Resources, Conservation & Recycling 201 (2024) 107218

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

A battery value chain independent of primary raw materials: Towards circularity in China, Europe and the US

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ARTICLE INFO

Keywords:
Lithium-ion batteries
Recycling
Circular economy
Sustainable supply chain
Raw material demand
Material flow analysis

ABSTRACT

As the production of batteries for electric vehicles continues to grow, so does the demand for primary battery raw materials. Against the supply risks and environmental issues associated with raw material mining and transportation, battery material circularity has become a burgeoning topic in academia, policy, and industry. While prior research has explored secondary supply and demand, an important gap remains regarding the break-even points (BEPs) where full circularity is reached (secondary supply = demand). Using a material flow analysis, this study offers two contributions: First, it calculates the BEPs for critical raw materials (lithium, cobalt, nickel) in different regions. The results show that China will realize full circularity more than ten years earlier than Europe and the US for lithium and nickel and seven years earlier for cobalt. Second, it identifies levers (e.g., earlier full electrification) that can accelerate full circularity, thereby demonstrating how independence from primary raw materials can be achieved earlier.

1. Introduction

Lithium-ion batteries (LIBs) for electric vehicles (EVs) are considered a key energy storage technology (Nature Editorial, 2021), as they can help pave the way towards sustainable transportation (Duffner et al., 2021; Richter, 2022; Asaba et al., 2022). In the last decade, global EV sales recorded a strong growth (Huang et al., 2018). Worldwide, there are currently approximately 20 million EVs on the road (BloombergNEF, 2022), while China, Europe and the US are the most important markets covering 95% of global EV sales together in 2021 (International Energy Agency, 2022). The International Energy Agency (IEA) predicts that the global number of EVs will substantially increase to 190 million by 2030 (International Energy Agency, 2022). This rapid 10-fold growth implies a drastic increase in the demand for LIBs and associated primary raw materials, such as lithium, cobalt and nickel (Xu et al., 2020).

The large quantities that will be required in the future impose environmental, social and supply issues associated with the sourcing of critical raw materials. Meanwhile, the rapid growth of EVs on the global roads leads to considerable amounts of future battery waste that can be used as secondary raw materials in EV batteries but must be handled according to environmental regulations (Huang et al., 2018). Today, the main sources of primary raw materials are globally distributed and their mining is associated with sustainability concerns. The vast majority of lithium is mined in Australia, Chile, China and Argentina (U.S. Geological Survey, 2023; Volkswagen, 2020). Mining of lithium requires large amounts of energy and water, which, combined with substantial transportation emissions, leads to negative environmental impacts (Nature Editorial, 2021). The DR Congo currently supplies approximately 70% of the cobalt used in batteries, while 90% of it originates from mines where child labour is common (Nature Editorial, 2021; U.S. Geological Survey, 2023). In addition to such serious social concerns (Harper et al., 2019), cobalt is costly (Gaines et al., 2018) and thus is set to be replaced in future battery technologies with other materials such as nickel and abundant metals such as manganese and iron (Xu et al., 2020; Zeng et al., 2022; Laveda et al., 2016; Mauler et al., 2022). For example, in NMC battery technologies (lithium nickel manganese cobalt oxides as

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https://doi.org/10.1016/j.resconrec.2023.107218
Received 18 March 2023; Received in revised form 15 June 2023; Accepted 21 September 2023
Available online 6 December 2023

cathode material), cobalt is successively being replaced by higher nickel content (Xu et al., 2020). However, regarding nickel, its mining and processing are linked to soil contamination and loss of biodiversity (Mauler et al., 2022). Another issue concerns nickel supply. The main producers of nickel are Indonesia, the Philippines and Russia (U.S. Geological Survey, 2023; Greenwood et al., 2021a). Recently, Indonesia announced plans to stop nickel export to scale up its own refining industry (Cabinet Secretariat of the Republic of Indonesia, 2021; CNBC, 2022). The Russia–Ukraine crisis raises additional questions over the securing of a stable and independent nickel supply. Therefore, the price of nickel was subject to substantial fluctuations in 2022 (Nature Energy Editorial 2022).

Against this background, there is an urgent need to address the recycling of raw materials from spent EV batteries (Harper et al., 2019; Nature Energy Editorial, 2019; Armand et al., 2020). Policy and industry have begun developing circular economy strategies that aim at decoupling future economic growth from the consumption of raw materials (Ellen MacArthur Foundation, 2013; World Economic Forum, 2019). To realize these circular economy strategies, companies need to introduce new circular business models (i.e., the system of activities through which a company creates, delivers, and captures value in concert with other partners in the circular economy). The two circular business models that are currently considered are (1) the extension of product life through reuse, remanufacture, and repair and (2) the recycling of products (Stahel, 2016). In support of circular business models, the EU has introduced a policy to include a minimum share of recovered cobalt (12%), lithium (4%), and nickel (4%) in produced EV batteries in 2030 (European Comission, 2020; Neumann et al., 2022; Melin et al., 2021; Bird et al., 2022). Similarly, China and several states in the US have issued regulations for the collection, reuse, and recycling of materials in EV batteries (Neumann et al., 2022; Melin et al., 2021; Bird et al., 2022). These measures challenge existing production and consumption models but also provide opportunities to introduce new circular business models that pave the way towards circularity. Circular business models unfold their full potential when the raw material demand is fully met by secondary recycled materials, i.e., when the break-even points (BEPs) of full circularity are reached and complete independence from primary battery raw materials is secured. However, so far it remains unclear when the supply from recycled EV battery materials will equal the regional demand (= full circularity) in China, Europe, and the US. In this study, this gap is addressed by providing a new dynamic material flow analysis (MFA) that estimates the BEPs for lithium, cobalt, and nickel in EV batteries in China, Europe, and the US. Further, we identify five levers that can accelerate full circularity, i.e., reaching the regional BEPs earlier, and demonstrate how regions can more quickly become completely independent from primary battery raw materials.

2. State-of-the-art of LIB recycling and material flow analysis

To gain access to the growing resource of secondary raw materials in EVs, recycling of spent LIBs elements is necessary. The main elements in a LIB are the cathode, anode, electrolyte, and separator (Armand et al., 2020; Schmuch et al., 2018). As critical and strategically important raw materials in commercial LIBs, lithium, cobalt, and nickel are found mainly in cathode materials, such as lithium iron phosphate (LFP), lithium nickel manganese cobalt oxides (NMC), or lithium nickel cobalt aluminium oxides (NCA) (Xu et al., 2020; Zeng et al., 2022; Schmuch et al., 2018). The different cathode materials (battery technologies) show individual performance characteristics and cost structures (Mauler et al., 2021). The processes for the recycling of battery materials focuses on recovering the valuable cathode material and can be divided into three categories: pyrometallurgical, hydrometallurgical, and direct recycling (Harper et al., 2019; World Economic Forum, 2019; Neumann et al., 2022; Ciez and Whitacre, 2019). In pyrometallurgical processes, the batteries are melted at high temperatures and further processed to obtain raw materials (Harper et al., 2019). This requires high energy input and results in high greenhouse gas emissions but is flexible in terms of input battery technologies (Ciez and Whitacre, 2019). In the hydrometallurgical process, battery materials are separated by wet-chemical processes (Neumann et al., 2022). This process requires mechanical pre-treatment (sorting, dismantling, shredding, etc.) (Hua et al., 2020), whereas the variety of battery technologies (cathode chemistry) and the non-standardized design of battery are a particular challenge (BloombergNEF, 2022; Neumann et al., 2022; Ciez and Whitacre, 2019; Baars et al., 2021). The advantages of hydrometallurgical processes are high potential recovery and purity rates of up to nearly 100% for lithium, cobalt, and nickel (Neumann et al., 2022), and low energy consumption (Ciez and Whitacre, 2019). In pyro- and hydrometallurgical processes, the batteries are recycled down to the metal level (Ciez and Whitacre, 2019). Direct recycling is a promising new method (Morse, 2021) where the cathode chemistry (NMC, NCA, etc.) is retained, which means that a separate process is required for each cathode material and battery technology (Gaines et al., 2018; Gaines et al., 2021). Because of the low economic and material value, direct recycling is especially useful for LFP batteries (Gaines et al., 2018; Neumann et al., 2022; Gaines et al., 2021). Additionally, this method can potentially be used for in-process recycling of production waste (Gaines et al., 2021; Hanisch et al., 2015). However, direct recycling plants can be tailored towards specific battery technologies in use but must be flexible to adapt to future changes and trends in battery cathode chemistries (Neumann et al., 2022).

The rapid growth of EV sales in the coming decades will provide recycling plants with high amounts of spent LIBs as recycling input. The amount of future secondary supply of recycled raw materials can be determined by a dynamic material flow analysis (MFA). The MFA is a commonly used method to calculate future demand of LIB raw materials in EVs and, more recently, to estimate waste flows of spent LIB materials from EVs.

Using MFA, prior research has determined the future demand for battery materials and supply of secondary materials from end-of-life (EoL) and waste batteries and examined material flows in a qualitative approach (Ziemann et al., 2012) (see Table 1). In addition to a global perspective on LIB material flows, several studies focus on important markets such as China, Europe, or the US, on individual countries, such as Brazil (Duarte Castro et al., 2021) or Sweden (Nurdiawati and Agrawal, 2022), or on urban regions such as Berlin (Moore et al., 2020). However, these studies use different assumptions, making a comparison between countries and regions difficult. As Table 1 shows, on a material level, prior research has focused mainly on lithium and cobalt as the two of the most important raw materials for LIBs, while other research has also included materials such as nickel and others. Also, prior research considers the material flow on battery (Chang et al., 2009; Moore et al., 2020; Richa et al., 2014; Ai et al., 2019; Aguilar Lopez et al., 2022; Zhou et al., 2022) or cathode material level (Abdelbaky et al., 2021; Gaines and Nelson, 2009; Richa et al., 2014; Song et al., 2019; Liu et al., 2021; Shafique et al., 2022a; 2022b; Zhou et al., 2022). Based on the analysis on these material levels, recent research compared the future raw material demand with the future supply of secondary, recyclable materials to derive a circularity potential or degree (Xu et al., 2020; Baars et al., 2021; Dunn et al., 2021; Song et al., 2017; Kamran et al., 2021; Dunn et al., 2022; Neidhardt et al., 2022; Shafique et al., 2022a). However, paving the way towards full circularity, the review of previous MFA studies for LIB materials (Table 1) shows that a comprehensive analysis of the regional BEPs for lithium, cobalt, and nickel in EV batteries in China, Europe, and the US is thus far missing – a gap the present study aims to address (see last column Table 1).

This study offers two core contributions. First, it advances prior circularity research that has studied different levels of circularity in different regions and under various technology scenarios (see Table 1), but not when full circularity is reached and thus complete independence from primary battery materials can be established in different regions. For example, while prior BEP research (Neidhardt et al., 2022) has

Table 1
Overview on previous LIB studies that used material flow analysis (MFA) (Abdelbaky et al., 2020; Ambrose and Kendall, 2020; Deetman et al., 2018; Guo et al., 2021; Hao et al., 2017; Hao et al., 2019; Jiang et al., 2021; Lu et al., 2017; Matos et al., 2022; Pehlken et al., 2015; Sun et al., 2017; Sun et al., 2018; Tabelin et al., 2021; Weil et al., 2018; Ziemann et al., 2018).

Article	Region					Material Level						Material Demand/ Production	EoL & Waste Battery Stream/Recyclable Material Supply	Analysis of Potential Circularity	Analysis of BEPs	Time Horizon
	Global	China	Europe	US	other	Battery Level	Cathode Level	Li	Co	Ni	other					
Gaines & Nelson (2009)				●			●	Li	Co	Ni	■	●				to 2050
Chang et al. (2009)					●	●		Li	Co	Ni	■	●				2006
Ziemann et al. (2012)	●							Li								-
Richa et al. (2014)				●		●	●	Li	Co	Ni	■	●	●			to 2040
Pehlken et al. (2015)	●							Li	Co			●	●			to 2050
Lu et al. (2016)		●						Li								2007 - 2014
Hao et al. (2017)		●						Li				●				2015
Song et al. (2017)		●							Co	Ni		●		●		2001 - 2013
Sun et al. (2017)	●							Li				●				2014
Deetman et al. (2018)	●							Li	Co			●				to 2050
Sun et al. (2018)	●							Li				●				1994 - 2015
Weil et al. (2018)	●							Li	Co	Ni	■	●	●			to 2050
Ziemann et al. (2018)	●							Li				●	●			to 2050
Ai et al. (2019)				●		●							●			to 2040
Bobba et al. (2019)			●					Li	Co			●	●			to 2030
Hao et al. (2019)	●							Li				●				to 2100
Song et al. (2019)		●					●	Li	Co	Ni	■	●				to 2025
Abdelbaky et al. (2020)			●			●							●			to 2040
Ambrose & Kendal (2020)	●							Li				●	●			to 2100
Moore et al. (2020)					●	●							●			to 2040
Xu et al. (2020)	●							Li	Co	Ni		●	●	●		to 2050
Abdelbaky et al. (2021)			●				●	Li	Co	Ni	■	●	●			to 2040
Baars et al. (2021)			●						Co			●	●	●		to 2050
Duarta Castro et al. (2021)					●			Li	Co	Ni	■	●	●			to 2030
Dunn et al. (2021)		●	●	●	●			Li	Co	Ni	■	●	●	●		to 2040
Guo et al. (2021)		●						Li				●	●			to 2030
Jiang et al. (2021)		●				●	●					●	●			2006 - 2040
Kamran et al. (2021)					●			Li	Co	Ni	■	●	●	●		to 2050
Liu et al. (2021)		●					●	Li	Co	Ni	■	●				2000 - 2018
Tabelin et al. (2021)	●							Li				●				to 2019
Aguilar Lopez (2022)	●					●						●	●			to 2050
Dunn et al. (2022)				●				Li	Co	Ni	■	●	●	●		to 2050
Matos et al. (2022)			●					Li	Co	Ni	■	●				2016
Neidhardt et al. (2022)	●							Li	Co	Ni	■		●	●	●	to 2035
Nurdiawati et al. (2022)					●			Li	Co	Ni	■	●	●			to 2050
Shafique et al. (2022)		●		●			●	Li	Co	Ni	■	●	●	●		to 2030
Shafique et al. (2022)	●						●					●	●			to 2038
Zeng et al. (2022)		●	●	●	●				Co			●	●			to 2050
Zhou et al. (2022)		●				●	●	Li				●				to 2020
This article		●	●	●				Li	Co	Ni		●	●	●	●	to 2070

provided useful insights by calculating the global BEP for cobalt, a region-specific analysis for a broader range of critical raw materials is thus far missing. Second, this article contributes an analysis of parameters that may accelerate full circularity of raw LIB materials. Here, the study identifies five levers that could lead to earlier BEPs and analyses their impact: (1) early full electrification of sales, (2) no 2nd use, (3) a shorter lifespan of EV batteries, (4) a reduction in EV battery size, and (5) high production scrap rates. In doing so, this article extends prior research that has used sensitivity analyses to demonstrate how the absolute demand for EV battery materials or the supply of recyclable materials depends on and changes with the adoption of individual model parameters in the MFA (Xu et al., 2020; Abdelbaky et al., 2021; Dunn et al., 2021; Neidhardt et al., 2022), but not how circularity can be accelerated.

To estimate the BEPs for lithium, cobalt, and nickel in China, Europe, and the US, this study extends prior research by using recent data (e.g., latest IEA forecasts for EV sales) and a novel dynamic MFA that combines existing approaches to supply/demand modelling with the modelling of production scrap as an alternative input material. Specifically, a circular economy approach (Richter, 2022; Hua et al., 2020) is used to analyse the battery life cycle and consider production, EV life, 2nd use life (e.g., as stationary storage systems) (Tao et al., 2021) and recycling, while assuming sufficient future recycling capacities and collection of spent batteries. The supply of recycled materials comprises return of EoL batteries and production scrap with a delay of one year. EoL batteries include batteries after EV life, early returned EV batteries (because of defects or accidents), and batteries returning from 2nd use life. Production scrap combines battery component waste (e.g., scrapped slurry, electrode sheets, cell stacks), defect finished cells and scrap from EV production. The use of production scrap is a way to scale recycling plants at a time when there is insufficient return of recyclable batteries. The derived future supply of recycled batteries is compared with the demand for battery materials for EVs to determine when primary raw materials from globally distributed mining will no longer be required.

3. Materials and methods

3.1. Methodology overview and model structure

A dynamic MFA is conducted to analyse the annual future demand ($D_{t,i,r}$ in kg) of critical cathode materials (lithium, cobalt, nickel) for EV batteries and the future supply of recyclable secondary raw materials ($S_{t,i,r}$ in kg) until 2070. The future demand for EV battery materials (here, it is solely distinguished between battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)) and the supply of recyclable secondary raw materials is compared. The results show to what extent secondary raw materials can potentially cover the demand for battery materials (the secondary supply–demand gap $G_{t,i,r}$ in percent) for each market (r), year (t) and metal (i) and when the break-even points (BEPs) of full coverage of secondary raw materials will be achieved (Eq. (1)). The difference from the annual demand represents the annual need for primary raw material supply ($P_{t,i,r}$ in kg) (Eq. (2)).

$$G_{t,i,r} = \left(1 - \frac{S_{t,i,r}}{D_{t,i,r}}\right) * 100\% \tag{1}$$

$$P_{t,i,r} = D_{t,i,r} - S_{t,i,r} \tag{2}$$

3.2. Future demand for EV battery cathode materials

The future demand ($D_{t,i,r}$ in kg) for EV battery materials (lithium, cobalt, nickel) is calculated by combining forecasts of annual EV sales ($EV_{t,r}$), BEV/PHEV shares of sales ($BEV_{t,r}$; $PHEV_{t,r}$), average BEV/PHEV battery sizes ($BS_{BEV,t}$; $BS_{PHEV,t}$ in kWh), battery cathode chemistry market shares ($C_{t,j,r}$) (derived from battery technology scenarios) and specific battery technology parameters, such as specific cathode energy density (d_j in kWh/kg) and individual metal weight shares in battery cathode material (w_i) (Xu et al., 2020; Wentker et al., 2019; Greenwood et al., 2021b; Rosenman et al., 2015; Geng et al., 2016).

$$D_{t,i,r} = \sum_j EV_{t,r} * \left(BS_{BEV,t} * BEV_{t,r} + BS_{PHEV,t} * PHEV_{t,r}\right) * C_{t,j,r} * \frac{w_i}{d_j} \tag{3}$$

3.3. Annual EV sales and BEV/PHEV shares (Supplementary Tables 1, 2)

The forecast of annual EV sales ($EV_{t,r}$) and BEV/PHEV shares ($BEV_{t,r}$; $PHEV_{t,r}$) in China, Europe, and the US is based on data derived from the IEA Global EV Outlook (2022). EV sales in Europe include the EU27, Norway, Iceland, Switzerland, and the United Kingdom. Past data of annual EV sales and BEV/PHEV shares for 2020 and 2021 and forecasted data for 2025 and 2030 based on the Announced Pledges Scenario (APS) are adopted as fixed parameters (International Energy Agency, 2022). The APS assumes that the announced sustainability targets of governments around the world will be fully met in time. Considering the EV sector, the APS includes all recent major announcements of electrification targets (such as net-zero emission in 2050) and other pledges. For 2040, EV sales data are obtained from (BloombergNEF, 2022). Achievement of the net-zero emission target in 2050, resulting in full electrification of EV sales, is assumed (International Energy Agency, 2022). In total, it is assumed that 100 million EVs will be sold annually by 2050 across the world (BloombergNEF, 2022), with the level remaining constant in the following years until 2070. The number of EV sales in 2050 in China, Europe, and the US is calculated as the total amount of sales worldwide (100 million), in consideration of the pre-COVID market shares of total car sales in 2019. In 2019, approximately 88 million cars were sold globally (25 million in China, 15.8 million in Europe, 17 million in the US) (International Energy Agency, 2020). China is thus expected to sell 28.4 million EVs in 2060 Europe 18.0 million, and the USA 19.3 million. Missing data for years in between these fixed parameters are filled by linear interpolation.

3.4. Average BEV/PHEV battery size (Supplementary Table 3)

The average EV battery sizes for BEVs and PHEVs ($BS_{BEV,t}$; $BS_{PHEV,t}$ in kWh) in this model for 2020, 2030 and 2040 is fixed, assuming linear growth between these parameters and a constant level from 2040 to 2070. The average battery size of BEVs (PHEVs) increases from 43 kWh (9 kWh) in 2020 to 60 kWh (15 kWh) in 2030 and to 82 kWh (20 kWh) in 2040 (Abdelbaky et al., 2021).

3.5. Battery cathode chemistry market shares (battery technology scenarios) (Supplementary Tables 4–6)

The battery technology scenarios in each market, which determine the battery cathode chemistry market share ($C_{t,j,r}$), are based on the NCX and LFP scenario obtained from Xu et al. (2020) and expanded until 2070. Moreover, high-performance post–lithium-ion technologies are considered, such as lithium-sulfur (LiS) and lithium-air batteries (LiO) (Duffner et al., 2021; Xu et al., 2020; Geng et al., 2016) and sodium-ion batteries (SIB) (Duffner et al., 2021; Tapia-Ruiz et al., 2021; Vaalma et al., 2018) as future low-cost technologies, will enter the market slowly over the coming decades. For China, the LFP scenario with a higher baseline LFP share in 2020 (50%) is assumed, as LFP is currently the dominant cathode chemistry in China (International Energy Agency, 2022). Due to the focus on the low-cost technology LFP (International Energy Agency, 2022), China can keep EV prices low while simultaneously expanding its charging infrastructure (International Energy Agency, 2022). The average EV price in 2021 was approximately US$41, 000 in China, US$61,000 in Europe and US$69,000 in the US (Mobility Market Outlook, 2022). Due to the high safety, low costs, and high life-cycle stability of LFP and SIB (Tapia-Ruiz et al., 2021; Peters et al., 2016), in this model is assumed that LFP will partly be substituted by SIB in the future within the Chinese battery market. Here, SIBs are modelled to enter the market in 2025 (Nature Energy Editorial, 2022; CATL, 2021), whereas expensive high-performance technologies for high-range requirements, such as LiS and LiO (Duffner et al., 2021; Geng et al., 2016), are not integrated at all in view of the trend of rapid growth in low-budget EVs and charging infrastructure in China. In the basic NCX scenario, LFP is eliminated. Currently, there is almost no production or use of LFP in Europe and the US, but LFP is expected to surge in these markets (International Energy Agency, 2022). Tesla is, with 300,000 sales in 2021 (=50% of EV sales (Tesla, 2021)), the main EV manufacturer in the US. Because of the high share of NCA in Tesla models (Harper et al., 2019), the NCX scenario is assumed to be the dominant scenario in the US, with LFP emerging in 2030 and future high-energy technologies and SIB in 2040. The battery technology scenario in Europe is also based on the NCX scenario. In comparison to that in the US, a higher baseline of the NMC cathode technologies in 2020 is assumed for Europe due to current market shares (International Energy Agency, 2022). NMC111 (33% nickel, 33% manganese, and 33% cobalt within the lithium metal oxide cathode) and NMC523 (50% nickel, 20% manganese, 30% cobalt), mainly used in 2020, will be slowly substituted with nickel-rich technologies such as NMC811 (80% nickel, 10% manganese, 10% cobalt) and NMC955 (90% nickel, 5% manganese, 5% cobalt) by 2050 (Xu et al., 2020). In Europe, LFP will enter the market in 2025. Increasingly, US-based Tesla and other companies like China-based Nio are seeking to gain market share in Europe (NIO, 2022), which will result in the adoption of LFP and low-cost batteries. Further, it is assumed that SIB will enter the European market in 2035 and alternative high-energy technologies in 2040.

3.6. Future supply of recyclable secondary raw materials

The supply of secondary raw battery materials ($S_{t,i,r}$ in kg) is the sum of the number of annually returning end-of-life (EoL) batteries from EVs and 2nd use ($EoL_{t,i,r}$ in kg) and the amount of recyclable battery material scrap from battery production processes ($PS_{t,i,r}$ in kg). It is assumed that 100% of each battery technology and battery material returning from EV life and 2nd use and production scrap is recycled (recycling rate; $RR_{t,r}$) without losses and therefore available as secondary raw material for EV batteries (Harper et al., 2019; Neumann et al., 2022) (Eq. (4)).

$$S_{t,i,r} = \left(EoL_{t,i,r} + PS_{t,i,r}\right) * RR_{t,r} \tag{4}$$

3.7. Return of EoL batteries from EVs and 2nd use (Supplementary Tables 7, 8)

To estimate the return flow of recyclable EV batteries ($EoL_{t,i,r}$ in kg), an average battery EV lifetime (l) of 10 years is assumed in this model (Abdelbaky et al., 2021; Bobba et al., 2019). The battery EV lifetime follows a Weibull distribution with 3.5 for the shape parameter value (α) (Ai et al., 2019; Shafique et al., 2022b). Adding the forecasted future demand for EV batteries ($D_{t,i,r}$ in kg), the return of the respective battery cathode material from EVs for each year and market is calculated (Eq. (5)). Furthermore, a basic battery collection rate ($CR_{t,r}$) of 100% after EV life in all markets is assumed. Parts of these batteries enter in 2nd use for 10 years (k), expressed in 2nd use rates (Xu et al., 2020). The 2nd use rates ($R_{t,j}$) are based on (Xu et al., 2020). LFP and SIB will reach 100% in 2030 and 2055, respectively, whereas all other technologies will reach a maximum of 75% in 2035.

$$EoL_{t,i,r} = \begin{pmatrix} R_{t-k,j} * D_{t-l-k,i,r} * C_{t-k-l,j,r} * \frac{w_i}{d_j} \\ + (1 - R_{t,j}) * D_{t-l,i,r} * C_{t-l,j,r} * \frac{w_i}{d_j} \end{pmatrix} * CR_{t,r} \quad (5)$$

3.8. Battery production scrap (Supplementary Tables 9, 10)

To estimate the battery production scrap in each market ($PS_{t,i,r}$ in kg), which flows directly into the amount of recyclable materials, the annual total capacity demand in each market ($D_{t,r}$ in GWh; Eq. (6)) is divided by the average battery production plant size ($BPPS$ in GWh) (Mauler et al., 2021), resulting in the total number of potentially newly installed battery production plants in each market and year ($nBPPS_{t,r}$) (Eq. (7)). A specific production scrap rate dependant on years after the start of production is assumed, decreasing from 15% in the first year to a constant 1% after ten years (Mauler et al., 2022). With an assumed 3% constant scrap rate for battery modules during EV production, this results in combined scrap rates of 18% to 4% (PSR_t). An average production scrap rate per year and market ($\phi PSR_{t,r}$) is determined to combine the scrap of all battery production plants generated in a certain year and market (Eq. (8)). Combined with information on the battery technology scenarios in each market ($C_{t,j,r}$), this supplies the final amount of recyclable cathode material from production scrap with a delay of one year after waste generation (Eq. (9)).

$$D_{t,r} = EV_{t,r} * (BS_{BEV,t} * BEV_{t,r} + BS_{PHEV,t} * PHEV_{t,r}) \quad (6)$$

$$nBPPS_{t,r} = \frac{D_{t,r}}{BPPS} \quad (7)$$

$$\phi PSR_{t,r} = f(nBPPS_{t,r}; PSR_t) \quad (8)$$

$$PS_{t,i,r} = D_{t-1,r} * \phi PSR_{t-1,r} * C_{t-1,j,r} * \frac{w_i}{d_j} \quad (9)$$

4. Results

4.1. Analysis: break-even points (BEPs)

In this analysis, different future battery technology scenarios in China, Europe and the US are provided (see Methods and Supplementary Tables 4–6). For China, a low-energy battery technology scenario is assumed, with the use of LFP in the short-term and rapid introduction of sodium-ion batteries (SIBs) as a future battery technology. For the US, it is that high-energy NCA will be the dominant technology, accompanied by NMC. Europe is expected to continue focusing on NMC technologies. The LFP share in the US and Europe is expected to grow over the next decades when large-scale electrification reaches volume and budget segments of the automotive market.

Fig. 1 shows the shares of primary raw materials in EV batteries over time against the forecasted recycling in different markets. The results of the analysis indicate that China will be first to reach the BEPs, followed by Europe and the US. This stark contrast between China and the rest of the world can be attributed to two main factors. First, China is expected to sell an increasing number of EVs in the next decades (see Supplementary Table 1). In 2021, most EVs were sold in China, with its sales of approximately 3.3 million, up from 1.2 million in 2020 (International Energy Agency, 2022). While Europe and the US have also experienced increasing electrification in recent years, their growth rates are considerably smaller than China's. In 2021, 600,000 EVs were sold in the US (2020: 300,000) and 2.3 million in Europe (2020: 1.4 million) (International Energy Agency, 2022). The electrification in all three markets will result in an early high absolute return of EoL batteries, which consequently requires recycling or 2nd use. However, it will also

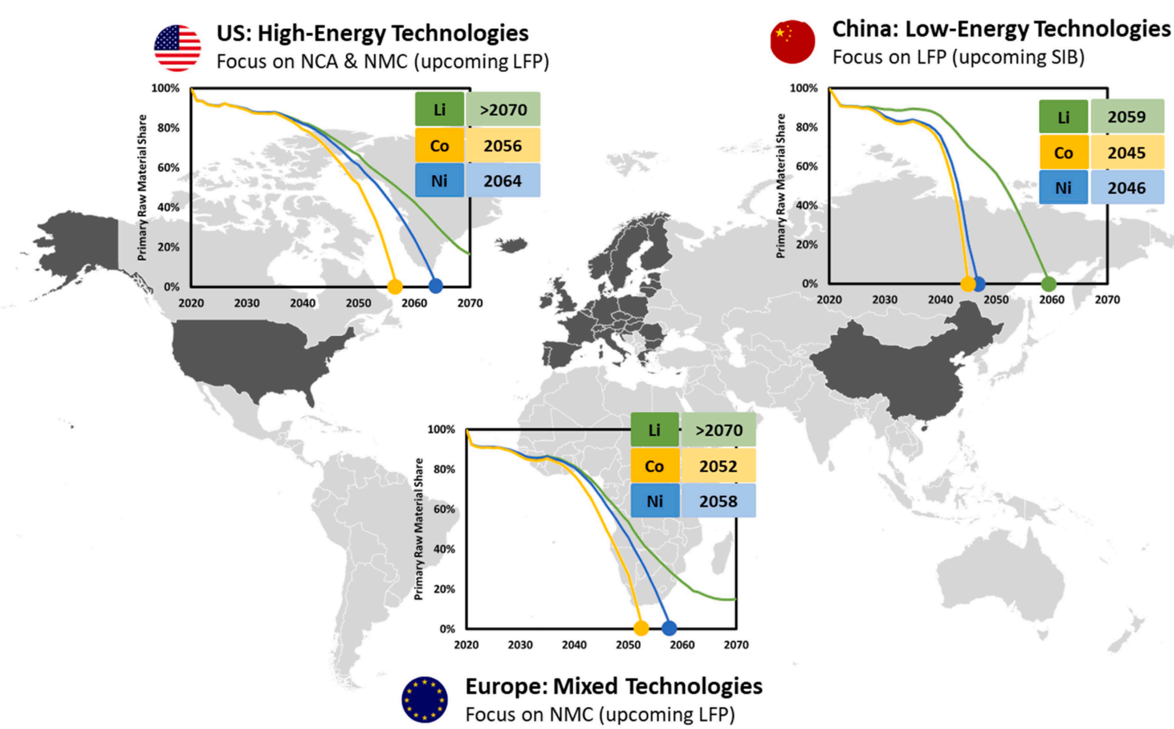

Fig. 1. Forecasted break-even points (BEPs) of full demand coverage by secondary supply for lithium, cobalt and nickel in China, Europe, and the US.

increase the absolute demand for battery materials in the future. The results also suggest that large-scale recycling of spent EV batteries will be required earlier in China (2035) than in the US and Europe (2040), which poses major challenges for circular business models as large-scale recycling plants need to be setup, made operational and be sufficiently utilised. There is, therefore, a need to globally scale-up recycling capacity. Although EoL batteries are lacking as an input for recycling plants (Nature Editorial, 2021; Gaines et al., 2018; Gaines et al., 2021) in the short term, this can be compensated by production scrap.

Second, early material independence in China is associated with the use of LFP. In all markets, cobalt and nickel can be covered by recycled materials much earlier than lithium, which supports the trend towards independence from critical and expensive cobalt in batteries. LFP (which contains no cobalt or nickel) is currently the dominant technology and will increasingly be used in China in the coming years (International Energy Agency, 2022). This will reduce the future market shares of other technologies. Here, the results show that the displacement of cobalt- and nickel-based technologies (NMC and NCA) by LFP will drastically reduce the demand for cobalt and nickel in China. The rapid electrification of the Chinese automotive sector will lead to an early high return of cobalt and nickel from NMC and NCA. As a consequence, the lower future market shares of NMC and NCA will be able to be covered to a larger extent by returning secondary cobalt and nickel, resulting in early BEPs. In addition, China is expected to adopt future lithium-free technologies (SIB) that can successively replace the low-cost technology LFP (Tapia-Ruiz et al., 2021; Peters et al., 2016), which will reduce future lithium demand, leading to an early BEP of lithium. In contrast, Europe is expected to mainly rely on NMC while the US will focus on high-energy NCA and NMC. Currently, in both markets, LFP is used on a very small scale but is expected to rapidly expand in this decade (International Energy Agency, 2022). Concerning NMC technology, it is assumed that cobalt will be progressively replaced by nickel. As a result, nickel demand can be covered at a later stage than cobalt demand. In comparison to China, Europe and the US are expected to introduce high-energy technologies with metallic lithium anodes. This will result in a significant increase in lithium demand and, consequently, in later BEPs.

4.2. Five levers: shifting the break-even points

By conducting a sensitivity analysis, potential levers that shift the BEPs (Supplementary Tables 11–19) are also analysed. Here, five levers are identified that result in the material demands being met earlier by secondary materials (see Table 2). Fig. 2 shows the effect of each lever on the BEPs in comparison to the outcomes in the base scenario. The results show that none of the levers can eliminate the gap between China and the US and Europe.

Table 2
Five levers that accelerate reaching the BEPs for lithium, cobalt, and nickel.

Lever	Adopted model parameter	Parameter setting in base scenario	Parameter adoption to leverage BEPs
(1) Early full electrification of sales	Annual EV sales	100% electrification of car sales in 2050	100% electrification of car sales in 2030
(2) No 2nd use	2nd use rates of battery technologies	increasing over time to 100% for LFP and SIB and to 75% for all other technologies	constant at 0% for all battery technologies
(3) Shorter lifespan of EV batteries	Average battery lifespan in EVs	10 years	8 years
(4) Reduction in EV battery size	BEV battery size	increasing from 43 kWh in 2020 to 82 kWh in 2040 (then constant to 2070)	decreasing from 43 kWh in 2020 to 23 kWh in 2040 (then constant to 2070)
(5) Higher production scrap rates	Combined production scrap	decreasing from 18% to 4%	constant rate of 18%

4.3. Early full electrification of car sales

In this scenario, only EVs as passenger cars will be sold in the three markets by 2030. Although early full electrification of car sales increases the short-term demand for raw materials, it also results in an earlier high return flow of EoL battery materials. Specifically, this lever has a strong impact on the BEPs for cobalt and nickel in Europe and the US. This is because of an early maximum return flow of heavily used cobalt and nickel before 2030 combined with an ongoing technological change towards less cobalt in NMC technologies and the replacement of NMC by LFP. In this scenario, the US reaches the BEPs for cobalt and nickel earliest latest. The situation is different in China: Although the BEPs for cobalt and nickel move forwards only one year, this lever shifts the BEP of lithium substantially. Due to the rapid growth of EV sales and the LFP share in China, reaching full electrification of car sales by 2030 yields a considerable amount of lithium to be recycled early, while lithium demand decreases with emerging SIB shares by 2025.

4.4. No 2nd use

The elimination of 2nd use increases the immediate return of EoL batteries after EV life. Through this lever, BEPs for nickel and cobalt are reached much sooner than in the base scenario in all three markets. Additionally, China reaches the BEPs of lithium earliest because of the dominance of LFP and a rising SIB share. Compared to the 2nd use rates in the base scenario (Supplementary Table 7), the majority of cobalt and nickel from NMC and NCA is returned 10 years (the assumed duration of the 2nd use) earlier through this lever, causing a significant shift of the cobalt and nickel BEPs, especially in the NMC- and NCA-dominated markets in Europe and the US. In the base scenario, in line with circular economy principles (Ellen MacArthur Foundation, 2013), a longer battery life is realized by the 2nd use of batteries. However, this lever shows that when batteries do not enter 2nd use applications, the BEPs can be reached earlier. Consequently, there is a conflict between two important sustainability goals: circularity and extending product life cycle and product value.

4.5. Shorter lifespan of EV batteries

Batteries are assumed to remain in EVs for 10 years on average in the base scenario (Supplementary Table 8). Reducing this to eight years mainly increases the return of batteries in the first decade, which can potentially cover short-term recycling capacity. In the long term, this lever has a maximum impact of only two years on all BEPs. In addition, as already shown with the previous lever of no 2nd use, extending product life is a circularity principle and, as such, a shorter lifespan of batteries might not be desirable. While shorter lifespan accelerates BEPs, longer lifespan might conserve resources but delay BEPs (e.g., a 2-year longer lifespan delays the BEP for cobalt in Europe by 2 years). There is thus again a trade-off between these sustainability goals.

4.6. Reduction of EV battery size

In the base scenario, the average battery size is assumed to increase over time, e.g., to compensate for a lack of charging infrastructure (Abdelbaky et al., 2021; Dunn et al., 2021). However, if the charging infrastructure becomes more widespread or EVs become lighter, battery size can decrease. If a decrease in average battery size is assumed here, China and Europe could meet the cobalt demand significantly earlier through recycled materials, while there is only a small accelerating effect on the late BEPs, such as nickel in the US. As in the base scenario, the battery size of EVs is assumed to be constant after 2040, but at a

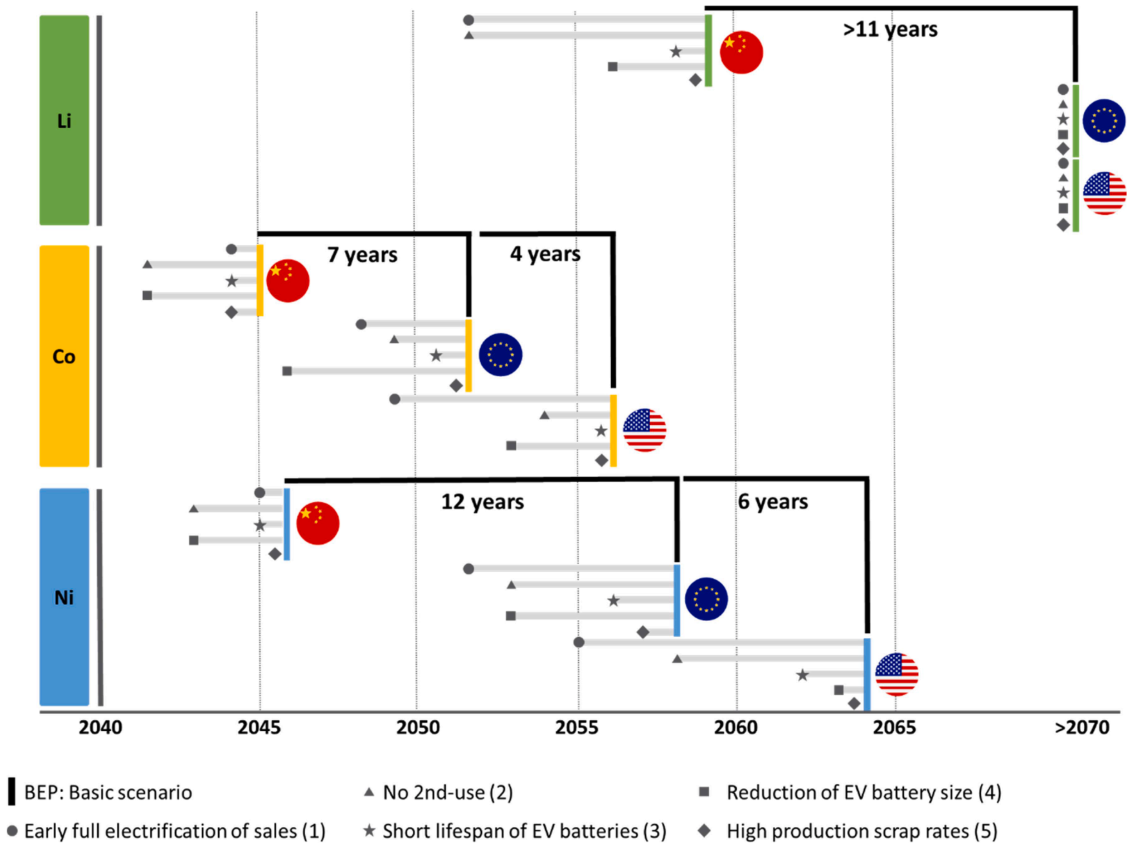

Fig. 2. Break-even points (BEPs) of each raw material after the five levers are applied.

considerably lower level. In contrast to the flattening growth in Europe and China by 2040, the electrification of car sales in the US is expected to rapidly increase not before 2040, resulting in a substantial increase in the demand for battery materials by 2040. However, irrespective of the absolute level of battery size from 2040, the increase in nickel demand after 2040 through growing EV sales is covered later due to low nickel return levels from EV sales before 2040.

4.7. High production scrap rates

In the base scenario, production plants are optimized, and scrap rates decrease over time. Assuming a constant combined scrap rate over time along the production process results in earlier BEPs: one year earlier for cobalt in China and nickel in Europe. Even though production scrap will be an important source of recycled battery materials in the short term, it is assumed that it will be surpassed by EoL batteries as the main recycling input in the long term.

5. Discussion

This article advances prior circularity research by calculating the regional break-even points for critical and strategic important raw materials (lithium, cobalt, nickel) in China, Europe, and the US. The results show that China will be the first to achieve independence from primary battery raw materials, doing so more than ten years earlier than Europe and the US for lithium and nickel and more than seven years earlier for cobalt. The difference between China and the rest of the world is driven by the rapid electrification of the Chinese automotive market, the focus on LFP as the dominant battery technology, and an expected early industrialization of non-lithium-containing chemistries.

Nevertheless, covering the demand for EV battery materials, especially lithium, remains a major global challenge. The five levers included in this study show that faster electrification of car sales in Europe and the US can accelerate full coverage of cobalt and nickel from secondary materials. Policymakers and industry may therefore consider actions to increase EV sales, e.g., reducing battery costs (Mauler et al., 2021), scaling up production processes, or accelerating the implementation of low-cost technologies such as LFP and SIB.

Demand for battery materials can also be reduced by lowering average battery sizes. This leads to significantly earlier BEPs, especially for critical cobalt. Sufficient charging infrastructure, lighter EVs, battery technology that allows for faster charging, or battery-swapping business models can enable the use of smaller battery sizes.

Another way to reach BEPs faster is by only selectively applying 2nd use for spent EV batteries. Especially for valuable high-performance metals such as cobalt and nickel in NCA and NMC, it seems reasonable not to adopt 2nd use applications (e.g., stationary systems). However, for low-performance and low-cost LFP and SIB, 2nd use is likely to be more effective because of the abundance and inexpensiveness of materials such as iron. This suggests a role for re-collection and post-EV life application regulation, as is currently being considered by the EU (European Commission, 2020).

In this study we present optimal numerical results for reaching and accelerating a circular economy for lithium, cobalt, and nickel in EVs in China, Europe, and the US. Key driver is that regional battery recycling capacity needs to be expanded in line with battery production and EV sales. Additionally, battery recycling must guarantee the quality of secondary materials in order to ensure replacement of primary materials (Sommerville et al., 2021; Rajaeifar et al., 2022).

However, this study is not without limitations, but these limitations may present opportunities for future research. This study focused on lithium, cobalt, and nickel as raw materials because these three are considered most critical, but future research may include additional raw materials, such as manganese. Furthermore, this study assumed that recovery materials can replace primary raw materials in a 1:1 relation. Given this is the first study to model regional BEPs and levers to reach the BEPs earlier, this assumption seems justified, but it is a simplification. Future research is encouraged to further develop the model presented in this study by considering how the quality of secondary raw materials impacts recyclability and thus the potential to (fully) replace primary materials.

With respect to the modelling approach, there are further limitations that can be addressed by future studies. For example, recycling and collection rates are assumed that represent complete return of EoL batteries without losses into the value chain. Regulations, such as those in the EU (European Commission, 2020; Neumann et al., 2022) do specify future rates, but nevertheless circular business models for collection and recycling of EV batteries are strongly influenced by other factors such as price development of primary raw materials, costs of reverse logistics for EoL batteries, and the costs of recycling processes. Future studies can incorporate these additional factors for supply and demand of EoL batteries and recycling into the model. Furthermore, this study assumed that 2nd use rates will increase to a high level, which implies a high future demand for batteries in stationary storage and other applications. Based on this model, the future demand for 2nd use can be further integrated with respect to the battery technologies considered in order to model an accurate picture of the complex material flow of batteries after EV life.

Another limitation concerns the future technology scenarios. While the choice of these scenarios is grounded in prior research, especially the emerging and optimized recycling of cobalt, and thus the increasing independence from critical cobalt supply chains, can cause this high-performance raw material to become more attractive again and influence technology scenarios. Future research may hence conduct a dynamic sensitivity analysis of the technology scenarios presented in this study to incorporate future changes in battery technology trends.

Furthermore, as seen in the reaction to the Russia–Ukraine crisis, regional and international developments can influence national and international regulations. Recently, and similarly to Indonesia's announcements for domestic nickel processing (Cabinet Secretariat of the Republic of Indonesia, 2021; CNBC, 2022), the US initiated the Reduced Inflation Act aiming at strengthening the national battery and EV industry (Inflation Reduction Act Guidebook, 2022). This can affect battery policy and industry in Europe and China. Future studies can therefore include scenarios for the development of international policy trends to show how these affect the regional development of circular EV supply chains. Future research can also consider potential downcycling as well as how potential regional restrictions to manufacture EV batteries with secondary raw materials impact levers and BEPs. Finally, future research can model BEPs on a federal state or province level (e.g., California, Guangdong) or even a local level (e.g., comparing cities).

6. Conclusion

In this study, the BEPs of full secondary material coverage of lithium, cobalt, and nickel for EV battery demand in Europe, the USA and China are identified by a dynamic MFA approach. The results show that in all scenarios, China will be the first to realize a circular battery value chain, doing so more than ten years earlier than Europe and the US for lithium and nickel and seven years earlier for cobalt. However, reaching the BEPs for lithium will be the main global issue in the next decades. Based on this, five levers to accelerate reaching these break-even points are proposed and each impact on the different regions and metals is examined. According to the findings, policymakers thus need to continue to set effective and supporting regulations to help companies establish viable and sustainable business models for circularity. Early full electrification of sales, a technology selective application of 2nd use and a reduce of EV battery size in time are options to make future batteries and supply chains more sustainable and circular earlier.

CRediT authorship contribution statement

Jannis Wesselkämper: Conceptualization, Formal analysis, Visualization, Methodology, Writing – original draft, Writing – review & editing. **Laureen Dahrendorf:** Methodology, Writing – original draft. **Lukas Mauler:** Conceptualization, Methodology, Writing – original draft. **Simon Lux:** Writing – original draft. **Stephan von Delft:** Writing – original draft, Writing – review & editing, Supervision.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.107218.

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