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Forecasting the Global Battery Material Flow: Analyzing the Break-Even Points at Which Secondary Battery Raw Materials Can Substitute Primary Materials in the Battery Production

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Citation: Neidhardt, M.; Mas-Peiro, J.; Schulz-Moenninghoff, M.; Pou, J.O.; Gonzalez-Olmos, R.; Kwade, A.; Schmuelling, B. Forecasting the Global Battery Material Flow: Analyzing the Break-Even Points at Which Secondary Battery Raw Materials Can Substitute Primary Materials in the Battery Production. *Appl. Sci.* **2022**, *12*, 4790. https://doi.org/10.3390/app12094790

Academic Editors: Julia Kowal and Daniela Chrenko

Received: 12 April 2022
Accepted: 4 May 2022
Published: 9 May 2022

Abstract: Growing numbers of electric vehicles (EVs) as well as controversial discussions on cost, scarcity and the environmental and social sustainability of primary raw materials that are needed for battery production together emphasize the necessity for battery recycling in the future. Nonetheless, the market for battery recycling is not fully understood and captured in data today. The underlying reasons are found in both market size and various parameters such as the battery-technology mix, the resulting material demand and expected battery lifetime. In consequence, the question of when secondary-material availability from battery recycling is sufficient to satisfy the global cobalt demand for EV applications has not yet been clarified. To address this question, this study estimates the global battery raw-material demand together with the expected amount of the recycled materials by 2035, taking into account a number of parameters affecting future battery material flows. While focusing on cobalt, nickel, lithium, and manganese, the results indicate that the global cobalt demand can be satisfied from secondary sources by the early 2030s in three out of four different technology forecast scenarios. Furthermore, a sensitivity analysis highlights the amount of waste occurring during battery production and battery lifetime as the main drivers for secondary-material availability by 2035.

Keywords: battery recycling; material-flow analysis; lithium-ion battery; automotive; secondary raw material; circular economy

1. Introduction

The growth of electric-vehicle (EV) sales observed today is expected to continue in the upcoming years in order to achieve a decarbonization of the transport sector [1,2]. In this regard, the battery represents a large share of both the cost and weight of an EV [3]. At the same time, EV batteries are subject to ongoing discussions regarding the environmental and social impacts of the mining and production stage, as well as potential supply risks resulting from a scarcity of the required resources [4]. Especially the raw materials of the cathode are controversial due to their sensitivity to geopolitical market trends, as well as the required infrastructure for an efficient treatment and recovery at the end of life (EoL) [5].

More specifically, the battery raw materials that are considered critical in terms of supply risks are cobalt (Co), nickel (Ni), and lithium (Li) [6]. Additionally, Manganese (Mn) is a key material for the electrification of the transport sector and is therefore also included in the scope of the present study. In many cases, the extraction of materials is linked to environmental impacts on local ecosystems, e.g., water use for the extraction of Li from brines or hard-rock mining, as well as soil contamination related to the high-pressure acid leaching for Ni extraction. Elsewhere, studies referring to social risks in relation to battery raw materials state that almost two thirds of the Co extraction required for batteries comes from the Democratic Republic of the Congo (DRC) and can entail risks of child labor or artisanal small-scale mining [7].

Furthermore, some materials are subject to ongoing price fluctuations, showing frequent peaks associated with the increase in EV sales volumes. As stated in an EU study, price volatility from 03/17 to 02/18 has been significant for battery raw materials: 21.7% for Co, 17.2% for Li, and 22.2% for Ni [8]. This is mainly due to the long timeframes needed to increase raw-material production, combined with the limited number of mining companies in control of market supply. Consequently, both price volatility and availability are key factors for the criticality of battery raw materials. This is similar to platinum in fuel-cell vehicles [9].

In order to address the abovementioned challenges, battery recycling is considered a strategy to establishing an increasing supply of secondary raw materials for battery production, thereby minimizing the need for primary raw materials. Recycling is thereby part of the ambition of implementing a circular economy (CE) for batteries. The concept of a CE has established the principle of "keeping products, components, and materials at their highest utility and value at all times" in scientific sustainability research and in industry [10,11]. In this regard, batteries and vehicles are mentioned as a key product value chain in the EU Circular Economy Action Plan 2020, indicating that political action towards waste prevention, reuse, and recycling of batteries is needed [11]. At the same time, legislation encourages automotive original equipment manufacturers (OEM) to actively engage in the EoL management of batteries as part of their ambitions towards extended producer responsibility (EPR) and beyond minimum regulatory requirements [12,13]. Driven by the notion of a CE as a vessel for the sustainability performance of products, reduced material consumption, and economic profitability [14], several companies have started to investigate the benefits of circular strategies for lithium-ion batteries (LIBs) [15]. Here, the recycling and recovery of materials represents one of the key action fields for OEMs when implementing a CE for LIBs [16].

Meanwhile, the recycling industry for LIBs is still in the early stages of development. Currently, there are only a few established recycling companies, and the recycling methods primarily focus on pyro-metallurgical recycling, whereas other efficient methods such as mechanical-hydrometallurgical recycling are still lacking (see Figure 1). A main factor for the slow evolution of the recycling industry is low volumes, hindering the business case for implementing highly efficient recycling methods at scale. Here, the number of batteries available for recycling determines the feasibility of investing in innovative recycling facilities.

Moreover, the materials used for LIB production today determine the economic benefits of battery recycling in the future. In a previous study, different rollout scenarios for cell chemistries until 2030 have been identified [17]. In order to account for these scenarios, the objective of the present study is to simulate the secondary-raw-material supply from battery recycling in relation to the expected global demand for battery materials. The underlying goal is to identify challenges and opportunities for both automotive manufacturers and the recycling industry in satisfying future battery demands for the transition towards e-mobility. To achieve that, the simulation is based on validated and industry-wide market forecasts and takes into account relevant parameters that can be addressed by practitioners in the industry.

Company	pyro-metallurgy	hydro-metallurgy	mechanical recycling
ACCUREC			X
AEA Technologies Inc.		X	
BATREC	X		X
Chemetall		X	
CRISOLTEQ fortum		X	
Duesenfeld		X	X
eramet			X
ERLOS			X
GLENCORE	X		X
Nickelhuette Aue	X	X	
REDUX			X
SNAM	X		
umicore	X	X	
VEOLIA		X	

Figure 1. List of LIB-recycling companies in Europe (data based on published sources [12,18] (ERLOS), [19] (Nickelhuette Aue)).

2. Materials and Methods

Based on the outlined challenges and knowledge gaps, the goal of the present study is to address the following research question: When is the availability of secondary Co, Ni, Li or Mn from LIB recycling sufficient to satisfy the global cobalt demand for EV applications?

In order to arrive at an answer to this question, we firstly determine the global demand for the materials in scope, taking into account different rollout scenarios in terms of battery chemistries. Afterwards, we calculate the expected number of LIBs entering recycling between 2020 and 2035 worldwide. Based on the results, we determine the break-even point of global material demand and available secondary materials. Finally, we analyze and discuss the effects of different modelling parameters on the available LIB quantities for recycling as part of a sensitivity analysis and derive implications for the future recycling industry.

For the calculations, we use an Excel-based simulation tool which allows to adopt different sources of EV battery-technology forecasts and to adjust specific input parameters. For each scenario, we used verified data sources (see Appendix A) in order to estimate the amount of recovered LIB materials. In this respect, the following input factor categories have been identified and integrated in the simulation tool:

- The number of battery electric vehicles (BEVs), plug-in electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs) can be varied between different market projections by Bloomberg, IHS and a mixture of T&E, IEA, etc., [20–24].
- The regional split can be adjusted between worldwide, Europe, NAFTA, China, and the rest of the world. The split is based on annual regional shares as defined by Bloomberg [20].
- The average battery capacity for BEVs, PHEVs, and FCEVs has been calculated as the average of the EVs available in 2019 [25].
- The LIB lifetime can be varied between 8 and 15 years with a standard value of 10 years being assumed as a baseline. Although this value exceeds the average warranty period of 8 years defined by several OEMs, it can be considered a pessimistic assumption,

given that further development in battery technology to prolong battery lifetime is expected in multiple studies [26–28].

Generally, it is necessary to define the percentage of batteries returning from the market, i.e., the vehicle owners, and enter a recycling process. As a baseline, we assume that all batteries return and enter a recycling process, thereby neglecting that a certain share of market losses can occur. Furthermore, based on statistics by insurance companies such as HUK-COBURG [29] we assume that a share of 1% of all batteries is damaged during lifetime and thus enters recycling before reaching their EoL.

In addition, another input parameter is the number of batteries entering a repurposing process. Battery repurposing—also called battery 2nd life—describes the possibility of further using batteries in stationary applications at the end of their useful life in the vehicle [30]. Battery 2nd life thereby extends the lifetime of the battery before reaching the EoL and entering the recycling stage, and thus needs to be included in the simulation. In this regard, Bobba et al. assumed a 20% repurposing rate in Europe in 2030 [31]. Elsewhere, Richa et al. assumed a 10% share of batteries entering 2nd life for LMO batteries [32]. Taking into account uncertainties regarding the adoption of battery 2nd life at scale, a pessimistic repurposing rate of 5% was initially assumed in this study [33]. Furthermore, the effect of the parameter was critically assessed as part of the sensitivity analysis.

Moreover, besides EoL batteries returning from the market, we include two additional sources of batteries that directly enter recycling: firstly, a fixed share of production waste occurring at battery-production facilities, and secondly, pre-serial samples occurring at OEM's testing facilities. For both together, we define a constant share of 2% of the battery production, which is based on previously published data [34,35]. While the share of production waste at the time of this study can be assumed to be higher, significant efforts to reduce the scrap rate at the LIB-production stage justify this assumption. Meanwhile, we assume that scrap occurring at the cell-production stage is also directly reused locally and is thus not considered as recycled material.

Lastly, the key driver of the effectiveness of providing secondary raw material is the selection of the recycling method. In this case, the efficiency rates per raw material for the applied recycling methods are modelled as part of the simulation [1,36–38]. The combination of a mechanical and a hydrometallurgical recycling process promises the highest efficiency rates to recover up to 99% for Ni and Co, 100% for Mn, and 94% for Li, which together correspond to the range of 90–100% found by Mathieux et.al. [3,36,38]. The recycling yield in general, i.e., for all battery materials as discussed by Diekmann et al., can reach up to 75% [39]. Meanwhile, several research projects and new recycling companies are using a mechanical-hydrometallurgical battery-recycling process. In addition to reaching higher recycling efficiencies, this process is characterized by a lower carbon footprint due to lower energy demand [40–42]. Therefore, this method is used as the preferred process in the simulation.

In order to answer the research question, we obtain different results from the simulation:

- The number of batteries entering recycling in GWh per cell chemistry and per year.
- The amount of recovered material in metric tons in total per year and in tones for Co, Ni, Li, and Mn per year.
- The projected demand for batteries in GWh and in tons per year.

Regarding the analyzed scenarios, the study follows the approach taken by Mas-Peiro et al. of differentiating between four possible scenarios for premium OEMs using high-energy cell chemistries of LIBs [17]. The base scenario A assumes a LIB chemistry with Ni, Mn and Co in the proportion 6-2-2, called NMC622, as major technology in the early 2020s. The scenario includes NMC622 as the preferred chemistry today, with NMC811 being used in 2024/2025 and NMC9055 beginning to play a role from 2025 onwards.

While being used as a baseline, it needs to be mentioned that Scenario A represents an ambitious uptake of novel battery cell chemistries before 2030. Therefore, other scenarios need to be taken into account, which describe less favorable adoption rates of new technologies. In this regard, the "high Mn scenario B" assumes that NMC9055 is substituted with high energy NMC (HE-NMC). Furthermore, the "Co scenario C" assumes that NMC622 remains the mainstream for a longer time and is replaced by NMC811 only in 2030. As the last alternative, the "NCA scenario D" assumes that NMC811 is substituted with a currently used NCA chemistry [43].

Together, these rollout scenarios for premium OEMs (different NMC and NCA chemistries) are combined with other expected cell technologies, e.g., LFP, LMNO, LMO, and LMnP [44]. The resulting battery-technology rollout is presented in Figure 2. Additionally, Table A1 provides a summary of the data sources used in the material-flow analysis.

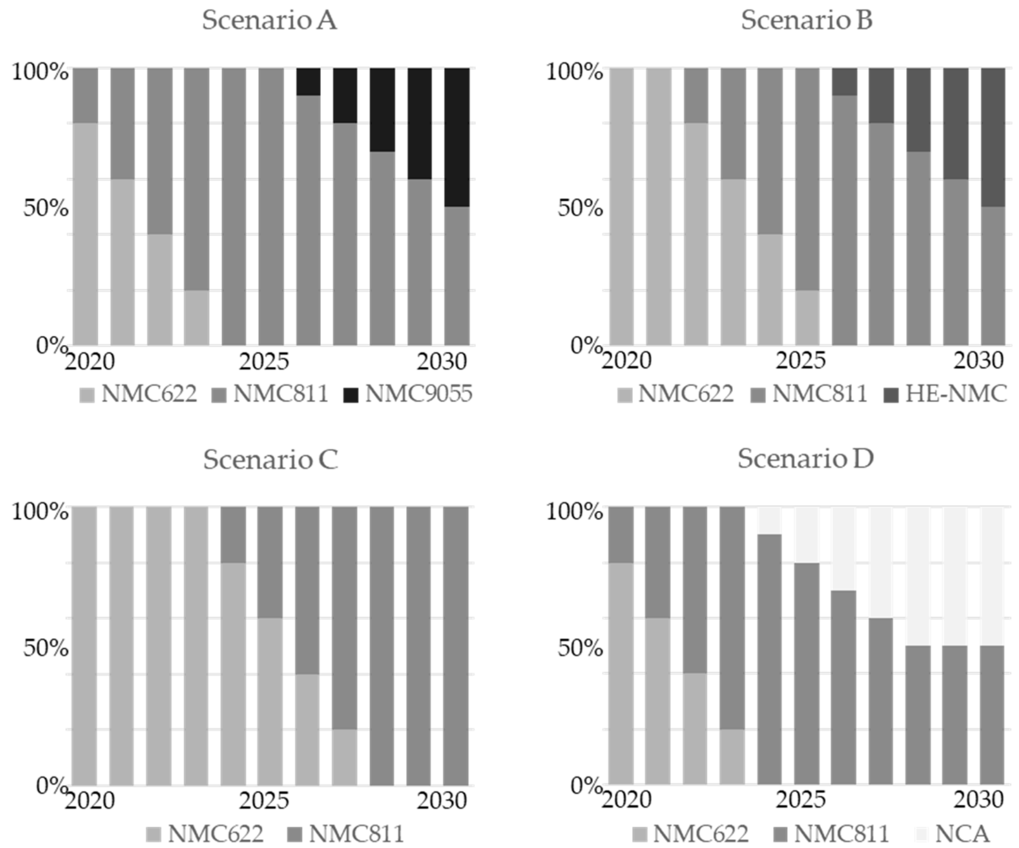


Figure 2. Four scenarios for cell-chemistry rollouts in the premium segment (data based on published study [19]).

The main goal is to determine the break-even points of the annual material demand and secondary-material availability. For that, we define the following parameters.

The material demand weight (D) is calculated for each year (i) and each critical raw material (j), as follows (see Equation (1)): the projected number of vehicles per year (V_i) is multiplied by the material weight per vehicle for each raw material (M_j), depending on the vehicle type. Additionally, the demand for testing and certification (T) is also multiplied by the material weight per vehicle (M_j). The sum of both parts will result in the material demand per year and per raw material:

$$D_{i,j} = V_i \times M_j + T \times M_j. \quad (1)$$

The available secondary raw material, i.e., the mass of material recovered from recycling (W), is calculated as shown in Equation (2). This includes the amount of material recovered from used vehicles—after the battery lifetime (LT)—and the amount of material recovered after the 2nd life. The material recovered from used vehicles is calculated using the battery demand (D) of the corresponding year to determine the number of LIBs that return from the market (B). From that, we subtract the number entering 2nd life (S) and the amount of production waste (P). The material recovered after 2nd life is calculated by multiplying the repurposed LIB quantities of the corresponding year ($S_{i\text{-}LT\text{-}10}$) with the amount of material used per vehicle type (M_j). The resulting amount is then multiplied by the efficiency of the recycling process of each material (E):

$$W_{i,j} = (V_{i-LT} \times M_j \times (B - S - P) + T \times M_j + S_{i-LT-10} \times M_j) \times E_j. \quad (2)$$

Additionally, in order to validate the robustness of the input data and verify the results, a sensitivity analysis is conducted. For that, we adjust selected input parameters, which can affect the number of batteries entering recycling and thereby potentially reduce the cumulated available secondary materials. These parameters include battery lifetime, 2nd life rate, batteries entering recycling and the scrap rate at battery-production stage.

3. Results

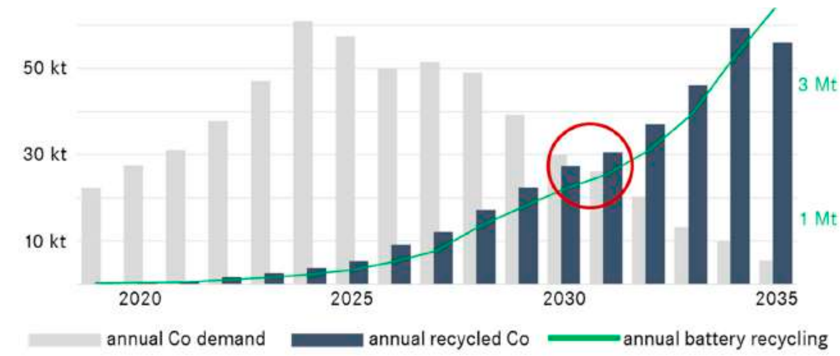
The results of the simulation firstly indicate that the number of LIBs entering recycling is characterized by an ongoing increase starting in 2025. Based on the chosen scenario, the calculated global cumulated supply of recycled batteries amounts to approximately 5 Mt until 2030, which corresponds to about 650 GWh. The main cell chemistry that will be recycled until 2030 is NMC technology in all scenarios, thereby dominating the battery-recycling market. Based on the results, the following amounts of secondary cathode materials are expected globally until 2030: 103 kt Co, 344 kt Ni, 71 kt Li and 152 kt Mn.

3.1. Break-Even Analysis

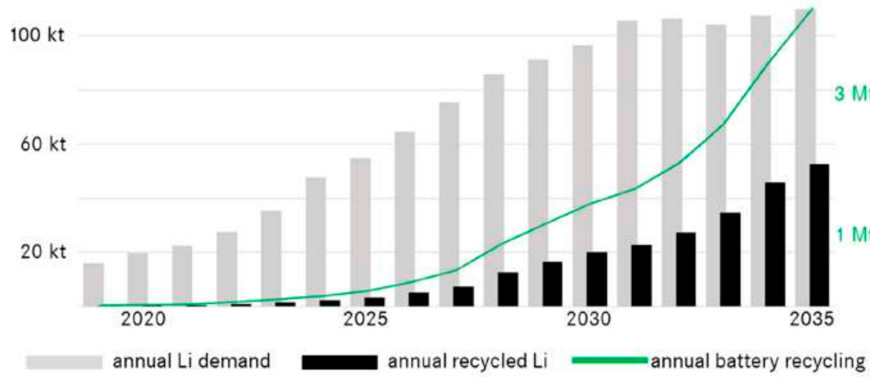
In response to the research question of when the availability of secondary Co, Ni, Li or Mn from LIB recycling is sufficient to satisfy the global cobalt demand for EV applications, the results show that secondary Co supply will be sufficient to start satisfying the demand between 2029 and 2035. This is under the assumption that a closed material loop for batteries is implemented by that time (see Figure 3a).

For the remaining materials, the secondary-material supply is not sufficient to cover the material demand for new battery production. Instead, the gap between secondary-material availability and material demand is increasing for Li and Ni and in all scenarios. Here, Ni shows the highest total demand (see Figure 3b,c). This can be linked to the increasing use of LIB cell chemistries with high contents of Ni and Li as part of the battery-technology rollout. This means that the amount of recycled material for Li and Ni cannot match the demand for new batteries if the EV development continues as forecasted. A similar trend can be observed for the less critical material Mn (see Figure 3d).

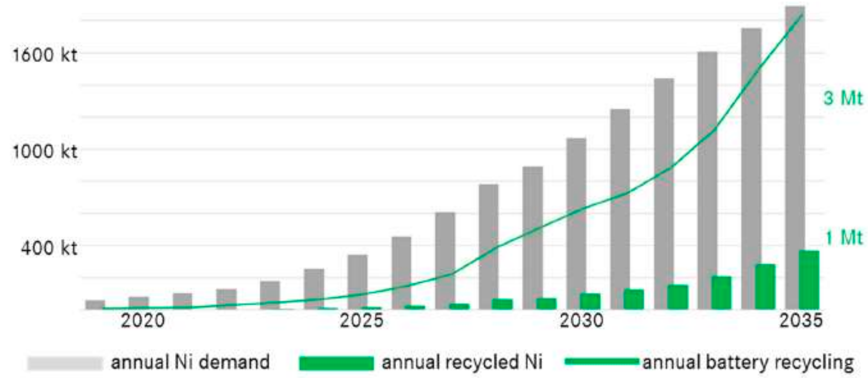
Furthermore, the results obtained for the other technology-rollout scenarios indicate that the supply of secondary Co can satisfy Co demand at the earliest in 2030 (Scenario A) and the latest in 2035 (Scenario C) (see Figure 4). Meanwhile in Scenario D, no break-even point is observed for the secondary-material availability and the projected material demand. This can be explained by the rising Co demand, which results from the LIB cell chemistries used in the technology rollout in Scenario D.



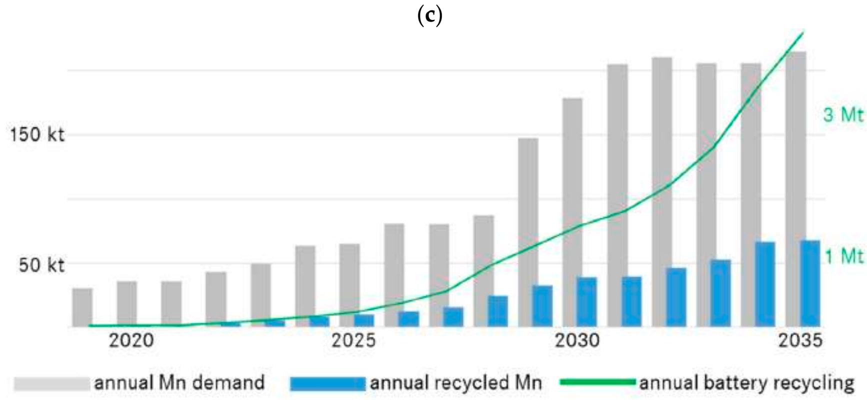
(**a**)



(**b**)



(**c**)



(**d**)

Figure 3. Raw-material demand vs. availability of secondary raw material worldwide and total annual battery recycling in green all in t; (**a**) Cobalt with intersection marked in red; (**b**) Lithium; (**c**) Nickel; (**d**) Manganese.

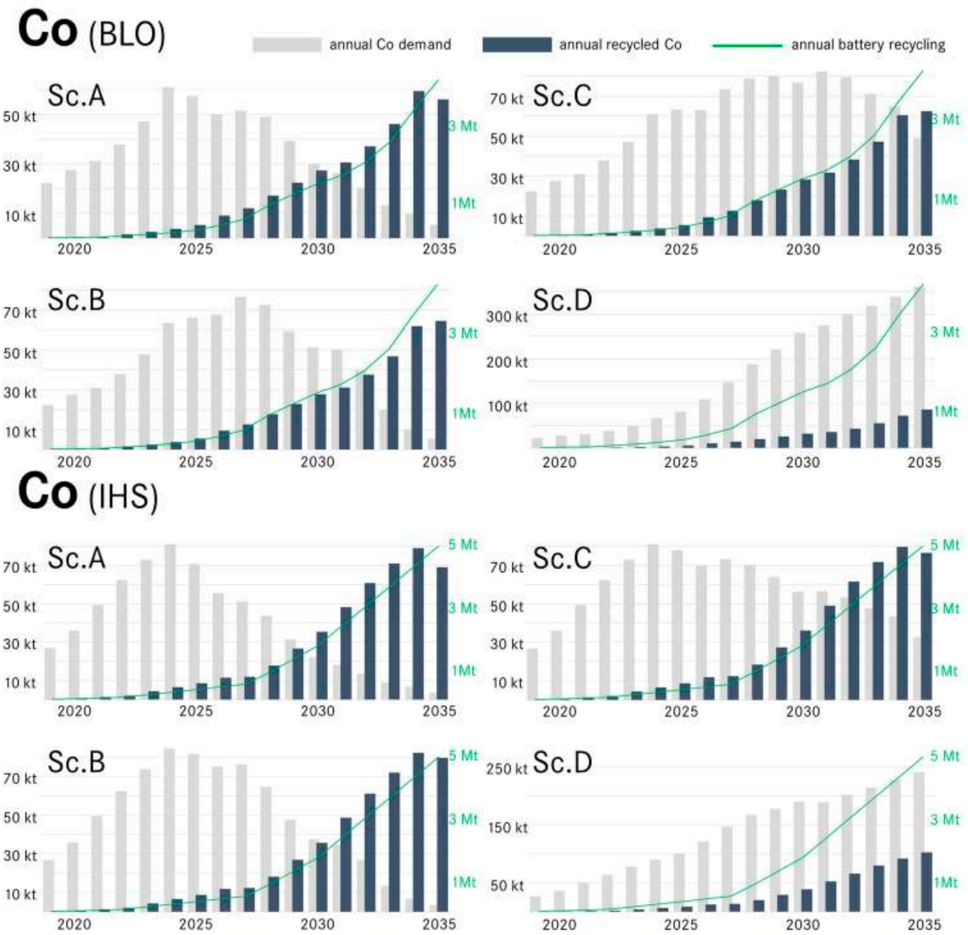


Figure 4. Comparison of scenarios (Sc) regarding cobalt (Co) trend with Bloomberg (BLO) and IHS forecast.

At the same time, none of the other materials in the scope of the study show an intersection of secondary-material supply and demand before 2035 in any of the scenarios investigated. This again is under the following assumptions: worldwide scope, 10 years battery lifetime, 5% 2nd life rate, 1% failure rate before warranty lifetime, 2% production waste and mechanical-hydrometallurgical recycling.

3.2. Sensitivity Analysis

The aim of the sensitivity analysis is to determine the effect of the selected parameters on the cumulated amount of secondary material available, thereby validating the robustness of the results [45]. These are selected due to the uncertainty in either the current assumptions, or in the potential development of the parameters in the future.

The analysis is based on the following parameter variations, which potentially reduce the amount of recoverable LIB materials in different ways:

- Increasing LIB lifetime by 10%, i.e., 11 years instead of 10 years, thereby delaying LIB recycling.
- Increase the share of LIB entering 2nd life from 5% to 15%, thereby reducing the number of LIBs available for recycling.
- Reducing the share of LIBs entering an efficient hydrometallurgical recycling process by 10%. These LIB instead enter a less efficient pyro-metallurgical recycling, leading to a lower amount of recovered material.
- Reducing the amount of production waste by 10%, thereby lowering the number of LIBs entering recycling.

The results are presented in Figure 5. These firstly indicate that increasing the LIB lifetime by 10% leads to a reduction of the cumulated recoverable material by 15,072 tons (or 15%) compared to the base case. Secondly, increasing the share of LIBs entering 2nd life causes a reduction of 9706 tons (10%). Thirdly, reducing the number of batteries entering recycling leads to a similar reduction of 9706 tones. Lastly, decreasing the production waste by 10% leads to a reduction of 52,452 tones (49%). Consequently, the sensitivity analysis reveals that the production waste and the battery lifetime have the highest impact on the cumulated amount of recovered material, followed by the recycling method, i.e., the share of hydrometallurgical recycling. Since the amount of production waste follows the growth in battery demand and dominates the LIB quantities directly entering recycling, the adjustment of this parameter has the highest impact on the availability of secondary materials. The analysis is carried out only for Co, given that it is the only material for which an intersection of secondary-material supply and demand can be expected.

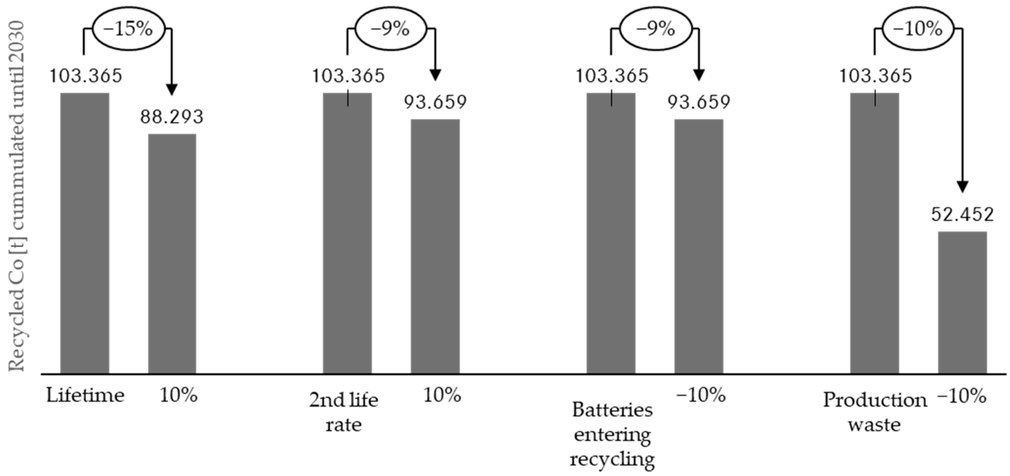


Figure 5. Sensitivity analysis to assess the impact of different parameters on the cumulated amount of recovered cobalt from battery recycling until 2030.

Based on the results, the sensitivity analysis shows how the availability of secondary materials from LIB recycling until 2035 is largely driven by the amounts of production waste. On the one hand, production waste is considered so-called "post-industry waste", which cannot be interpreted as an improvement in waste management and EoL operations for BEV. On the other hand, the results imply that improvements in LIB production process efficiency, which reduce the amount of waste occurring at the production stage, will reduce the amount of available secondary material. Consequently, using the amount of secondary LIB materials as a performance indicator in a CE does not incentivize measures for waste reduction in the first place. Therefore, automotive manufacturers and LIB producers additionally need to apply other metrics in order to measure and stir the material circularity of their products.

4. Discussion

In order to verify the assumptions made, a comparison of the results with other existing projections of battery material demand is conducted. Here, Bloomberg predicts that battery demand will reach 1460 GWh in 2030 [20], which is similar to the result of 1531 GWh obtained in this study. Furthermore, Bloomberg calculates a projected Co demand of 64 kt for the year 2024, which corresponds well with the 61 kt obtained in the simulation. Furthermore, the results obtained for the recycled Co in Europe in 2030 of roughly 6 kt match the findings by Bobba et al. [31].

Compared to the results of previous studies such as Reuter et al. [1] or Sauer et al. [46], the simulated results for recycled Co in the present study differ. This is due to the fact that a specific cell-chemistry rollout has been assumed in this study, whereas Reuter et al.

have assumed NMC111 and LFP exclusively. Additionally, different vehicle forecasts have been implemented in the present study. Moreover, Reuter et al. calculate that in 2030, Co demand will be appr. 200 kt while the amount of available secondary Co will amount to 100 kt in 2030 [1].

Meanwhile, a study by Baltac estimates that the capacity for LIB recycling with 33 kt of batteries per year in the EU would not be enough to cover the demand [47]. The study estimates that the demand will increase to almost 100 kt of batteries in 2040. Drabik et al. forecast a quantity of 1,163,500 EoL batteries, which corresponds to a capacity of 46.5 GWh in the EU in 2030 [26]. Within the LithoRec project, a quantity of 22,500t EoL batteries has been calculated for Germany in 2030 [48], while an EU Recycling specialists journal projects 15 kt of LIBs to be recycled in 2030 [49]. At the same time, Umicore, a recycling company, estimates that 75 kt of batteries were already at their EoL before 2019 and need to be recycled [50]. Generally, these figures indicate that recycling forecasts for LIBs exist; however, the estimates significantly differ depending on the scope, data sources used, as well as assumed battery technologies and other parameters. Therefore, future studies should provide updated calculations and challenge the assumptions made for LIB recycling on an ongoing basis in order to provide robust and precise projections on secondary-material availability.

Furthermore, future research should take into account that due to innovation in battery technology, the assumptions on battery size in terms of capacity and weight can be subject to changes, depending on the vehicle segment and cell chemistry. Additionally, the material compositions should be adjusted for the different types of vehicle (BEV, PHEV, FCEV) and the non-plug-in batteries should be added. Moreover, the rate of the batteries exceeding the assumed lifetime of 10 years should be further analyzed, together with the increasing risk of market losses, i.e., batteries that do not find their way into professional recycling facilities. Lastly, the rollout of different recycling methods and corresponding improvements in achievable recycling rates and material qualities should be closely monitored.

In this study, the focus was only on automotive battery demand. However, it might also be reasonable to consider material flows from other industries that share the recycling path of automotive batteries. For that, integrating battery-recycling initiatives across industries could enable companies to jointly increase recycling-market capacities and to share the investment costs. This should be analyzed in further studies.

Moreover, and in the context of a CE, remanufacturing describes the process of refurbishing a product towards the same properties as the original one [51]. It thus represents another strategy to further use LIBs at their EoL. Similar to repurposing, it affects the inputs and outputs of battery recycling. While the potential of implementing LIB remanufacturing at scale is difficult to quantify, its effects on future EoL flows for LIBs require further research and should be analyzed in detail.

Another aspect linked to the adoption of a CE is that in the present study, the amount of secondary raw materials available has been calculated without taking into account battery costs as well as environmental impacts. Here, the implications of future recycling markets on the reduction in GHG emissions in a CE are not fully transparent and need further research, as suggested in previous studies [52]. In this regard, it has also been assumed in this study that the implementation of a CE for LIB leads to a so-called "closed-loop production", meaning that the secondary raw material is suitable for use in the production of new batteries in terms of purity and other material properties. This should be validated in future studies, and supported in corresponding legislation such as the EU battery directive [13], as also mentioned in the findings of the Circular Economy Initiative Deutschland [53]. Additionally, more work is needed to investigate how the results on secondary-material availability in a closed-loop production can be used for decision making in a CE in the context of organizations, e.g., at automotive manufacturers.

Lastly, the simulation uses various sales projections by established providers of market forecasts. These sales projections are the basis for the results of the present study and are mostly based on retrospective data, political goals, industry analytics or expert interviews.

Meanwhile, no studies exist to our knowledge that analyze the influence of the consumer behavior on the vehicle EoL and thus on the recovery rates for LIBs, thus representing a starting point for future research.

5. Conclusions

Battery recycling is a mandatory task along with the electrification of the transport sector. Therefore, providing methods for assessing the availability of secondary materials is a necessary task in order to address issues related to supply risks, environmental sustainability and costs.

In this regard, the present study provides a quantification of the cumulated supply of battery materials from secondary sources between 2019 to 2030, which in total amounts to appr. 5 Mt. In response to the research question, we find that the available secondary Co from LIB recycling is sufficient to satisfy the Co demand for EV applications in the early up to mid-30s. By observing different technology-rollout scenarios, this finding can be linked to the reduced Co share in future battery technologies. For the other raw materials, Li, Ni and Mn, no intersection between material demand and availability of secondary material is found before 2035. Furthermore, the sensitivity analysis reveals that the parameters with the highest impact on the availability of secondary materials are the production waste and the battery lifetime.

From a CE perspective, the results thereby underline the potential of EV battery recycling to reduce the dependency on primary-resource extraction by keeping materials at their highest value at all times. This emphasizes the importance of effective legislation and policy making towards a CE, which supports the adoption of highly efficient battery recycling and the implementation of a closed-loop production. While focusing on the potential for reducing primary-material consumption for the production stage of new batteries, our findings suggest that more work is needed to investigate the relationship between recycling and other CE strategies for batteries such as remanufacturing and repurposing (2nd life). In this context, the results show how companies such as OEMs need to navigate between different CE strategies when managing battery EoL flows and the resulting secondary-material supply. Consequently, future research should investigate how other performance indicators can be used in order to maximize the material circularity of the company as a whole.

Moreover, the results of the present study indicate that for the case of Co, combining measures for reducing the amount of Co by deploying new battery technologies with an increase in efficient recycling processes provides a feasible pathway for establishing a closed material loop. In order to make this possible and to find similar opportunities for other raw materials, efforts should be dedicated to both product development for LIBs and the upscaling of global recycling infrastructures, especially for the time beyond 2025. This would reduce the environmental and social impacts associated with LIB production, as well as the dependency on the price fluctuations of critical battery materials. Furthermore, strategic procurement activities are recommended for Li and Ni, given that the future material demand cannot be fully satisfied by secondary sources.

Finally, future studies should focus on measures for reducing battery-production waste and increasing battery lifetime, thereby ensuring a more sustainable use of battery raw materials in general. Here, including waste streams from other industries and markets, e.g., electric trucks, stationary batteries, etc., in future studies seems to be a promising avenue of research, which would allow a more holistic view on the potential for implementing a CE for batteries.

Author Contributions: Conceptualization, M.N.; methodology, M.N. and B.S.; software, M.N.; validation, J.M.-P. and M.S.-M.; formal analysis, M.N., M.S.-M. and J.M.-P.; investigation, M.N. and J.M.-P.; resources, M.N.; data curation, M.N.; writing—original draft preparation, M.N.; writing—review and editing, J.M.-P., J.O.P., R.G.-O., A.K. and B.S.; visualization, M.N. and J.M.-P.; supervision, B.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

Acknowledgments: IQS researchers that participated in this study are in the GESPA group (J. Mas-Peiro, J. O. Pou, R. Gonzalez-Olmos) which has been recognized as Consolidated Research Group by the Catalan Government with code 2017-SGR-1016.

Conflicts of Interest: Jordi Mas-Peiro, Magnus Schulz-Moenninghoff and Michael Neidhardt declare a relationship with Mercedes-Benz AG due to employment. The funders had no role in the design of the study or the interpretation of the results. The views presented in this article reflect the opinions of the authors and do not represent the position of Mercedes-Benz AG.

Appendix A

Table A1. Summary of sources per section used in the simulation.

Vehicle forecasts	Bloomberg BNEF [20], IHS MarkitInsight [21], Mix (transportenvironment [22], IEA [23], Statista [24])
Region split	[20]
Average size of batteries	[25]
Lifetime analysis	[26]
2nd life	[24,31,32]
Percentage of EV accidents with battery damage	[29]
Percentage for production waste and testing	[34,35]
Recycling method (efficiency)	[1,36–38]
Material data	[1,22,46,54,55]
Rollout scenarios	[19]

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