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Comparing the circularity and life cycle environmental performance of batteries for electric vehicles

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ABSTRACT

Batteries account for a significant share of the life cycle impact of electric vehicles (EV). Nonetheless, the circularity and environmental performance of EV batteries remains underexplored in the literature. This paper compares the circularity (Circularity Index and Product Circularity Indicator) and environmental performance (Global Warming Potential (GWP) and Abiotic Depletion Potential of minerals (ADPm)) of lithium nickel manganese cobalt (NMC) and lithium iron phosphate (LFP) batteries subjected to pyrometallurgy and hydrometallurgy recycling. Lifetime extension, improved energy efficiency, and material recovery ratios were also calculated to identify the optimal battery design. The findings show that NMC batteries are 6–25% more circular and environmentally sustainable (<4–6% GWP and <13–16% ADPm) than LFP batteries, primarily due to better material recovery ratios. Moreover, the longer lifetime of LFP does not sufficiently offset resource and environmental impacts. Finally, the study discusses the results to support circular and environmental innovation in EV battery design.

1. Introduction

At least 30 million electric vehicles (EV) are forecast to be operational in the European Union (EU) by 2030 (European Parliament, 2022). This will contribute to the long-term EU goal of becoming the first carbon neutral continent by 2050 (European Commission, 2022). It should be noted, however, that although EV represent an improvement over internal combustion engine vehicles, they are not exempt from environmental impact. For instance, it is estimated that the EU demand for lithium (a critical material used in the manufacture of EV batteries) will increase 18 times by 2030, and as much as 60 times by 2050 (European Parliament, 2022). Considering that currently only 1% of the lithium from batteries is recycled globally (Bae and Kim, 2021), the global potential impact of EV batteries could worsen due to geopolitical supply chain constraints (Rajaeifar et al., 2022). One further drawback of EV is that battery manufacturing is an energy-intensive process (Liu et al., 2021).

Circular economy (CE) strategies, as defined by Bocken et al. (2016) aim at narrowing (consuming less resources), slowing (using resources for longer), and closing (facilitating material recycling) (Bocken et al., 2016). Accordingly, CE can improve resource efficiency and, ultimately, the environmental life cycle performance of EV batteries, if solutions are properly designed, planned and managed over time(Quinteros-Condoretty et al., 2021; Richa et al., 2017). This is mainly caused by the use of critical raw materials in many of the EV battery chemistries, such as lithium, graphite, nickel, cobalt or manganese (European Commission, 2023a). However, increased circularity based on the definitions by Blomsma et al. (2019) does not always lead to environmental sustainability improvements (Kara et al., 2022). For example, spinel $Li_4Ti_5O_{12}$ anodes could increase the lifespan of the battery, thus slowing the

Abbreviations: ADPm, Abiotic Depletion Potential for minerals; BLE, Battery Lifetime Extension; CE, Circular Economy; CI, Circularity Index; EV, Electric Vehicles; EoL, End of Life; EU, European Union; GWP, Global Warming Potential; HyR, Hydrometallurgy Recycling; IEE, Improved Energy Efficiency; ILR, Improved Lithium Recovery; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LFP, Lithium Iron Phosphate; MCI, Material Circularity Indicator; NMC, Lithium Nickel Manganese Cobalt; PCI, Product Circularity Indicator; PyR, Pyrometallurgy Recycling; SF, Supplementary File.

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material cycle of the battery, while the graphite anodes generate relatively less environmental impacts compared to the use of titanium anodes (Canals Casals et al., 2017).

Therefore, battery eco-design decisions (Zwolinski and Tichkiewitch, 2019) must be supported by robust and holistic analytical tools and indicators. These can be used to inform industrial designers and manufacturers about the most circular and environmentally sustainable choices on a case-by-case basis from an integrated life cycle thinking perspective and considering the potential trade-offs (Schulz-Mönninghoff et al., 2021a, 2021b). Life cycle assessment (LCA) is a robust methodology that can be used to assess potential environmental impacts throughout the life cycle of a product, i.e., from natural resource acquisition, via production and use stage, to waste management (including disposal and recycling). The LCA methodology, considering the complete life cycle of a product and multiple environmental impact categories, help prevent burden shifting from one life cycle stage to another, or from one environmental impact to another (Finnveden and Potting, 2014).

The advantages of coupling circularity and LCA assessment studies for decision-support in the eco-design and sustainable life cycle management of EV batteries are evident (Rigamonti and Mancini, 2021). However, circularity indicators alone do not necessarily help to identify the potential environmental aspects of a particular product design, and some of them fail to include energy consumption and polluting emissions, resulting in an incomplete view of the environmental performance (Rigamonti and Mancini, 2021). Additionally, the abundance of circularity indicators and the lack of clarity about their goals (in some cases) could make their selection and comparison for a specific context challenging (Rigamonti and Mancini, 2021). On the other hand, LCA was primarily designed from a linear economy approach (Samani, 2023), hence LCA studies may not cover technical quality specifications, such as total lifetime or recyclability (Peña et al., 2021; Saidani and Kim, 2022). Consequently, multiple authors propose a combined use of circularity metrics and LCIA indicators to provide a more accurate view of the resource and environmental impacts of products. However, the full interconnections between circularity assessment and LCA have not been fully explored (Brändström and Saidani, 2022). This is why, in the meantime, it is important to perform integrated circularity and LCA studies. Schulz-Mönninghoff et al. (2022) analysed the company-level material circularity of an automotive manufacturer by means of the Circular Transition Indicator (WBCSD, 2021) and Material Circularity Indicator (MCI) (EMF and Granta design, 2015). Although the study found that improved business processes can increase the material circularity for EV batteries, the relationship between circularity improvements and life cycle environmental impact reductions was not analysed.

Other studies have applied LCA to compare the environmental performance of EV battery chemistries. Dunn et al. (2015) analysed five different Li-ion battery chemistries through their Global Warming Potential (GWP) impacts and SOx emissions, as well as the energy consumption per battery weight. The results were calculated for a cradle-to-gate approach, showing two to six times higher impacts in all three categories analysed for batteries containing cobalt than for other chemistries. Second life applications such as repurposing the battery for stationary applications were analysed by Ahmadi et al. (2014) examining six indicators: GWP, photochemical oxidation formation, particulate matter formation, freshwater eutrophication, metal depletion, and fossil-resource depletion. Additionally, Tao and You (2020) investigated GWP and Cumulative Energy Demand for three batteries, while Canals Casals et al. (2017) evaluated four battery chemistries and Schulz-Mönninghoff et al. (2021a) specifically focused on one battery, both for GWP reduction. These works used functional units (FU) ranging from battery weight to energy delivered to the end-user. Cobalt-containing batteries exhibited significant potential for savings through repurposing, with reported impact reductions ranging from 10% to 65% in terms of GWP. These findings underscore the favourable outcomes of battery second use, while also emphasizing the influence of raw materials and electric mix on overall environmental impacts. However, it's important to note that these studies primarily focused on GWP and did not comprehensively consider circularity in their calculations, indicating a limitation in their sustainability assessment approach.

Similarly, both Ciez and Whitacre (2019) and Mohr et al. (2020) explored recycling and environmental impacts of lithium-ion batteries, analysing various chemistries, recycling methods and impact categories. Both studies highlighted the challenges and potential of recycling methods, with emphasizing the superior performance of hydro processes with 80–120% more savings for cobalt-containing EV batteries than pyrometallurgy methods. However, none of these articles evaluated the life cycle circularity performance of the EV batteries under study which can be identified as a common knowledge gap in LCA studies related to batteries. Finally, the work from Glogic et al. (2021) evaluates the environmental impacts through LCA and circularity trough MCI for alkaline batteries. The results concluded that the circularity metric could be indicative of environmental results, although the variability of results was too high. Still, the widespread use, single-use life cycle, small size and high presence of zinc made the study on alkaline batteries not representative for EV batteries.

There is a growing consensus that employing a combination of circularity and life cycle impact assessment indicators can form a suitable methodological approach and represent best practice in supporting sustainability-oriented design decisions. This could be applicable not only for EV batteries (Rigamonti and Mancini, 2021) but also for other product systems (Brändström and Saidani, 2022; Niero and Kalbar, 2019). However, the lack of attention to the integration of CE principles and LCA in the evaluation of EV batteries represents a notable gap in the literature. As highlighted by Picatoste et al. (2022a), there is a scarcity of comprehensive analyses from an integrated CE and LCA perspective. This absence of scientific articles and robust data significantly hampers the capacity of LCA researchers to effectively address CE adoption in the EV battery sector. Without such integration, it becomes challenging to minimize trade-offs and optimize strategies aimed at achieving crucial climate goals, as emphasized by Richter (2022). Therefore, bridging this gap through comprehensive analyses is imperative to inform sustainable decision-making and advance the transition to a circular economy in the EV battery industry. The present research, therefore, aims to:

i) identify the most circular and environmentally sustainable EV battery design and management scenario, and
ii) analyse the relationship between circularity and environmental sustainability and determine to which extent circularity improvements lead to environmental savings.

To this end, two circularity indicators Product Circularity Indicator (PCI) (Bracquené et al., 2020) and Circularity Index (CI) (Cullen, 2017) were calculated and a LCA performed, highlighting Global Warming Potential (GWP) and Abiotic Depletion Potential of minerals (ADPm). Two EV battery chemistries were considered: a lithium nickel manganese cobalt (NMC) and a lithium iron phosphate (LFP). Both batteries were analysed considering two different recycling processes: hydro- and pyro-metallurgy recycling.

2. Methodology

The Methodology is illustrated in Fig. 1. First, the design and EoL management of the NMC and LFP batteries is characterised from a technical standpoint (Section 2.1). The circularity and life cycle environmental performance of the batteries are then evaluated, including a sensitivity analysis (Section 2.2). Finally, guidelines for industrial research and innovation for the circular and sustainable design, manufacture and management of EV batteries are developed by analysing the relationship between the circularity performance and environmental

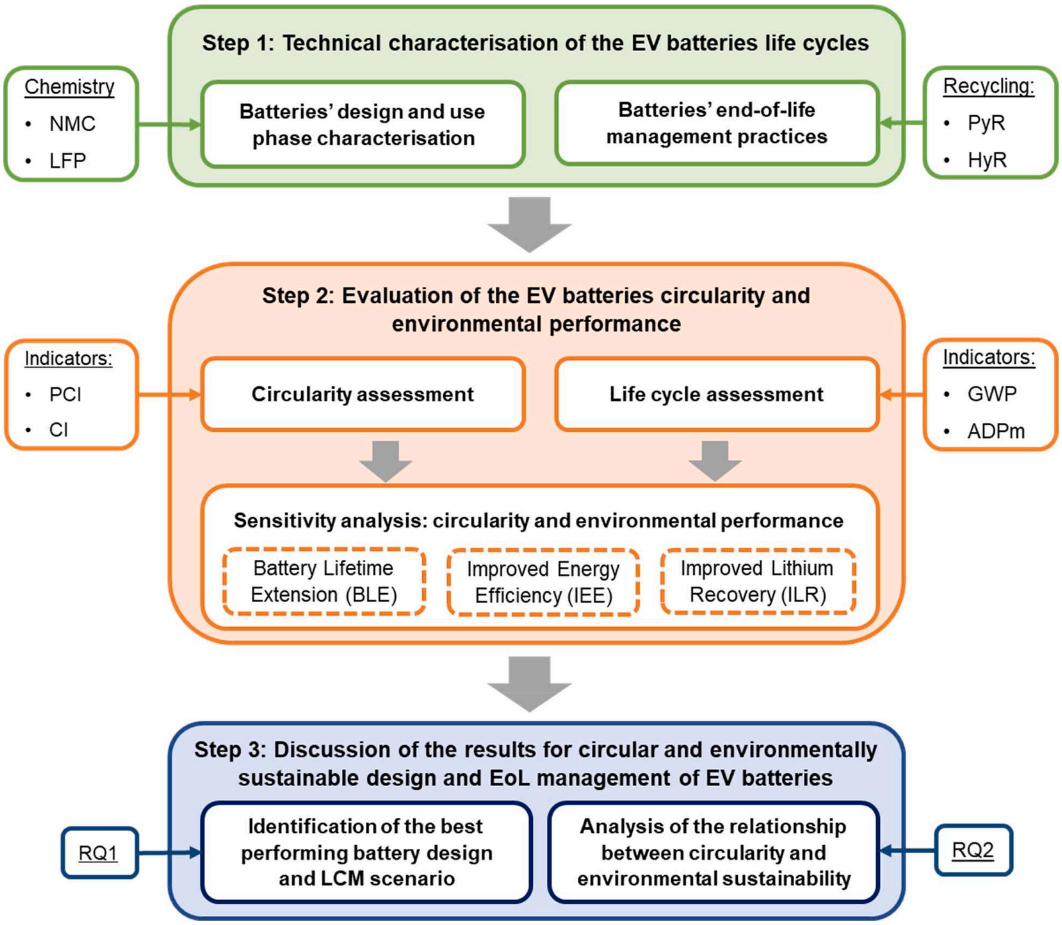

Fig. 1. Research methodology. Acronyms: CE (circular economy), EoL (end-of-life), EV (electric vehicle), LCA (life cycle assessment), LFP (lithium iron phosphate), NMC (nickel manganese cobalt), PCI (Product Circularity Indicator), CI (Circularity Index), GWP (Global Warming Potential), ADPm (Abiotic depletion potential of minerals), PyR (pyrometallurgy recycling), HyR (hydrometallurgy recycling).

sustainability of the batteries (Section 2.3).

2.1. Technical characterisation of the EV battery life cycles

The circularity performance and environmental sustainability of the EV batteries was analysed from cradle-to-grave, as shown in Fig. 2.

LFP and NMC batteries are currently the most widely used of the lithium-ion battery family, due to their long lifespan, high energy density, and good driving performance (Quan et al., 2022). Table 1 presents the main technical characteristics and life cycle inventory (LCI) for these batteries, based on Ellingsen et al. (2014), Majeau-Bettez et al. (2011), Peters and Weil (2018), and Xiong et al. (2019). Detailed LCI data can be

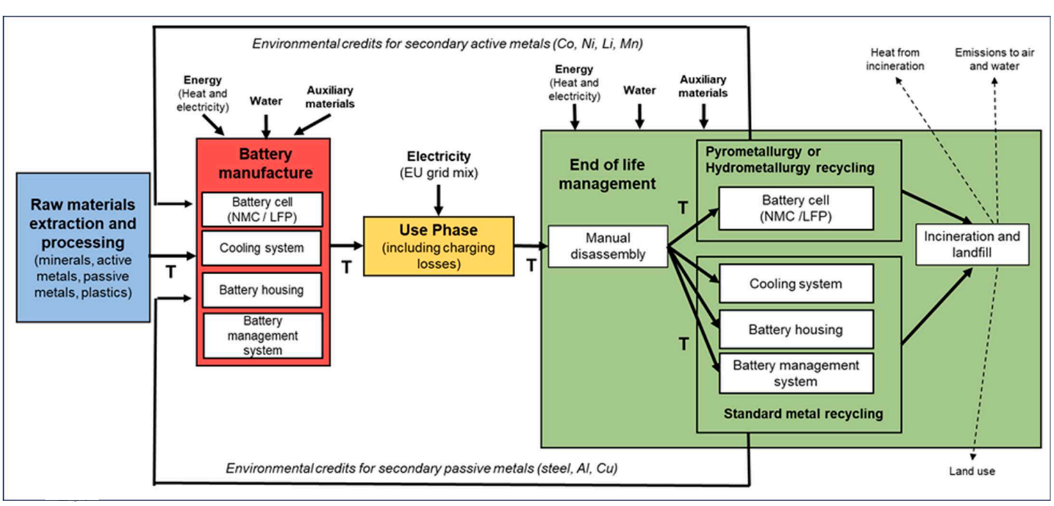

Fig. 2. System boundaries for the assessment of the circularity and environmental performance of the EV batteries. Dotted lines indicate flows not included in the system boundaries. Acronyms: NMC (nickel manganese cobalt), LFP (lithium iron phosphate), T (transport).

Table 1
Technical characteristics and life cycle inventory of NMC and LFP EV batteries. The inventories refer to a complete battery of each chemistry. For the calculation of the LCA according to the functional unit defined (1 kWh of delivered energy) the inventory was divided by the "Total consumed electric energy during lifetime (kWh)" expressed in the table. Acronyms: NMC (nickel manganese cobalt), LFP (lithium iron phosphate), EV (electric vehicle), BMS (Battery Management System), pyrometallurgy recycling (PyR), hydrometallurgy recycling (HyR).

Life cycle stage	Component	Elements	NMC		LFP	
Raw materials	**Cell**	Iron sulphate (kg)	-		30.6	
		Phosphoric acid (kg)	-		19.9	
		Copper (kg)	33.7		20.7	
		Cobalt sulphate (kg)	30.8		-	
		Nickel sulphate (kg)	30.8		-	
		Manganese sulphate (kg)	29.7		-	
		Graphite (kg)	24.2		19.1	
		Ethylene carbonate (kg)	21.1		28.0	
		Lithium hydroxide (kg)	13.5		14.1	
		Aluminium (kg)	7.5		53.1	
		Others (kg)	11.5		12.7	
	Cooling system	Aluminium (kg)	9.3		10.2	
		Dielectric fluid (kg)	0.5		0.5	
		Steel (kg)	0.2		0.3	
		Others (kg)	0.2		0.2	
	Battery housing	Aluminium (kg)	28.7		31.5	
		Steel (kg)	28.7		31.5	
		Nylon (kg)	13.4		14.7	
		Plastics (polypropylene) (kg)	5.0		5.5	
		Others (plastics and organics) (kg)	4.3		4.7	
	Battery management system	Steel (kg)	3.8		4.2	
		Electronic component (kg)	2.0		2.2	
		Cables (kg)	1.3		1.4	
		Others (kg)	2.2		2.4	
	Complete Battery	Total (kg)	250		275	
Manufacturing	**Battery assembly energy**	Electricity (kWh)	4420.4		5027.2	
	Battery assembly auxiliary materials	Water (kg)	57,524.2		8253.7	
		Sodium hydroxide (kg)	47.5		-	
		Other auxiliary materials (kg)	3.2		3.7	
Transport	**Cradle-to-Gate**	Train (tkm) freight train	266.2		245.5	
		Lorry (tkm) >32t, EURO	123.0		128.1	
		Ship (tkm) freight, sea	1609.0		1769.9	
	Gate-to-User	Lorry (tkm) >32t, EURO	125.0		137.5	
	User-to-EoL	Lorry (tkm) >32t, EURO	125.0		137.5	
Use Phase	**Battery operation in EV**	Total consumed electric energy during lifetime (kWh)	26,500		36,000	
		Energy efficiency	95%		90%	
		Total lifetime distance driven (km)	150,000		200,000	
End of life	**Type of recycling**	Cell recycling process	PyR	HyR	PyR	HyR
	Energy	Electricity (kWh)	162.4	63.4	178.6	69.7
	Material recovery	Lithium hydroxide	0%	91%	0%	24%
		Aluminium (cell)	93%		93%	
		Copper (cell)	96%		96%	
		Cobalt sulphate	84%		-	
		Nickel sulphate	84%		-	
		Manganese sulphate	84%		-	
		Steel	95%		95%	
		Aluminium (housing and cooling loop)	99%		99%	
		Copper (BMS)	51%		51%	

found in sections S1 and S2 of the supplementary file (SF). The most significant components of the battery can be grouped into the cell, cooling system, housing, and battery management system (BMS) (Fig. 2). The main difference between NMC and LFP batteries is the cell chemistry, which determines the use phase performance and influences end of life (EoL) management.

During the use phase, batteries are installed in the EV where they are used until their energy capacity is reduced to 80% of its original value (Martinez-Laserna et al., 2018). Afterwards, the batteries are sent to a waste treatment plant where they are manually disassembled into the main components for material recycling. Battery cells are recycled using either the pyrometallurgy (PyR) or hydrometallurgy (HyR) process, and the remaining components undergo standard metal recycling (Fig. 2).

The design and manufacturing requirements of LFP and NMC batteries are similar. The difference lies in the cells (different chemistries) that determine key performance aspects, such as the energy efficiency of the batteries (90% for LFP and 95% for NMC) (Arshad et al., 2022), lifespan (33% longer for LFP) (Xiong et al., 2019), and energy density, where LFP batteries are 10% heavier but achieve the same energy capacity as NMC (Hao et al., 2017; Majeau-Bettez et al., 2011).

Based on the available literature for the batteries, the following technical assumptions were made:

i. The capacity of both batteries was set at 26.6 kWh based on Ellingsen et al. (2014), which is used for the NMC battery and as reference to build the LCI for the LFP battery, following the procedure described by Majeau-Bettez et al. (2011) and Hao et al. (2017). Using energy capacity as the reference value for battery design comparison overcomes the issue of unaccounted differences of energy efficiency caused by different capacity EV batteries (Weiss et al., 2020).
ii. The lifetime energy delivery of the batteries was modelled using an average of the data published by Xiong et al. (2019) and Peters and Weil (2018). Accordingly, a lifetime of 150,000 km and 200,000 km was assumed for the NMC and LFP, respectively. The energy delivered during the lifetime was calculated by deducting the energy losses, as proposed by Arshad et al. (2022), for the duration of the

battery operation in the EV. This corresponded to 0.648 MJ/km and 0.635 MJ/km for LFP and NMC powered vehicles, respectively (Xiong et al., 2019). The effect of greening the electricity mix over the lifetime of the batteries was not considered in the calculations. The impacts were modelled considering the average European electricity mix.

The baseline inventories used in the research were developed around 10 years ago (Majeau-Bettez et al., 2011; Ellingsen et al., 2014), which is a limitation of the study regarding a developing technology, such as EV batteries. Nonetheless, a thorough review on the topic (Picatoste et al., 2022a) indicated that they were the most used and detailed inventories for the scientific analysis. Additionally, this article completed the LCI for both batteries with relevant use phase and recycling data, providing complete, comprehensive, and openly available LCI for a cradle to grave scope of EV batteries. To incorporate the most recent data, it's crucial for EV battery manufacturers to be more transparent in sharing information to support LCA studies. Digital product passports for batteries (Berger et al., 2022) could play a vital role in this process, and active steps are being taken towards its implementation (European Commission, 2023b).

Once the EV batteries reach EoL, they are sorted, stabilised, and disassembled (Ali et al., 2022). The components subsequently undergo separated recycling processes (Fig. 2). The cooling system, housing, and BMS are subjected to the same metal recovery recycling, regardless of the type of battery. The recycling process for battery cells differs between chemistries, however, leading to different outcomes (Golmohammadzadeh et al., 2022; Neumann et al., 2022). More detail on the EoL management of the EV battery can be found in S3 of the SF.

Currently, the main processes for EV battery cell recycling are PyR (Makuza et al., 2021) and HyR (Liang et al., 2021). PyR recycles materials through a high-temperature process (Zhou et al., 2021), while HyR is based on the extraction and purification of metals through leaching (Brückner et al., 2020). Hence, the recycling process inventory from Mohr et al. (2020) for NMC and LFP cells is employed in this research, as it includes both PyR and HyR (Table 1, Fig. 2). The recycling for the rest of the components was modelled on the data provided by Cumbul-Altay et al. (2011) for metals at the EoL of vehicles.

2.2. Evaluation of the EV battery circularity and environmental performance

The NMC and LFP batteries were evaluated by calculating two circularity and two environmental LCA-based indicators and considering three sensitivity scenarios to determine the variability of the results. Adhering to the circularity definitions by Blomsma et al. (2019), the CE strategy of "reduce" was investigated by examining the different raw materials used in each chemistry. The operational phase was assessed using the extension of battery lifetimes and enhancements in efficiency as sensitivity parameters. Additionally, different recycling methods and an improved recycling parameter were analysed to assess the circular economy strategy of "recycle".

2.2.1. Circularity assessment

Circularity assessment entails identifying and selecting appropriate circularity indicators and defining data and assumptions for their calculation. Product circularity aims to conserve both the quantity and quality of the material and components of a product, encouraging to maintain their level of value for as long as possible (Bracquené et al., 2020). Therefore, the circularity assessment of the EV batteries was addressed by calculating product-level circularity indicators.

The Circularity Indicators Advisor tool developed by Saidani et al. (2019) was used to select product-level circularity indicators suitable for calculation by applying the following criteria:

i) Type of products: as this study focuses on comparing the circularity performance of two alternative batteries, the use of product-level circularity indicators was employed to provide meaningful results.
ii) EoL management scenarios: since both batteries were recycled through the same processes (PyR and HyR), the calculation of circularity indicators with a focus on EoL management was considered crucial.
iii) Capability of the indicator to support decision-making: as the research was targeted at industrial designers, manufacturers and EoL managers of batteries for EV, using practical and easy to understand circularity indicators was critical to effectively communicate the results.

Research carried out by Picatoste et al. (2022b) on CE design criteria for EV batteries, found that performance, total lifetime, manufacturing efficiency, reduced material toxicity, and recycling legislation should be considered in the development of more circular and environmentally sustainable batteries. These criteria were thus included in the selection of circularity indicators, since the development of sustainable EV batteries must rely on an appropriate balance of design criteria (Schulz-Mönninghoff et al., 2021b).

From the 20 micro-level circularity indicators proposed by Saidani et al. (2019), two indicators were selected for the present research: the MCI (EMF and Granta design, 2015) and the Circularity Index (CI) (Cullen, 2017). Then, the MCI was substituted by its improved version, the Product Circularity Indicator (PCI) (Bracquené et al., 2020). The main improvement for the PCI was the inclusion of data regarding material efficiency and the material quality loss of recycling, which was a limitation of the MCI (Glogic et al., 2021). Other improvements of PCI over the MCI were: accounting for the tightness of the material cycles, considering the relationship with other product system (e.g. for the use or supply of recycled material) and including the material losses during manufacturing as data inputs for circularity calculation (Bracquené et al., 2020). The Circularity Index (CI) (Cullen, 2017) is a quantitative metric covering both recycling and raw material stages with four datapoints for the analysed product. The efficiency and energy consumption of the recycling process are compared to the energy cost of producing virgin raw material to determine the circularity of products. The calculation details and formulas of each of the indicators are presented in S4 and S5 of the SF file, for PCI and CI respectively.

The PCI includes the complete life cycle of the product for its analysis, with several data points for each life cycle stage. It considers the quantity of raw material, including the material lost in extraction. For manufacturing, the datapoints include the process efficiencies as well as the closed and open loop industrial recycling. During the use stage of the product, both the use intensity and the total lifetime of the product are included. At the end of life of the product, PCI considers the reuse and/or repurposing of any component of the product, as well as the recycling strategy and efficiencies. Finally, the PCI builds on this by considering the composition of each component (Soo et al., 2021).

These two different indicators were selected to specificallyanalyse the circularity performance of the from different perspectives, in order to determine which indicator was more useful for the EV battery sector. The reason why the PCI was chosen as an indicator was due to its complete product life cycle approach, covering every stage of the life cycle of EV batteries from a material perspective. The amount of virgin and recycled raw materials needed, manufacturing efficiencies, product lifetime (durability), use intensity, possible reuse of components/materials, the recycling efficiency and the waste generation were the datapoints needed to calculate the PCI. The complete coverage of the EV batteries by the PCI and the widespread use of its previous version (MCI) made the PCI choice a robust circularity metric.

For the CI, only four data inputs were required: the amount of virgin and recycled materials and the energy necessary to produce the virgin and recycled materials. The inclusion of the embodied energy aspect of the material production and recycling was also considered when selecting the indicator for analysis, as supplementing material resource indicators with energy use metrics throughout the product system is crucial for CE assessments (Cilleruelo Palomero et al., 2024). Moreover, the focused analysis on the closed loop of materials of the CI was also aligned with the recycling scenarios proposed in the article. Both the PCI and CI provide the results from 0 (completely linear) to 1 (completely circular), which makes the indicator results directly comparable, and the LCA would provide a third comparison value from the environmental savings perspective.

The LCI data for NMC (Ellingsen et al., 2014) and LFP batteries (Majeau-Bettez et al., 2011; Peters and Weil, 2018), together with the Ecoinvent v3.8 database (Moreno Ruiz et al., 2021) and the recycling inventories from Mohr et al. (2020) were used to calculate the circularity indicators. Further descriptions of the circularity indicators, including their formulas, variables, and data requirements, are set out in sections S4 and S5 of the SF.

2.2.2. Life cycle assessment

The environmental sustainability for both batteries was calculated according to the ISO 14040 and 14044 (ISO, 2006a, 2006b). Based on Xiong et al. (2019) and the new regulation of the European Union concerning batteries and waste batteries (European Commission, 2023b), the functional unit was defined as one kWh (kilowatt-hour) of the total energy provided by the battery system over the battery's service life, measured in kWh. The total energy was obtained from the number of cycles multiplied by the amount of delivered energy over each cycle. Accordingly, the data provided for each battery in Table 1 was divided by the total kWh delivered by each battery.

The batteries were manufactured in accordance with Ellingsen et al. (2014) and Peters and Weil (2018). All transport requirements from cradle-to-grave were considered, based on the assumption that the manufacturing facilities are located in central Europe. As regards collection and EoL management, it was assumed that the batteries needed to travel an average distance of 500 km from the user to the battery waste treatment site (Rallo et al., 2022). Based on the approach of Richa et al. (2017), the energy consumption during operation represents the well-to-wheel electricity requirements.

The complete life cycle of the EV battery was modelled with GaBi software v10.6 (Sphera, 2022), using Ecoinvent v3.8 (Moreno Ruiz et al., 2021). The environmental impact was calculated with the CML 2001 impact assessment method (Guinée et al., 2001). LCI modelling (Table 1) was based on the 'Allocation cut-off by classification' approach (Ecoinvent, 2023; Schaubroeck et al., 2021).

The EoL stage was modelled with the data presented in section 2.1 and Table 1. The material recovered from recycling was assumed to be of the same quality as the virgin raw materials, with the exception of BMS, thus earning environmental credits through substitution. For instance, 25.8 kg of cobalt sulphate was recovered from NMC for both recycling procedures. This is considered as avoided environmental burden for the calculation of environmental impact of the corresponding raw materials.

LCA evaluates the overall environmental impacts of a product or process throughout its life cycle. As a step within LCA, Life Cycle Impact Assessment specifically focuses on quantifying and analysing the environmental consequences associated with each stage of the life cycle. While LCA provides a comprehensive framework for assessment, the Life Cycle Impact Assessment stage delves deeper into the potential ecological implications identified in the LCA, aiding decision-making for sustainable practices.

The following life cycle impact categories were selected to be assessed in this work:

i) Global Warming Potential (GWP) (kg CO_2 eq.) (IPCC, 2007a): Climate change impact correlates with other environmental impact categories (IPCC, 2007b; US EPA, 2022) and represents one of the most significant indicators used to support sustainability-oriented decision-making processes. However, as stated by Laurent et al. (2012), GWP should not be the only environmental indicator used to assess alternative options and guide innovation.
ii) Abiotic Depletion Potential of minerals (ADP-ultimate reserves or ADPm) (kg Sb eq.) (van Oers et al. (2020): This indicator addresses the future availability of a raw material, a key aspect for EV batteries (Schulz-Mönninghoff et al., 2021a). There (Brändström and Saidani, 2022)

Although these two impact categories were selected for the assessment, the LCA calculation included all 12 categories of the CML method to avoid lack of harmonisation issues mentioned by Finkbeiner (2014). Detailed results of the calculation of LCA impacts are provided in section S6 of the SF for the highlighted categories and S7 for all the CML categories by life stage (both chemistries, both recycling methods).

2.2.3. Sensitivity analysis of circularity and environmental performance

To better understand the potential variability of the circularity and environmental life cycle performance between the NMC and LFP batteries, three sensitivity analysis were performed and three scenarios were defined accordingly:

i) Battery Lifetime Extension (BLE): According to Canals Casals et al. (2022) and Hoekstra and Steinbuch (2020), the real lifetime of EV batteries usually outperforms their design lifetime. Thus, it was considered that the lifetime of the NMC battery could equal the lifetime of the LFP battery (200,000 km). Likewise, LFP batteries show much less degradation over time than NMC, almost doubling their expected total lifetime (Preger et al., 2020). In this case, it was assumed that the LFP battery could reach 400,000 km. Hence, this scenario evaluates the effect on circularity and environmental performance by adjusting the parameter of battery lifetime.
ii) Improved Energy Efficiency (IEE): Some industrial reports (e.g., Sunon Battery, 2022) predict that the energy efficiency of LFP batteries could increase to 96–99% with appropriate charging strategies. Accordingly, the scenario considers that the energy efficiency of LFP can equal that of the NMC (95%).
iii) Improved Lithium Recovery (ILR): The EU has introduced a new regulation on batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020 (European Commission, 2020). This new legislation sets a minimum recovery target for lithium at 70% for EV batteries in 2030. Thus, it was considered that LFP HyR can achieve this target.

These scenarios were implemented using the LCI of both batteries with HyR. The remaining variables were kept equal and only the selected characteristic was modified.

2.3. Discussion of the results for circular and environmentally sustainable design and EoL management of EV batteries

The circularity and LCA results were evaluated from an integrated perspective to better understand the relationship between resource efficiency improvements and environmental savings (Laurent et al., 2012). The best and worst performing battery and EoL alternative was identified in accordance with the identification of the best battery design and EoL management option (Fig. 1). This included identifying intervention areas for future environmentally sustainable product innovation and recycling improvement (section 3.3). To analyse the relation between circularity indicators and environmental sustainability (Fig. 1), the LCA results were normalised from 0 (worst performance) to 1 (best performance) (see section 3.3), for comparison with the circularity indicators from the guidelines of Niero and Hauschild (2017). Detailed calculations of the normalisation and savings are presented in Section S8 of the SF. Finally, results were discussed from an industrial and research perspective for the circular and environmentally sustainable design and EoL management of batteries (see section 3.3).

3. Results and Discussion

First, the circularity results (PCI and CI) for the NMC and LFP batteries are presented, in section 3.1, followed by the environmental impact analysis (GWP, ADPm) and the sensitivity analysis in section 3.2. Finally, the results from the integrated circularity and environmental assessment are detailed in section 3.3, including a discussion of industrial and methodological considerations.

3.1. Circularity performance of NMC and LFP batteries

Fig. 3 plots the CI and PCI results, taking into consideration the baseline and sensitivity scenarios.

For both the CI and PCI indicators, the results show that the NMC battery is 6% to 25% (worst case LFP PyR, best case NMC HyR) more circular than LFP. This is due to the higher material recycling ratios of NMC batteries (59–69% mass recycled) at EoL (Table 1). These results indicate that material recovery, rather than product life-extension, is the determining factor for achieving circularity improvements. The LFP battery with PyR yielded the worst-case scenario, because the lithium, iron, and phosphate were not recycled. In contrast, the NMC with HyR scored 11–25% higher as a result of the recovery of lithium, cobalt, and nickel.

The CI results indicate that NMC batteries are 10% to 25% more circular than LFP. The lower energy requirement for recycling (21 kWh for HyR vs. 120 kWh for PyR), compared to the virgin raw material manufacturing energy (~1500 kWh) that it substituted, favours the circularity scores of NMC recycled through HyR (0.66). For LFP batteries, the circularity scores were as low as 0.42 for the PyR. This can be attributed to the lower material recycling (45% of recovered mass), higher recycling energy consumption and the fact that CI does not account for the longer lifetime of LFP.

The higher PCI material recovery ratio made the NMC batteries 8% to 10% more circular than LFP. In the case of the recycling scenarios, the higher material recovery of the HyR led to a 3% and 1% improvement for NMC and LFP, respectively.

The importance of material recovery in the circularity performance of the batteries was further confirmed by the sensitivity analysis. In the ILR scenario for LFP, improving lithium recovery (+2% recovered mass), increased the circularity proportionally for both indicators, although this might not be the case if the recycling technology improves. This is because the CI accounts for energy consumption and the PCI considers multiple factors for circularity.

Regarding the effect of the HyR-BLE scenarios, lifetime extension (+33% for NMC and +100% for LFP) had a relevant effect on the PCI scores, yielding 4% and 16% of circularity improvements, respectively. However, such circularity improvement is relatively small compared to the lifetime extension proposed for each battery. In PCI calculations, the extended lifetime exhibited small influence in the results compared to the recovered material, resulting in a lesser circularity improvement when material was not recovered (e.g., plastic lost in HyR). Similarly, the LFP HyR-IEE scenario was found to have little influence on the circularity scores, with no change for CI and just 1% improvement for PCI.

It can thus be concluded that improving battery recycling is the most effective strategy to improve circularity, while energy efficiency appears to be the factor with the lowest impact on the circularity score. Nevertheless, the circularity improvement gained by these factors does not guarantee better environmental performance. The LCA results presented in the following section provide a better understanding of the aspects critical to improving the analysed EV batteries.

3.2. Battery environmental life cycle impact assessment

Fig. 4 illustrates the life cycle environmental impact of the EV batteries per 1 kWh delivered energy, for baseline and sensitivity scenarios.

The NMC battery impact was 3–6% (GWP) and 12–16% (ADPm) lower than that of the LFP. The most environmentally friendly solution was the NMC undergoing HyR (0.56 kg CO_2 eq. and 8.6 mg Sb eq. per kWh delivered), while the LFP battery undergoing PyR presented the worst-case scenario (0.60 kg CO_2 eq. and 10.2 mg Sb eq. per kWh). As shown in Fig. 4, the GWP category was dominated by the operation phase (~75%) in all the analysed scenarios. This was due to the environmental impact of the electricity used to charge the EV batteries. Consequently, greening the electricity mix and improving energy efficiency are key aspects to consider for reducing the impact of the use phase. The second biggest source of impact was raw material extraction and processing (116 and 85 g CO_2 eq./kWh for NMC and LFP, respectively). These impacts were reduced by the recovery of material at EoL stage (Table 1), offsetting 61–72 g CO_2 eq. for NMC and 17–21 g CO_2 eq. for LFP.

Regarding the ADPm, the raw material stage determined 85–90% of the life cycle environmental impact. Although LFP contain critical materials as lithium and graphite (European Commission, 2023a), the presence of other critical materials with such as nickel, manganese and cobalt in NMC batteries makes the raw material stage of these batteries almost two times greater (+32 mg Sb eq./kWh) than the LFP. However, the EoL recovery of critical material (European Commission, 2023a) offsets 80% (25–26 mg Sb eq.) of total ADPm impact for NMC batteries. As the functional unit selected for the study was 1 kWh delivered, due to methodological process, longer battery lifetimes or use intensity directly

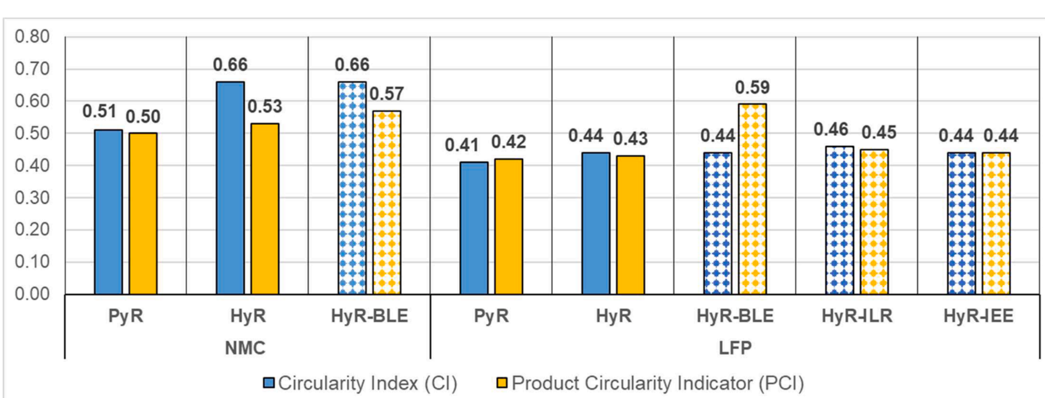

Fig. 3. Circularity performance of NMC and LFP batteries, considering baseline and sensitivity scenarios. Dotted columns refer to sensitivity scenarios. Acronyms: NMC (nickel manganese cobalt), LFP (lithium iron phosphate), PyR (pyrometallurgy recycling of cell), PyR (hydrometallurgy recycling of cell), BLE (battery lifetime extension), ILR (Improved Lithium Recovery), IEE (Improved Energy Efficiency).

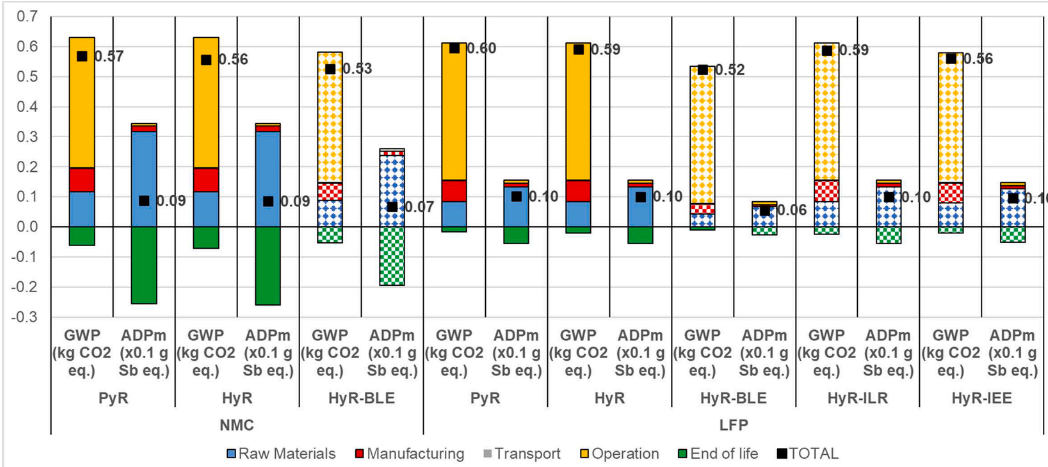

Fig. 4. Life cycle environmental impacts of NMC and LFP batteries per 1 kWh of delivered energy. Columns indicate the origins of the impact while the squares represent the total impact for each scenario. Dotted columns indicate results for sensitivity scenarios. Acronyms: NMC (nickel manganese cobalt), LFP (lithium iron phosphate), PyR (cell pyrometallurgy recycling), HyR (cell hydrometallurgy recycling), BLE (Battery Lifetime Extension), ILR (Improved Lithium Recovery), IEE (Improved Energy Efficiency), GWP (Global Warming Potential), ADPm (Abiotic Depletion Potential minerals).

affected the raw material impact (if the same battery provides 2 times more kWh during its lifetime, with the same material type and quantity used, the impact per kWh delivered will be halved). This functional unit choice helped account for the different longevities of LFP and NMC batteries. If the lifetime of a battery was halved, it would mean that a second battery (with new raw materials) would be necessary to fulfil the same function, thus relating the longevity to material availability the same way as the selected functional unit. Nevertheless, the 33% longer lifetime of the LFP compared to NMC (Table 1) did not compensate for the lack of material recovery of the LFP batteries, which performed the worst in ADPm (+12% compared to +16% NMC).

The sensitivity analysis results indicate the relative importance of the analysed aspects (total lifetime, energy efficiency, and material recovery) for the environmental performance of the batteries. Compared to the baseline lifetime, the HyR-BLE scenarios calculated for both NMC and LFP batteries resulted in 5% and 13% (GWP) and 25% to 45% (ADPm) impact savings, respectively. As a longer lifetime requires higher energy consumption from operation but not more raw materials, the savings generated from the BLE scenarios were naturally higher for ADPm. Hence, total lifetime is a key aspect to consider for the improvement of ADPm impact. Nonetheless, the savings derived from the HyR-BLE scenarios were not proportional to the additional battery lifetime achieved. With regard to the HyR-IEE scenario, improved charging efficiency delivered more kWh of electricity with no further material resource requirements. Thus, the GWP and ADPm impact were reduced in proportion to the improved energy efficiency. An efficiency improvement of 5% in the LFP battery with HyR resulted in 5% savings for both GWP (0.03 kg CO_2 eq. saved) and ADPm (0.4 mg Sb eq. saved).

Finally, in the HyR-ILR scenario for LFP, the results showed less than 1% savings in both impact categories compared to the LFP with regular HyR. Although 6.4 kg more lithium was recycled in the HyR-IRL scenario, virgin lithium is not as impactful as other critical metals such as nickel and cobalt in the ADP-m category; therefore, a higher recycling rate is not as influential.

Considering the results in their entirety, NMC batteries emerge as the most environmentally sustainable option. Nevertheless, circularity and environmental outcomes must be analysed from an integrated perspective to identify the most environmentally sustainable scenario, including critical aspects for further development. This is discussed in the following section.

3.3. *Discussion of the results for circular and environmentally sustainable design and EoL management of EV batteries*

For both the GWP and ADPm environmental indicators, the zero-savings (worst-case) scenario is LFP undergoing PyR. This was used as reference to normalise the environmental savings for the remaining scenarios, as explained in Section 2.3. Fig. 5 depicts the relationship between circularity performance and environmental savings of each battery design and EoL scenario, including the sensitivity analysis. The circularity score (CI and PCI) is plotted on the Y-axis and environmental savings (GWP and ADPm) on the X-axis. Each graph in Fig. 5 represents a circularity and environmental savings scenario. For instance, the NMC battery with HyR results in 0.66 circularity (in accordance with CI) and 0.06 normalised GWP savings compared to the worst-case scenario (top left graph).

Focusing on the best design and EoL management battery, the higher recycling ratio (59–69 of mass) for NMC batteries led to higher circularity scores (45–46% of mass recycled) and lower environmental impact than LFP. Thus, the results for LFP EoL management and sensitivity scenarios are grouped in the lower left corner of the graphs in Fig. 5 because of their low circularity and small environmental savings within the analysed scenarios. This is in line with similar LCA studies that compare both chemistries (Quan et al., 2022; Zhang et al., 2023). However, studies employing Material Flow Analysis perspectives and considering large scale implementation suggest that LFP could deliver a greater reduction in environmental impacts than NMC, due to the criticality of materials such as cobalt (Rossi et al., 2023).

As regards, LFP recycling, the HyR-IRL and HyR scenarios generated less than 6% improvement for any of the indicators (PCI, CI, GWP, ADPm) compared to the worst-case scenario (LFP PyR). Although improving recycling efficiency is considered a critical aspect for EV battery environmental sustainability (Reinhart et al., 2023), the findings from this study indicate that this might not be the case for LFP batteries. For the HyR-ILR scenario, it was assumed that the recycling process was able to recover 70% of the total lithium of the battery. However, high-quality lithium recovery from used batteries is still a technological challenge for EoL (Yanamandra et al., 2022), requiring additional refinement. This could lead to increased environmental impact, with few offsetting benefits from recovered material.

The HyR-IEE scenario for LFP batteries did not deliver significant improvements in terms of resource and environmental savings. However, it is important to note that in this study energy efficiency during the use phase was set as an average constant. This can be considered a

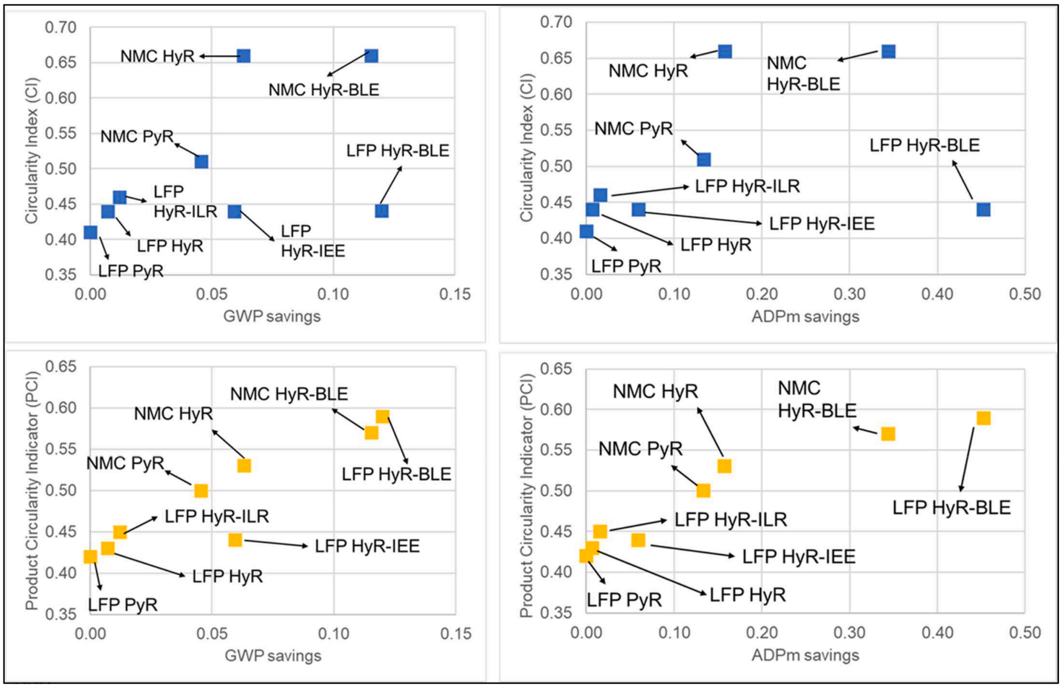

Fig. 5. Circularity and environmental performance correlation for both battery chemistries and scenarios evaluated. Acronyms: NMC (nickel manganese cobalt), LFP (lithium iron phosphate), PyR (pyrometallurgy recycling of cell), HyR (hydrometallurgy recycling of cell), BLE (battery lifetime extension), ILR (Improved Lithium Recovery), IEE (Improved Energy Efficiency), GWP (global warming potential), ADPm (Abiotic depletion potential minerals), CI (circularity index), PCI (Product circularity indicator).

limitation, since efficiency fade is a key factor in the operational stage of the EV battery life cycle, particularly in BLE scenarios (Koroma et al., 2022). For HyR-BLE, the PCI showed that NMC is 15% more circular than the worst-case scenario (LFP PyR) and LFP 19% more circular. As CI does not consider life-extension, these scores did not change in the HyR-BLE scenarios analysed. Noticeably, environmental savings were not proportional to circularity improvements, which is consistent with previous studies of circularity indicators and LCA (Samani, 2023). For example, the HyR-BLE scenario for the NMC battery was 15% (PCI) and 25% (CI) more circular than LFP undergoing PyR. This contributes to a reduction in GWP of 12% and ADPm of 34%.

Overall, when all scenarios analysed for both batteries are considered, the BLE delivers the greatest environmental savings. Based on literature data, the BLE scenarios were defined as passive lifetime extension as battery lifetime can be longer than expected (Preger et al., 2020). Circular innovations —such as more efficient thermal management (Chidambaranathan et al., 2020), efficient driving styles (Jambhale et al., 2020), increasing the use intensity through vehicle-to-grid (Etxandi-Santolaya et al., 2023b) or minimising super-fast charges (Mathieu et al., 2021)—can generate significant environmental savings on a global scale considering the magnitude of the future EV fleet (IEA, 2023). One further option for EV battery lifetime extension is giving batteries a second life. Currently it is considered that a battery has reached the end of their EV life at 80% of its state of heath (Etxandi-Santolaya et al., 2023a), which enables the possibility of employing the retired battery in a second life application. The second life would therefore reduce the raw material and manufacturing impacts through keeping the battery working longer. Moreover, the manufacturing of another battery could be avoided on account of the reused or repurposed battery, thereby further mitigating environmental impacts. The LCA of this second life could be included within the system boundaries of the EV battery through a system expansion. The savings of this second life would lead to a 10–22% reduction in life cycle climate change impact (Schulz-Mönninghoff et al., 2021a). There are still certain challenges for a second life of EV batteries. For example, the market value of certain raw materials, coupled with regulations and the imperative to increase recycled content, renders second life strategies less feasible for NMC batteries. Consequently, EoL operators, OEMs, battery producers, and other stakeholders may choose recycling to recover essential materials, such as cobalt, rather than pursuing reusing or repurposing initiatives (Fallah and Fitzpatrick, 2023). This is aligned with the risk identified by Ahmadi et al. (2014), who suggested that if battery longevity is extended through second-life applications, it could lead to shortages of recycled raw materials in the market.

Regarding recycling, the results of this study are consistent with those of Mohr et al. (2020), indicating that HyR was particularly advantageous for NMC batteries given their cobalt content, surpassing PyR in terms of circularity and environmental impacts by recovering a greater quantity of materials with reduced energy consumption. Although Mohr et al. (2020) focused on comparing the recycling processes, the influence of battery chemistry and recycling methods remains consistent within the cradle-to-grave scope of our study. However, despite environmental credits being attributed to recycled material in this study, the scalability of the process remains uncertain as identified by Ciez and Whitacre (2019). Additionally, ensuring the quality of recovered materials for reintroduction into the supply chain remains a challenge.

Hence, there are a number of CE strategies and design choices which can deliver circularity and environmental sustainability for EV batteries. However, it is crucial that these are evaluated in an integral manner to obtain the most appropriate and efficient combination. For instance, a selected strategy should ensure that a longer lifetime does not generate trade-offs in material or energy consumption and environmental impact, such as the energy efficiency losses caused by battery degradation (Omenya et al., 2023).

With regard to the relationship of circularity indicators and environmental sustainability of EV batteries, the results are different for PCI and CI. Fig. 5 shows that when the battery and EoL scenarios are more circular for PCI (higher on the Y-axis), they generate more environmental savings (right side on X-axis) than the worst-case scenario (LFP

HyR-BLE scenario at the top right corner for both GWP and ADPm savings). No clear relationship can be observed for CI. This demonstrates that circularity indicators can help the practitioner better understand the resource efficiency of different EV battery types and EoL scenarios and can be a useful metric during early design phases (Saidani and Kim, 2022). If a single variable change is analysed during the EV battery design phase—for instance improving a recycling process—limited scope indicators such as CI could be utilised to compare different design alternatives. This could function as a tool to facilitate communication between environmental practitioners and non-expert public (Jerome et al., 2022). However, the lack of general scope of CI excludes various CE strategies, as indicated by the fact that the CI results remained unchanged for the HyR-IEE and HyR-BLE scenarios. Nonetheless, results of this work indicate that circularity indicators such as PCI that consider a wide range of life cycle stages could be used as a proxy for the environmental performance of the selected EV batteries as an improvement in circularity would normally lead to a better environmental performance of the EV battery (Fig. 5). Such evaluations would not be without limitations, however, as circularity indicators mainly relate to materials and their preservation (Parchomenko et al., 2019). Therefore, the creation of a sector-specific and more complete indicator and a combined approach of circularity indicators and LCA are recommended. This would ensure a holistic and detailed analysis of the circularity and environmental sustainability of EV batteries, incorporating multiple aspects and identifying the hotspots of the battery life cycle.

Limitations of the study include the lack of dynamic background scenarios for the LCA. For example, only considering an average energy efficiency or battery capacity during the batteries' lifetime instead of a progressive degradation of their performance. In addition, the sensitivity parameters employed (BLE, IEE, and ILR) did not take into account the technological requirements and implications of achieving these advancements, potentially resulting in an inadequate reflection of the variability inherent in real-world situations. Another limitation was the lack of access to updated life cycle inventories for EV batteries, which could have provided more accurate and comprehensive data for the analysis and could enable including a broader range of chemistries of EV batteries to widen the scope of analysis. This is aligned with the lack of primary data for LCA practitioners, which is a common limitation for EV battery LCA (Picatoste et al., 2022a). Additionally, the chosen circularity indicators exhibit certain limitations in encompassing the entire life cycle of the battery and the environmental benefits derived from CE strategies. This could potentially affect the robustness of the findings, as discussed earlier. The lack of consideration of the safety aspect of the analysed batteries is also a limitation of this work. NMC batteries, while performing better in terms of circularity and environmental impacts, are more susceptible to thermal runaway and react more violently under abuse conditions such as overcharging, high temperatures, or physical damage (Ouyang et al., 2017). Therefore, this safety risks would be a great input to consider within this comparison. Conversely, LFP batteries tend to tolerate higher temperatures and mechanical abuse without entering thermal runaway. This makes them a preferred choice for applications such as residential energy storage and electric buses (Ohneseit et al., 2023). This analysis for safety would be needed for both first and second life applications of the EV batteries. Finally, incorporating more circular economy strategies to the analysis, particularly focusing on battery reusing or repurposing, would contribute to a more comprehensive and holistic assessment of sustainability in the EV battery industry.

4. Conclusions

The present paper evaluates the circularity (CI and PCI) and environmental performance (GWP and ADPm) of two EV batteries with different chemistries (NMC and LFP). Recycling alternatives, extended lifetime, improved energy efficiency, and increased material recovery were considered with the aim of identifying the most resource-efficient and low-impact design and EoL practices. In addition, environmental hotspots and opportunities for industrial eco-innovation and methodological development are identified.

The findings show that the NMC battery with HyR performed best in terms of both circularity (resource efficient) and environmental sustainability (lower environmental burden) EV battery design and the EoL management scenario. Based on the circularity indicators calculated, NMC was 6–25% more circular than LFP, despite the longer lifetime of the LFP battery (33% longer than NMC) which contributed to improved circularity performance. The highest circularity was achieved when the NMC was recycled through HyR processes. NMC batteries also represent a more resource-efficient choice due to the higher material recovery ratios (+13–24%). The LCA evaluation revealed that NMC batteries have 3–6% lower GWP (22.9–37.7 g CO_2 eq.) and 12–16% lower ADPm (1.3–1.6 mg Sb eq.) per kWh delivered than LFP. The integrated assessment of the circularity performance and the normalised environmental savings further demonstrate that NMC batteries represent a more resource efficient and environmentally sustainable choice than LFP. The only exception was the LFP HyR-BLE sensitivity scenario, where the exceptionally long lifetime (400,000 km) resulted in the best PCI (0.59) and environmental savings (0.12 GWP and 0.45 ADPm).

Consequently, raw material selection, total lifetime, electricity mix for operation, and efficient recycling processes are critical for the environmental sustainability of EV batteries. Similarly, although the analysis of the relationship between circularity indicators and LCA suggests that when comparing design options or EoL scenarios considering a single variable change, product-level circularity indicators (CI and PCI) could be used as a proxy for environmental sustainability, LCA studies are required to complete and validate the results. Circularity improvement results alone do not guarantee better environmental performance, due to the limited analysis of the complete battery life cycle. For instance, some critical life cycle aspects, such as the use phase electricity mix or the influence of the active components of the battery in the total environmental impacts, are not evaluated by the selected circularity indicators. As circularity indicators' results were dominated by the recycling stage, they were not covering the complete approach of CE for the EV batteries, as shown by the sensitivity parameters analysed in this work. Therefore, a more holistic analytical approach is required to develop circularity indicators which incorporate the life cycle thinking perspective and the whole circular economy concept for the EV battery sector.

Future studies could usefully focus on analysing alternative battery chemistries and other CE strategies, such as reuse or repurposing, to define a range of best design and EoL solutions to mitigate resource consumption and environmental impact. Additionally, circularity indicators could be standardized for easy adoption and interpretation by EV battery designers, producers and EoL managers. In this process, circularity indicators should be integrated into LCA or vice versa, to develop a single methodological approach and composite metric. Finally, the effect of CE strategies on the EoL of batteries could be further investigated from a circular and sustainable business model and value chain approach to identify the most suitable solutions from a system level perspective.

Supplementary file

A Supplementary File for this study is available. It provides detailed data on the LCI of the NMC battery (S1), the LCI of the LFP battery (S2), the EoL modelling of the NMC and LFP batteries (S3), detailed calculations of PCI (S4), detailed calculations of CI (S5), the environmental impacts for the baseline and sensitivity scenarios (S6), the impact assessment for the baseline scenarios for all the CML impact categories (S7) and the normalisation of environmental impact savings and integrated assessment with circularity indicators (S8)

CRediT authorship contribution statement

Aitor Picatoste: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Magnus Schulz-Mönninghoff:** Writing – review & editing, Conceptualization. **Monia Niero:** Writing – review & editing, Conceptualization. **Daniel Justel:** Writing – review & editing, Supervision. **Joan Manuel F. Mendoza:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107833.

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