug-in hybrid energy vehicles), PV (photovoltaic), RES (renewable energy source), SESS (stationary energy storage system), SiNW (silicon nano-wire)

References	Life cycle assessment approach						Circular economy approach	
	Goal	Characteristics of battery			Methodology choices		Main CE strategies	CE considerations
		Battery chemistry	Capacity (kWh)	Lifetime distance travelled (km)	FU	System boundaries		
Ahmadi et al. [19]	LCA for electric vehicle batteries, which are repurposed as SESS	LFP	–	160,000	1 kWh delivered	C2Gr (excluding transport)	repurpose, recycle	SESS used in a house. The battery is recycled after repurposing.
Ajanovic and Haas [44]	Investigate environmental impact of BEV operating in different regions by considering various driving patterns	NMC	30	8,000/ 15,000/ 23,000	1 km	C2Gr	reduce, recycle	Analysis of material use reduction, battery longevity and recycling
Bobba et al. [40]	Evaluate the environmental benefits of repurposed LIB, in multiple second life scenarios	LMO/NMC mix	11.4	136,877	1 year of kWh delivered	C2Gr (excluding 1st use phase)	repurpose, recycle	SESS for a house considering three scenarios i) Connected to grid ii) connected to grid + PV support iii) PV standalone house
Bouter et al. [10]	Analyse the trade-offs between several transport electrification scenarios, considering standard and urban driving patterns	NMC	30/60	150,000	1 km	C2Gr	recycle	Pyrometallurgy and hydrometallurgy methods, as stated by European directive 2006/66/CE
Casals et al. [45]	Analyse the environmental performance of various second life applications for electric vehicle batteries	LMO, LFP, NMC, LVP with Graphite, LTO anodes	–	–	1 kWh delivered	C2Gr (excluding repurposing processes)	repurpose, recycle	SESS for a house with three scenarios i) Connected to grid ii) connected to grid + RES support iii) RES standalone house
Ciez and Whitacre [13]	Compare different recycling processes for various electric vehicle battery chemistries and cell structures and evaluate the influence of the electricity mix	NMC, NCA, LFP	–	–	1 kWh storage	C2Gr (excluding use phase)	recycle	Pyrometallurgy, hydrometallurgy and direct cathode recycling methods for different chemistries
De Souza et al. [46]	Compare the environmental impacts of ICEV, BEV and PHEV	LFP, NMO	–	160,000	1 km	C2Gr	recycle	Hydrometallurgy recycling
Díaz-Ramírez et al. [32]	Compare the environmental impacts and recyclability of the battery, but active materials (Li, Mg) are left out of scope	LMO, Vanadium Redox (out of scope)	–	–	1 complete battery	C2Gr (excluding use phase)	recycle	Recyclability of the passive materials of the LIB.
Dranka and Ferreira [47]	Analyse several EV penetration scenarios in Brazil, including and analysis of environmental impacts	Fleet average mix	70.64	200,000	Brazil fleet, also 1 km travelled	C2Gr	Rethink, reuse, recycle	Smart grid, battery to grid strategies and battery reuse and recycling
Dunn et al. [48]	Study BEV manufacturing and recycling environmental impacts	LMO, LFP, NMC, LCO, LMR-NMC	28	–	1 km	C2Gr (excluding use phase)	recycle	Pyrometallurgy and intermediate physical and direct physical recycling methods
		NCM	26.6	150,000		C2G	reduce	

(continued on next page)

Table 1 (*continued*)

References	Life cycle assessment approach						Circular economy approach	
	Goal	Characteristics of battery			Methodology choices		Main CE strategies	CE considerations
		Battery chemistry	Capacity (kWh)	Lifetime distance travelled (km)	FU	System boundaries		
Ellingsen et al. [49]	Provide a C2G life cycle inventory and impact assessment for NMC				1complete battery, also 1 kg and 1 kWh capacity			Resource and energy efficiency of the battery manufacturing stage
Hendrickson et al. [41]	Analyse the impacts of EOL management for batteries	LMO, LFP, NMC	24	–	–	C2Gr (excluding use phase)	recycle	Analyse location and size of recycling plants
Ioakimidis et al. [50]	Examine the environmental benefits of battery reuse	LFP	24	–	4,000 cycles of the battery	C2Gr	repurpose, recycle	SESS for a house with two scenarios Connected to grid and stand alone use
Iturrondobeitia et al. [51]	Compare the environmental impacts of seven rechargeable Li–O2 batteries	LiO_2	60	–	1 kWh storage	C2G	reduce	Material efficiency of LiO_2 batteries
Karaaslan et al. [7]	Study of the environmental impacts of electric SUVs	NCA	90	322,000	–	C2Gr (recycling process cut-off)	recycle	Economic and environmental performance of the recycling process assessed
Lander et al. [52]	Compare cost and GWP of different thermal management scenarios for electric vehicle batteries	NMC	26,.6	–	1 km	C2Gr	reduce	Thermal management to increase battery lifetime and reducing material use
Li et al. [53]	Calculate environmental impacts of Li Battery with SiNW anode	NMC with SiNW anode	43.2	200,000	1 km	C2Gr+REC	reduce	Use alternative materials (e.g. SiNW instead of graphite) to improve resource efficiency
Lombardi et al. [54]	Compare impacts of: ICEV, PHEV, BEV and FCHEV	LFP	33	200,000	1 complete battery	C2Gr	reduce	Energy efficiency for different powertrains
Mayyas et al. [55]	Analyse the environmental impacts of electrification and lightweighting for different vehicle technologies	LFP, NMC	24/70/85	161,000–322,000	1 km	C2Gr	reduce	Lightweighting of the vehicle
Messagie et al. [56]	Calculate the environmental impacts of BEV in the Belgian context and compare the results with other vehicle technologies	-Lithium (not specified)	–	–	–	C2Gr	recycle	Hydrometallurgy recycling with high recovery rates for critical materials (Co, Ni, Mg)
Mohr et al. [57]	Compare three recycling methods for different chemistries of electric vehicle batteries	NMC, NCA, LFP, Na-ion	–	–	1 kWh storage	C2Gr (excluding use phase)	recycle	Pyrometallurgy, conventional hydrometallurgy and an advanced hydrometallurgy recycling processes
Oliveira et al. [58]	Analyse the environmental impacts of two battery chemistries	LMO, LFP	1	–	1 kWh delivered	C2Gr (excluding use phase)	recycle	Disassembly for recycling and safety
Padashbarmchi et al.[59]	Study the environmental impacts of using different anode materials	Anodes: Graphite, CO3O4, CuO, Fe2O3	–	–	1,000 Ah energy originated from anode active materials	–	recycle	Mixed hydrometallurgical and pyrometallurgical recycling processes
Qiao et al. [60]	Analise the energy consumption and GHG emissions of battery manufacturing and compare it to ICEV	NMC, LFP	–	–	1complete battery	C2G	reduce	Reduction of material and energy consumption during manufacturing

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Table 1 (*continued*)

References	Life cycle assessment approach						Circular economy approach	
	Goal	Characteristics of battery			Methodology choices		Main CE strategies	CE considerations
		Battery chemistry	Capacity (kWh)	Lifetime distance travelled (km)	FU	System boundaries		
Qiao, Zhao, Liu, He, et al [61]	Calculate the impacts of a BEV, and their evolution by greening the power grid	NMC	27	150,000	1complete battery	C2Gr	reduce	Hydrometallurgy recycling
Qiao, Zhao, Liu, and Hao [62]	Study the economic and environmental performance of battery recycling processes	NMC	27		Complete vehicle	C2Gr	recycle	Recycling of active cathode materials
Rathod et al. [63]	Analyse innovative LCA alternatives for BEV through ECQFD	Not specified	–	–		–	rethink	Economic and environmental performance of CE strategies analysed
Raugei and Winfield [64]	Study the environmental performance of a new LCP chemistry and compare the results to standard Li batteries	LCP	17		1 kWh capacity	C2Gr (excluding use phase)	recycle	Innovative hydrometallurgical recycling process
Reuter [65]	Analise the material flow and GWP of electric vehicle batteries	NMC, LFP	–	150,000	1 complete battery	C2Gr	recycle	Resource depletion and material recycling
Richa et al. [37]	Study environmental implications of second life extension from the manufacturer and consumer perspective	LMO	24	160,000	1 complete battery	C2Gr	repurpose, recycle	SESS for standalone houses
Sun et al. [66]	Assess the environmental impacts of NMC batteries	NCM	72.5	–	1 kWh storage	C2Gr (excluding use phase)	recycle	Combined pyrometallurgy and hydrometallurgy recycling rates, under optimised experimental conditions
Tao and You [38]	Calculate and compare the environmental impact of three battery chemistries and the effect of second life uses	LMO, NMC, NCA	23.53/ 88.17/ 52.94	160,000	1 kWh storage or 1 kWh delivered	C2Gr	repurpose, recycle	Battery repurposed to SESS. The battery is recycled after repurposing.
Wang and Yu [67]	Study the environmental impact of NMC batteries in China	NMC	–	–	1 complete battery	C2Gr (excluding use phase)	recycle	Hydrometallurgy recycling
Wewer et al. [68]	Analyse improvements in second life applications for electric vehicle batteries	LMO, LFP, NMC	34/26.6/ 24/23.5/ 24	150,000	Energy of operating battery	C2Gr	reuse, repurpose, recycle	Battery reuse in a BEV for 6 years and recycle, battery repurpose as SESS for smart grid for 8 years and recycle and direct battery recycling
Wilson et al. [69]	Present a novel physical allocation method for second use cycles for batteries in Australia	NMC	–	–	1 kWh storage	C2Gr (1st and second use phase excluded)	repurpose	SESS in an Australian house connected to grid
Xiong et al. [70]	Compare the environmental impacts of BEV and PHEV	LFP, NMC	47.5/ 60.5	120,000/ 160,000	1 km	C2Gr	repair and maintenance	NMC and LFP longevity and recyclability
Yang et al. [39]	Analyse the environmental performance of second life use of electric vehicle batteries in CBS	NMC	–	–	1 kWh delivered	C2Gr (excluding 1st use phase)	repurpose, recycle	SESS for a CBS connected to grid
		Lithium-air	–	200,000	1 km		recycle	

(*continued on next page*)

Table 1 (*continued*)

References	Life cycle assessment approach						Circular economy approach		
	Goal	Characteristics of battery			Methodology choices		Main CE strategies	CE considerations	–
		Battery chemistry	Capacity (kWh)	Lifetime distance travelled (km)	FU	System boundaries			
Zackrisson et al. [71]	Provide life cycle inventory and environmental hotspots of Lithium-air cells for BEV					C2Gr (excluding use phase)		Manual, mechanical, pyrometallurgy and hydrometallurgy recycling processes	
Zhao and You [72]	Compare LIB through a hybrid LCA approach	LMO, NMC	–	200,000	1 complete battery	C2Gr	recycle	Pyrometallurgy and hydrometallurgy recycling processes	

[39] or even negligible when batteries are used as a SESS [45]. Repurposing, therefore, allows the use of resources for longer periods. However, this is not an integral sustainable solution for electric vehicle batteries because they will still need to be handled as waste when the repurposed units reach the end of their life [44]. Ahmadi et al. [19] further highlighted that extending the lifetime of the LIB delays recycling processes and can temporally generate scarcity of recovered critical materials.

As repurposing is one of the most addressed CE strategies in the reviewed literature, the environmental savings are analysed in detail in Section 3.3.

3.2.7. Recycle and cascade

Recycling is defined as the extension of material lifespans by reprocessing them into new materials with quality comparable to that of the original material [36]. Cascading allows the subsequent use of a material in secondary applications, entailing a significant change in the physical and/or chemical nature of the original material [36]. Notably, the reviewed articles did not distinguish between these two concepts.

According to the literature, three recycling methods can be applied to the LIB (Table 1): i) pyrometallurgy (extraction and purification of metals using high-temperature processes [75]), ii) hydrometallurgy (metal recovery method using aqueous media [76]), and iii) cathode direct recycling [77].

Yang et al. [39] estimated an 80% recirculation rate for Li, Fe, and Al in a battery through a hydrometallurgy process. Sun et al. [66] analysed a combined pyrometallurgy and hydrometallurgy method that, under optimised experimental conditions, exhibited a recovery efficiency of 98.7%, 97.1%, 98.2%, and 81.0% for Ni, Mn, Co, and Li, respectively. These results are in contrast with those of Ajanovic and Haas [44] and Li et al. [53], indicating that the recovered material does not meet the quality requirements for a closed loop.

Direct cathode recycling is considered a more interesting technique to obtain the highest-quality materials, while pyrometallurgy causes Li slagging instead of quality recovery owing to its high oxygen affinity [78]. However, Ciez and Whitacre [13] reported that only pyrometallurgy could reach the EU legislative targets [79] for battery recycling (50% of the battery mass) with a single process, which inclines the choice towards this recycling process.

However, there are articles stressing the lack of a standard process for battery recycling [50], which explains the current low return of investment [60,71] and, therefore, a lack of interest from companies to pursue it. Nevertheless, the economic viability of recycling is expected to improve with Co usage in LIB and help standardise BEV recycling processes to develop appropriate technologies for the complete recirculation of materials [67].

3.2.8. Recovery

This entails recovering energy by incineration or the pyrolysis of materials [36]. Energy recovery from landfills has been considered by Bouter et al. [10] and de Souza et al. [46] in their LCAs. However, specific data on the energy recovered using this method were not present in the literature.

3.2.9. Primary CE strategies for electric vehicle batteries addressed in the literature

Product recycling (82%), resource consumption reduction (51%) and battery repurposing (26%) prevailed as the primary object of analysis in the reviewed LCA literature.

The remaining CE strategies were either unexplored or only mentioned as possibilities for future research, without fully analysing them, which does not match the holistic point-of-view of the CE [80] (Table S2 in the SI).

Moreover, the circularity potential of the battery repurposing and recycling strategies is at the lower end of the circularity performance hierarchy [81], as they deliver lower resource and environmental savings than the CE strategies focused on servitisation, reparation, or upgrading to preserve material quality and product functionality [82].

In addition, some studies [13,44] raised concerns about possible negative outcomes from the implementation of the CE strategies without the use of robust data to analyse all the life-cycle aspects of the batteries. Therefore, the LCA methodology for electric vehicle batteries should be examined and standardised to meet the aforementioned requirements as discussed in the following subsections.

3.3. Life-cycle assessment studies for electric vehicle batteries

The scope of the LCA studies for LIB is analysed in this section, by relying on the guidelines provided by the PEF [42] and PEFCR [43] methodologies. Accordingly, the methodological choices and key results of the LCA application in electric vehicle batteries, considering the CE criteria and strategies, are discussed.

3.3.1. Goal and scope

The reviewed literature provided a variety of choices regarding the definition of the goal and scope of the LCA studies (Table 1).

The most common goals included i) comparisons of environmental impacts between BEV technologies and other transportation solutions [46,54], ii) evaluation of different BEV technologies to determine the most environmentally sustainable alternative [53,58], and iii) assessment of the environmental impacts of the second life [37,40] and recycling alternatives for the LIB [57].

The LCAs comparing BEV to ICEV or other technologies (e.g. hybrid electric vehicles or fuel-cell electric vehicles) defined the FU based on either the complete lifetime of the batteries [60] or 1 km travelled [10,70]. Articles focused on comparing the battery technologies and recycling alternatives were more prone to defining the FU as one complete battery [67] or 1 kWh of capacity [13] because of the link between these FUs and the physical characteristics of the battery pack. Finally, the LCA studies analysing the second life of electric vehicle batteries defined the FU as 1 kWh of delivered energy [19], which is the best approach for determining the effects of the CE strategies on the complete life cycle of the batteries [45].

The researchers applied both cradle-to-gate (C2G) and cradle-to-grave (C2Gr) approaches to determine electric vehicle batteries' environmental impacts. Nevertheless, the life-cycle stages of battery operation and/or recycling are usually cut-off because of the lack of quality data, which compromises the development of robust comparisons between electric vehicle battery systems. Furthermore, partial approaches in analysing environmental impacts can lead to environmental burden shifting [83].

3.3.2. *Life-cycle inventory*

Life-cycle inventory (LCI) data to analyse the life-cycle environmental impact of products can be obtained first-hand through experimentation [40,53] and collaboration with companies [49] or second-hand through literature sources [84–86] and LCA software and databases [87,88].

Nevertheless, only 25% of the reviewed articles, such as Ellingsen et al. [49] and Sun et al. [66], had access to primary data from companies, laboratories, or research projects. Similarly, all reviewed articles utilised secondary data to complete their study. For example, Mohr et al. [57] utilised primary data for the recycling process and secondary data for the battery composition and manufacturing. A list of all sources of secondary data used in the reviewed literature is presented in Table S3 of the SI.

The lack of available primary data is an issue that has been identified in previous literature reviews of electric vehicle batteries [27]. The use of secondary data has several limitations. First, inventories vary in their scope and data, causing a lack of standardisation in the secondary data sources as highlighted by Peters and Weil [86], who called for a unified LCI framework for LIB benchmarking. Furthermore, the most utilised LCI databases [84,85] were published over a decade ago, which could compromise data quality and completeness by not reflecting the current reality of the LIB sector.

3.3.3. *Life-cycle impact assessment*

The life-cycle impact assessment (LCIA) of products depends on the goal and scope of the study, LCI data used, assumptions applied, and impact-assessment method and categories considered [42]. The reviewed articles exhibited a wide range of choices regarding these aspects. Thus, a direct comparison of the results was difficult, which could have compromised the definition of robust and meaningful solutions for the electric mobility sector, especially if decisions were based on the consideration of a few impact categories.

Fig. 2 shows the frequency of the environmental impact categories addressed in the reviewed articles. Categories in blue represent the 16 categories recommended by the PEFCR for batteries [43], whereas categories in yellow represent additional or complementary indicators analysed by the researchers [43].

As shown in Fig. 2, there was high variability in the impact categories analysed in the literature. Up to 40 impact categories were calculated by all researchers, although only 10 of the 39 articles evaluated included 10 impact categories or more (Table S4 of the SI). Thus, there was a lack of articles providing a complete overview of the environmental performance of electric vehicle batteries for robust decision making.

3.3.4. *Environmental impact of the CE strategies applied to electric vehicle batteries*

Based on the findings presented in Section 3.2., only three CE strategies could be meaningfully analysed from an LCA perspective: reduce, repurpose, and recycle.

To compare the results from the reviewed literature, two impact categories were selected: GWP (kg CO_2 eq.) (Fig. 3) and cumulative energy demand (CED) (measured in MJ eq.) (Fig. 4) [89]. GWP was the most used impact category within the reviewed articles (Fig. 2) and is

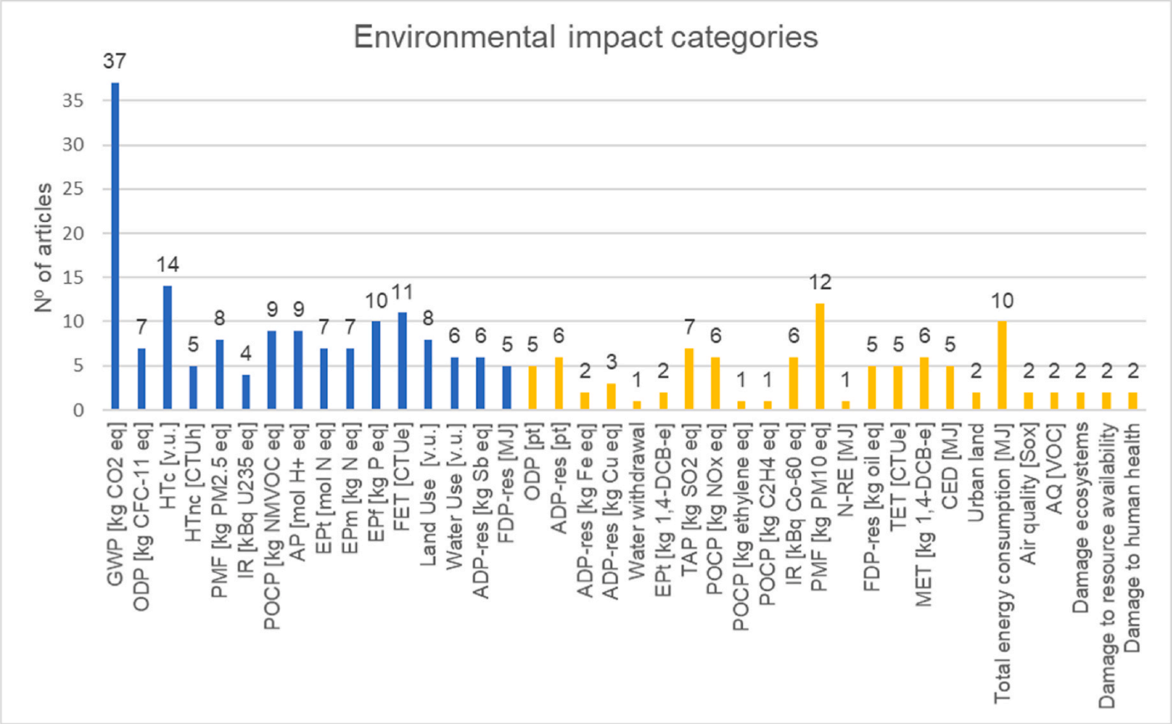

Fig. 2. Frequency of the impact-assessment categories addressed by the reviewed literature. Blue: PEFCR impact categories, yellow: impact categories not integrated in the PEFCR. Acronyms: ADP-res (Abiotic depletion potential-resources), AP (Acidification potential), AQ (air quality), CED (cumulated energy demand), EPf (Eutrophication freshwater), EPm (Eutrophication marine), EPt (Eutrophication terrestrial), FDP-res (fossil depletion potential-resources), FET (freshwater ecotoxicity), GWP (global warming potential), HTc (Human toxicity cancer), HTnc (Human toxicity non-cancer), IR (Ionising radiation), MET (marine ecotoxicity), N-RE (non-renewable energy), ODP (ozone depletion potential), PMF (Particulate matter/respiratory formation), POCP (Photochemical ozone formation), TAP (terrestrial acidification potential), TET (terrestrial ecotoxicity).

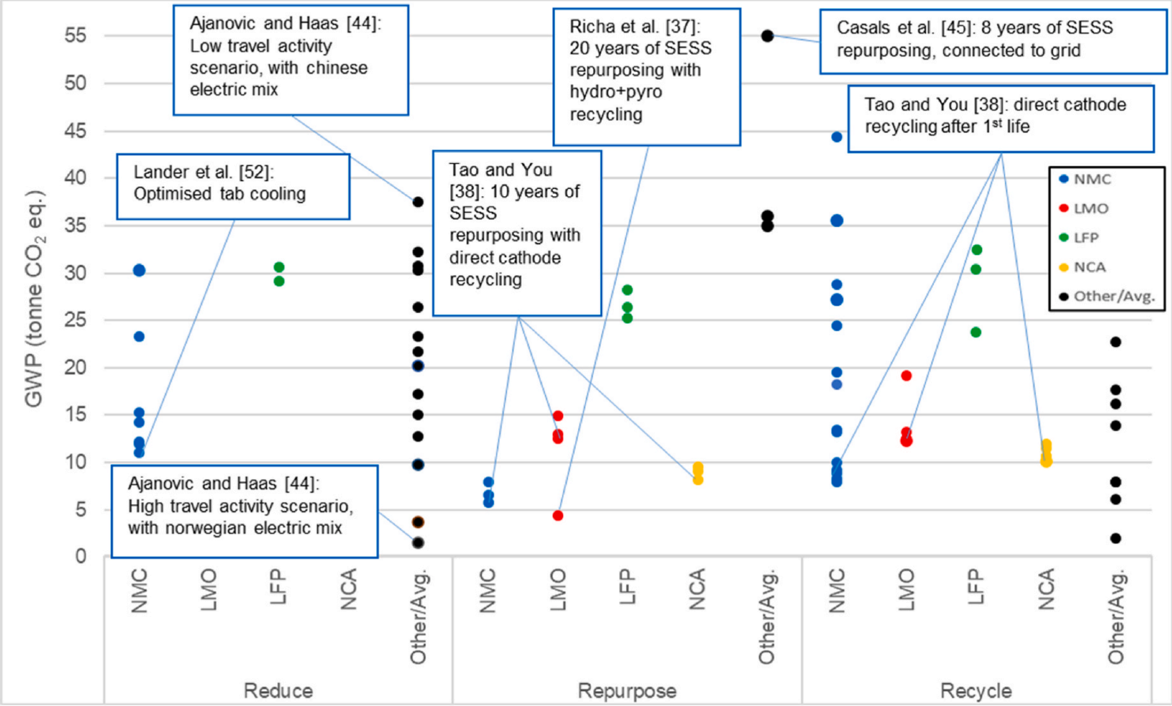

Fig. 3. Comparison of the total life-cycle GWP (tonne CO_2 eq.) for the three primary CE strategies applicable to LIB. Each dot in the graphs represents a result extracted from the literature, normalised for a battery of 150,000 km lifetime 30,000 kWh energy provided, 30 kWh capacity, 250 kg weight. Different colours represent different battery chemistries. Acronyms: LFP (Lithium Iron Phosphate), LMO (Lithium Manganese Oxide), NCA (Nickel Cobalt Aluminium), NMC (Lithium Nickel Manganese Cobalt Oxide), SESS (stationary energy storage system)). The Other/avg. category includes the rest of the chemistries and data for average/mixed chemistries: Lithium-air, LCO (Lithium cobalt), LCP (Lithium cobalt phosphate), LiO_2 (Lithium oxygen), LVP (Lithium vanadium phosphate) or average/ mixed chemistry.

primarily used by governments pursuing the deployment of BEV for reducing carbon emissions in cities. Similarly, CED is a key area for CE intervention to increase the energy efficiency of production and consumption systems [89]. Accordingly, the results of the different studies were normalised to a standard battery by applying the assumptions described in Section 2.2.2.

To provide a complete overview of the battery life-cycle environmental performance, only the C2Gr results are shown in Figs. 3 and 4. Detailed data for all normalised environmental impacts, including different system boundary settings, are presented in Table S5 of the SI.

As shown in Figs. 3 and 4, the GWP and CED indicators for the NMC, LMO, LFP, nickel cobalt aluminium (NCA), and other batteries vary greatly among the LCA studies analysing the three (reduce, repurpose, and recycle) CE strategies. This variability in the results was caused by the issues mentioned in Sections 3.3.1 to 3.3.3, which are analysed in further detail in the following sections discussing the major CE strategies addressed in the reviewed literature.

3.3.4.1. *Reduce resource consumption.*

The reduction in resource consumption is the strategy with the highest range of methodological choices owing to the possibility of improving the resource efficiency in battery production [49], operation [66], recycling [65], and second use [45].

In the C2G studies, the chemistry of the battery was one of the causes of variability in the results. Qiao et al. [60] indicated that the carbon emissions for a complete battery with NMC and LFP chemistries correspond to 4233 and 3362 kg CO_2 eq., respectively. However, battery chemistry was not the only cause of the impact variability. Ellingsen et al. [49] compared NMC batteries and calculated a GWP impact of 5200 kg CO_2, which was 22% higher than that reported by Qiao et al. [60]. The variability in the GWP impact corresponded to the type of the LCI data used: Ellingsen et al. [49] used primary data, whereas Qiao et al. [60] used a secondary data source (BatPac model [89]). Another aspect affecting the results was the LCIA method used: ReCiPe [90] by Ellingsen et al. [49] and GREET [87] by Qiao et al. [60].

In the C2Gr studies, additional factors caused impact variability, as shown in Figs. 3 and 4. Ajanovic and Haas [44] considered different electric mixes, resulting in impact variabilities of almost 500%. For instance, the total life-cycle GWP emissions for a BEV (including the glider) using the Chinese and Norwegian electricity mix corresponded to 36,000 and 7500 kg CO_2 eq., respectively.

Therefore, the variability in the GWP of reduced resource consumption for the LIB was caused by three primary factors: the diverse LCI dataset used; assumptions regarding key system boundary aspects (raw material and electric mix for manufacturing, impact of transportation, efficiency of the electric vehicle battery, and total lifetime km travelled); and the impact-assessment method utilised.

3.3.4.2. *Repurposing of electric vehicle batteries.*

Some LCA studies exclude the BEV operation phase and focus only on the analysis of the impacts related to the second use cycle scenarios [40]. A similar study was conducted by Richa et al. [37] where the GWP of the manufacturing and first-use cycle of the battery were assumed (35,000 kg CO_2 equivalent), and the LCA study focused on the repurposed battery alone.

The allocation method, defined in the PEFCR [43] as the approach to solving multifunctionality problems, is another relevant methodological choice influencing the LCIA results. As battery life is extended through repurposing, the battery manufacturing impacts are either allocated to the first life cycle [40] or shared between both use cycles (BEV and SESS) by applying a quality based (both physical and market value) cut-off or 50/50 share approach [37].

The management scenario for the repurposed LIB is the largest factor to assess when considering the impacts of this strategy. The highest GWP (Fig. 3) and CED (Fig. 4) impacts corresponded to a battery repurposed

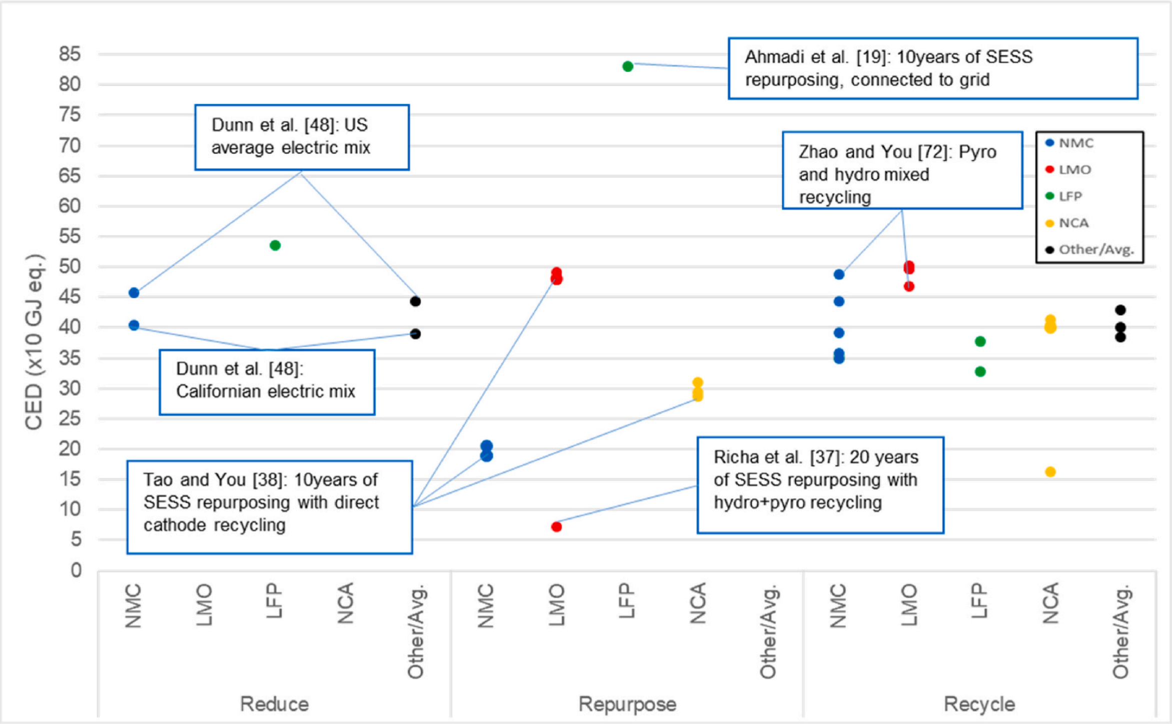

Fig. 4. Cumulative energy demand (× 10 GJ eq.) for the three primary CE strategies applicable to LIB. Each dot in the graphs represents a result extracted from the literature, normalised for a battery of 150,000 km lifetime, 30,000 kWh energy provided, 30 kWh capacity, 250 kg weight. Different colours represent different battery chemistries. Acronyms: LFP (Lithium Iron Phosphate), LMO (Lithium Manganese Oxide), NCA (Nickel Cobalt Aluminium), NMC (Lithium Nickel Manganese Cobalt Oxide), SESS (stationary energy storage system), US (United States). The Other/avg. category includes the rest of the chemistries and data for average/mixed chemistries: Lithium-air, LCO (Lithium cobalt), LCP (Lithium cobalt phosphate), LiO_2 (Lithium oxygen), LVP (Lithium vanadium phosphate) or average/mixed chemistry.

as a smart-grid stationary battery [19,45], both generating 10 times more impact than the best-case scenario as a standalone house with renewable energy generation [37]. This is primarily because the LIB is charged by the standard electric mix in comparison with scenarios where the battery is charged by RES.

Similarly, it must be noted that repurposing is not an end-solution for the LIB as repurposed batteries must undergo a recycling step after the second life, which is discussed in the next section.

3.3.4.3. Recycling of electric vehicle batteries. For the NMC batteries, by using a 1 kWh capacity as the FU and leaving out the scope of the use phase, Sun et al. [66] and Mohr et al. [57] estimated a GWP impact equivalent to 93.6 and 54.5 kg CO_2 eq./kWh, respectively. This difference was caused by raw materials and manufacturing phases as well as the recycling strategy used. Sun et al. [66] proposed a mixture of pyrometallurgy and hydrometallurgy processes that save 25% of the environmental impacts, whereas Mohr et al. [57] utilised an optimised hydrometallurgy recycling method, representing 29% GWP savings.

The reviewed literature indicated that direct cathode recycling was the most environmentally friendly technique, followed by hydrometallurgy and pyrometallurgy. For example, Ciez and Whitacre [13] highlighted that recycling batteries through direct cathode recycling resulted in 33% and 25% lower impact than pyrometallurgy and hydrometallurgy processes, respectively. However, robust data on recycling procedures are required to analyse the environmental impacts between different recycling alternatives.

3.3.4.4. Integrated assessment of the environmental performance of reducing, repurposing, and recycling strategies for electric vehicle batteries. Comparing the LCA results for reducing resource consumption, battery repurposing, and battery recycling is a complex task. Nonetheless, some key conclusions were drawn from the analysis.

- Repurposing the LIB is the CE strategy with the best environmental performance, particularly for repurposing to SESS in a standalone house with RES [37] (Fig. 3).
- Optimised standard recycling processes are necessary to maximise the potential environmental benefits [71].
- NMC is the most beneficial battery chemistry for both repurposing and recycling [38]. A repurposed battery with direct cathode recycling generates approximately 10% less GWP impact and saves 30% more energy compared to that by an LIB sent to a landfill after use [38]. The benefits of the NMC batteries depend upon their high energy density and the presence of critical materials (Co and Mn) that can be recovered.
- Focusing on the material reduction CE strategies, the LIB lifetime (use cycle) is observed to be the biggest factor influencing the environmental savings. Ajanovic and Haas [44] indicated that, increasing the total lifetime km of BEV from 8000 km to 23,000 km in the EU would reduce the GHG emissions for a complete vehicle from 0.17 kg CO_2 eq./km to 0.11 kg CO_2 eq./km. Lander et al. [52] calculated that improvements in thermal management would allow a longer lifetime for the LIB, resulting in 30% impact reduction in optimised tab cooling (13,695 kg CO_2 eq.) compared with that of an air-cooled battery (21,150 kg CO_2 eq.).
- Nevertheless, the mapping of all the CE strategies was not integrated into the reviewed LCA studies. Since specific CE indicators were not utilised, the effect of the CE strategies on the resource efficiency of the LIB has not yet been analysed using a system level approach.

Accordingly, the best strategy for reducing both the resource use and life-cycle environmental impacts lies in the combination of the three CE strategies, which requires planning the battery design and life-cycle management process, including the required logistics and infrastructure requirements. This calls for a holistic CE approach for electric vehicle battery management, backed by robust data provided by standardised LCA studies.

3.4. *Challenges and best practices for the LCA of CE management strategies applicable to electric vehicle batteries*

Based on the key findings from the analysis of the LCA studies, the technical and methodological challenges and best practices for the assessment of CE solutions for electric vehicle batteries are shown in Table 2.

These industrial challenges and best methodology practices (Table 2) have not yet been properly addressed in the academic and industrial literature on electric vehicle batteries and, hence, represent future research lines.

For example, one key area for intervention in the development of integrated CE and LCA studies for electric vehicle batteries is the combination of circularity and LCIA indicators to analyse the correlation between improving circularity performance and environmental sustainability [91]. This can be helpful in providing robust results for decision makers as the LCA does not usually inform about the recirculation potential of products and materials, while the CE does not usually inform about the environmental improvement of resource efficiency strategies [92].

Further research should consider how the new circular business models [93] for BEV and electric vehicle batteries can influence the value chain, hence, the technical, economic, social, and environmental performance of electric vehicle battery life-cycle management systems.

Nevertheless, to properly address these assessments, integrated and standardised CE and LCA frameworks, including step-by-step guidelines, tools, and indicators, should be developed for practitioners to rely on for well-informed decision-making processes.

Table 2
Challenges and best practices identified in the literature. Acronyms: BEV (battery electric vehicle), CE (circular economy), EOL (end of life), FU (functional unit), LCA (life cycle assessment), LCIA (life cycle impact assessment), LIB (lithium-ion battery), NMC (nickel manganese cobalt), PEFCR (product environmental footprint category rules), RES (renewable energy sources), SESS (stationary energy storage system)

Life-cycle stage	Technical aspects for improvements in electric vehicle battery circularity	
	Challenges	Best practices
Raw materials	Different battery chemistries offer benefits and handicaps to environmental performance	NMC batteries are the ones with the best environmental results. Repurposing and recycling these batteries are especially effective for life-cycle impact reduction
Manufacturing	Battery manufacturing processes and lifetime are key variables in LCA results	The efficient thermal management of the battery improves the lifetime, significantly reducing the environmental impacts
Transport	The transport stage is not properly assessed by LCA practitioners	Design an efficient transport strategy that would minimise cost and impacts. Include recollection, repurposing, and recycling phases in the transport plan
Operation	Batteries chemistries, structures and components are different and cause challenges for maintenance and EOL	Propose standardised battery components for better maintenance, repurposing, and recycling
End of life (repurposing)	There are many second-life alternatives	The most beneficial second-life scenarios are repurposing the batteries as SESS attached to RES. Reusing or repurposing the battery as energy arbitrage tool are not as beneficial
End of life (recycling)	The recycling process is not optimised for the batteries	Establish a standard recycling process: direct cathode recycling, with a second step of hydrometallurgy and final pyrometallurgy. This may increase the environmental and economic revenue
End of life (other strategies)	Holistic point-of-view of CE requires a deeper analysis of the EOL possibilities for batteries (upgrade, reuse, and refurbish)	Analysing the business cases for several CE strategies and comparison with traditional EOL scenarios (recycling/landfill) is required to determine resource efficiency and environmental improvements
LCA steps	**Methodological guidelines for LCA studies integrating CE strategies for electric vehicle batteries**	
	Challenges	**Best practices**
Goal and Scope	The influence of factors, such as battery weight, energy density, or efficiency are difficult to assess in an LCA not integrating the operation phase	A complete LCA is recommended to evaluate the effect of the CE strategies on the total life-cycle impacts
	The choice of the FU narrows the capability of the LCA to analyse and compare the life cycle of LIB, especially in repurposing scenarios	The FU of '1 kWh energy delivered' relates better to the performance of the LIB than physical characteristics of batteries (weight and capacity) and can support the analysis of second-life scenarios
	Operation and EOL scenario analysis are not standardised; results vary	Set standardised allocation methods for EOL. Common steps for credit and burden distribution for first and

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4. Conclusions

This study focused on a comprehensive review of LCA studies integrating the CE strategies for electric vehicle batteries with three primary research goals: i) to identify the most studied CE strategy for electric vehicle batteries, ii) to evaluate the causes of environmental impact and savings variability, and iii) to propose guidelines for the development of LCA studies for electric vehicle batteries by integrating the CE criteria.

Multiple battery chemistries have been analysed in the reviewed literature, with a predominance of Li-ion NMC (61%), LFP (38%), and LMO (23%). The optimal FU for C2Gr LCA studies of electric vehicle batteries, including second-life scenarios, is defined as 1 kWh delivered by the battery. This FU was closely related to the performance specifications of batteries. Hence, it is useful in functionally equivalent comparisons.

Regarding inventory data, few articles had access to primary data (25%), whereas the majority utilised secondary (and not updated) LCIs. In the impact-assessment phase, there was a lack of evaluation categories, with only 26% of the articles evaluating 10 LCIA impact categories or more.

CE strategies, such as reducing resource consumption and recycling, were considered in 51% and 82% of the reviewed articles, respectively, while repurposing was analysed in 26% of the reviewed articles. Repurposing and improving the recycling process of the NMC batteries can reduce the environmental impacts by up to 50%, while the application of an optimised recycling procedure can greatly increase the circularity of the materials by recovering over 80% of the metals.

However, a holistic approach for the integrated assessment of the circularity and environmental aspects of electric vehicle batteries is lacking. For example, apart from reducing, repurposing, and recycling, other CE strategies, such as repair and maintenance, upgrades, and/or remanufacturing have not yet been addressed in LCA literature. In addition, available studies usually analyse a single CE strategy rather than a combination of several strategies. LCA studies also do not usually

Table 2 (*continued*)

Life-cycle stage	Technical aspects for improvements in electric vehicle battery circularity	
	Challenges	Best practices
	based on practitioner choices	second use cycles as well as recycling.
Life-cycle inventory	Lack of high-quality inventories: little primary data availability combined with relatively old secondary inventories available	Creation of life-cycle inventories that are complete and up-to-date for the LCA practitioners to freely-access and perform LCA studies
Life-cycle impact assessment	LCIA results presented in few and not-standard impact categories. Comparison between different studies is difficult and the less the categories analysed, the higher the risks of environmental burden shifting	Follow the guide provided by the PEFCR for batteries to present the results in all the impact categories recommended with the corresponding units
Interpretation	Temporal and market evolution is not usually assessed in the LCA studies for electric vehicle batteries	Include temporal dimension in the assessment, specifically in the energy demand or resource scarcity caused by the market evolution of BEV, as well as the technological advances expected in these fields
	There are no studies that merge CE indicators with the LCA impacts	Integrate robust CE criteria and indicators in the LCA studies to properly evaluate the correlation between circularity and environmental improvements.

integrate the circularity indicators.

Thus, it is recommended that future research focuses on developing integrated CE and LCA studies by combining the circularity and LCIA indicators to better understand the potential impact of the CE strategies by not only considering changes at the product level but also incorporating business model and value chain considerations for the CE strategies. Such results could support the creation of circular and sustainable business models for electric vehicle batteries to improve the overall resource efficiency of electromobility. This calls for an analysis of the influence of dematerialisation and servitisation strategies and/or the implication of original equipment manufacturers in battery waste management.

Another aspect to consider is the analysis of the effect of new legislation for BEV integrating the CE criteria. The EU has already regulated some of the environmental strategies for BEV and electric vehicle batteries [43,79,94], but a wider scenario assessment for the development of more holistic legislation could help industries find the best solutions to current sustainability challenges.

CRediT author statement

Aitor Picatoste: Methodology, Investigation, Writing – original draft, Writing – review & editing and Visualization. Daniel Justel: Writing - Review & Editing. Joan Manuel F. Mendoza: Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration and Funding acquisition.

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Declaration of competing interest

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

Data availability

All the data utilised in this research can be found on the Supporting Information file

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112941.

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