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Material bottlenecks of batteries within the energy transition

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ABSTRACT

The growing adoption of electric vehicles has significantly increased demand for advanced energy storage solutions. Lithium-ion batteries are at the forefront, primarily used in electric vehicles and increasingly in stationary renewable energy storage systems. However, their reliance on critical resources has spurred research into alternative cathode materials and next-generation battery types. Since it is unclear whether such advances can offset expected material shortages, we assess whether global reserves, production, and recycling capacity can support the projected battery growth. Based on IPCC scenarios up to 2050, our analysis shows that even under optimistic assumptions, the planned battery expansion in the *Sustainability* and *Middle of the Road* scenarios cannot be achieved. Excluding recycling would lead to a 33% increase in cumulative primary material demand, exacerbating supply risks and resulting in greater underproduction. These findings underscore the importance of expanding recycling, second-life, and production infrastructure, as well as pursuing a diversified technology strategy.

1. Introduction

As part of the transition to a low-carbon economy, energy storage technologies are becoming increasingly important to balance variable renewable energies (International Energy Agency, 2024a). At the forefront of this are batteries, currently especially lithium-ion batteries (LIB), which are mainly used in electric vehicles and stationary energy storage systems (International Energy Agency, 2024a). However, LIB face severe material challenges as they contain critical materials, such as cobalt, lithium, nickel and graphite (International Energy Agency, 2021), potentially limiting the huge capacity expansion required to achieve greenhouse gas neutral energy systems (International Energy Agency, 2021). Therefore, research into new cathode types for LIB, away from high cobalt contents in the cathode (International Energy Agency, 2021), as well as post-lithium-ion battery (Post-LIB) technologies, such as sodium-ion (International Energy Agency, 2024a), lithium-sulfur (Deng et al., 2017), and solid-state batteries (International Energy Agency, 2024a), have attracted much attention in recent years.

For lithium-ion batteries, numerous studies have addressed future raw material demand and recycling potential. Given the expected role of the electric vehicle sector in driving demand for critical raw materials, most of these studies focus on LIB applications in electric vehicles (Habib et al., 2020; Xu et al., 2020; Yang et al., 2021). One notable difference among these studies is their consideration of various cathode chemistries. For instance, Shafique et al. (2023) analyze material flows specifically for lithium-nickel-manganese-cobalt (NMC) cathodes, whereas other studies examine multiple cathode types in hypothetical market share scenarios (Baars et al., 2020; Bobba et al., 2019; Dunn et al., 2021). The most commonly considered chemistries are lithium-nickel-cobalt-manganese oxide (NCM), lithium-nickel-cobalt-aluminum oxide (NCA), and lithium-iron-phosphate (LFP). Some studies, such as that of Maisel et al. (2023), consider additional active materials, such as lithium- and manganese-rich oxides (LMR), which are being explored for next-generation LIBs.

Recycling potential is another critical focus in literature, especially for key materials, as it can reduce dependence on primary resources and ensure long-term material availability. Many studies assume closed-loop material cycles, where materials from end-of-life products are recovered and reused for the same applications. However, the rapid growth in demand for electric vehicles means that recycling alone is unlikely to meet the full demand for raw materials (Dunn et al., 2021; Maisel et al., 2023). Maisel et al. (2023) find that in the IPCC's SSP1, SSP2, and SSP5 expansion scenarios, recycling could meet over half of the lithium and nickel demand for LIB by 2040.

Some studies have investigated the potential or capacity for LIB to be repurposed for secondary applications in energy storage systems,

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achieving material savings by reusing batteries that are no longer suitable for electric vehicles but are still viable for stationary energy storage (Bobba et al., 2019; Dunn et al., 2021; Xu et al., 2020, 2023). For instance, Bobba et al. (2019) estimate that approximately 38 500 electric vehicles batteries in the EU could be reused for energy storage by 2025, covering about 14% of the energy storage capacity required for self-consumption applications, in which locally generated renewable energy is used on-site rather than of being fed into the grid. This second life use would help reduce the demand for primary materials in the stationary energy storage sector and provide a valuable complement to the recycling of electric vehicle batteries. While electric vehicles remain the primary driver of LIB demand, research increasingly recognizes the importance of recycling and secondary use in maximizing resource efficiency and addressing supply challenges.

While previous research primarily focused on the electric vehicle sector, recent studies have begun integrating stationary energy storage systems into material flow assessments. For example, Zhou et al. (2024) created a detailed dynamic material flow model to evaluate the EU's recycled content targets for lithium, nickel, and cobalt in lithium-ion batteries. The study considered electric vehicle and stationary energy storage applications with different cathode chemistries, including second-life use and end-of-life recycling. Zhou et al. (2025) applied this analysis to Australia, estimating the battery repurposing and material recycling potential of various battery materials and cathode chemistries in lithium-ion batteries used in electric vehicles and stationary energy storage systems up to 2050. Extending the focus to a major battery-producing region, Liu and Domenech Aparisi (2025) examined lithium flows and stocks in China, providing insights into domestic lithium demand and circularity strategies. Their results show that cumulative lithium demand could reach 6.65 Mt between 2021 and 2050, nearly equivalent to China's current reserves.

Although these studies represent important advances, they remain limited to lithium-ion battery chemistries and specific regional and material scopes. What is missing is a comprehensive, globally oriented, technology-inclusive assessment that considers emerging post-lithium-ion chemistries, such as sodium-ion, lithium-sulfur, and solid-state batteries. These technologies are considered potential alternatives to lithium-ion batteries in the electric vehicle and energy storage sectors due to their promising characteristics in terms of specific energy, safety, and cost (Baumann et al., 2022; Benveniste et al., 2022; Schmaltz, 2022). Direct comparisons with established LIB chemistries would be valuable to better estimate future raw material requirements and identify potential resource bottlenecks. This would help determine if new technologies offer advantages in terms of resource efficiency or sustainability.

This paper addresses the aforementioned gaps by examining the current and future material demand for LIB and Post-LIB technologies in various growth scenarios up to 2050. These scenarios include recycling and second life options. The analysis determines whether global reserves, resources, production, and recycling capacity are sufficient to support the projected growth of battery technologies. Considering multiple scenarios and sensitivities provides a comprehensive understanding of the material needs and challenges in battery production. These insights will enable us to determine if batteries can fulfill their intended role in the energy transition or if a broader mix of energy storage technologies is necessary to ensure the planned transformation of the energy system.

2. Material and methods

This section provides a comprehensive analysis of the material requirements for current and future battery technologies in electric vehicles and energy storage systems, including recycling and second life potential. First, it presents the methodology for calculating the total primary material demand (see Section 2.1). Next, the main factors affecting the absolute material demand for batteries are analyzed in detail in Section 2.2 to quantify their impact and provide a basis for strategies to address or prevent potential material shortages.

2.1. Modeling material demand across the battery life cycle

A dynamic, stock-driven material flow analysis (MFA) model was developed to estimate the evolution of material demand, in-use battery stocks, and secondary material flows to 2050. Following the established approach in dynamic MFA studies (Müller et al., 2014), the model combines historical data on battery capacity deployment and lifetime distributions with projections of future capacity expansion and sectoral market shares to derive time-dependent inflows, outflows, and accumulated stocks. In Fig. 1 you can see the considered scheme of the battery life cycle. Batteries used in electric vehicles and stationary energy storage systems are considered, as they are expected to account for approximately 95 % of the global battery demand (International Energy Agency, 2023; Pillot, 2021). At the end-of-life of batteries used in electric vehicles, some of the batteries can be given a second life in stationary energy storage systems. The remaining batteries with inadequate characteristics are recycled or disposed of directly. Second life batteries and first life batteries in stationary energy storage systems are also either recycled or disposed of once they reach their end-of-life. The secondary material gained through recycling can be used to reduce the primary material demand. If recycling is not possible due to technological or economic constraints, they are usually landfilled.

The total primary material demand m^T_{tot} in a given year T for all applications a and all battery types b can be calculated using Eq. (1). It consists of the material demand due to the exogenous assumed annual capacity expansion of batteries of new batteries $m^T_{new,a,b}$ (see Eqs. (2a) to (2b)), for both electric vehicles and stationary energy storage, and the material demand induced by the required replacement of batteries at the end-of-life $m^T_{EOL,a,b}$ (see Eqs. (3a) to (3b)), reduced by the secondary material supply due to battery recycling $m^T_{Recycling,a,b}$ (see Eqs. (4a) to (4b)).

$$m^T_{tot} = \sum_{a,b}(m^T_{new,a,b} + m^T_{EOL,a,b} - m^T_{Recycling,a,b}) \tag{1}$$

The demand $m^T_{new,EV,b}$ for a certain material caused by the installation of new electric vehicle batteries is calculated according to Eq. (2a) by multiplying the expansion capacity per year $P^T_{cap,EV,b}$ by the specific material load w^T_b of the battery type b. For all applications a the capacity is $P^T_{cap,a,b} = P^T_{cap,a} \cdot \alpha^T_b$ where α_b is the market share for the specific battery type b. The same calculation initially applies to the demand $m^T_{new,ESS,b}$ arising from the installation of new stationary storage batteries $P^T_{cap,ESS,b}$ in year T (see Eq. (2b)). However, this demand is reduced by a proportion q of batteries that are returned from their initial use in electric vehicles and can be repurposed for stationary energy storage. Additionally, the term z reflects the capacity loss of the battery compared to its initial capacity.

$$m^T_{new,EV,b} = P^T_{cap,EV,b} \cdot w^T_b \tag{2a}$$

$$m^T_{new,ESS,b} = (P^T_{cap,ESS,b} - P^{T-\tau_{1st,EV}}_{cap,EV,b} \cdot z \cdot q^T) \cdot w^T_b \tag{2b}$$

To calculate the material demand due to replacement needs $m^T_{EOL,a,b}$, the end-of-life year for each battery must first be determined based on the age structure of the battery portfolio and battery size. Although each individual battery has a specific lifetime, the overall distribution of battery lifetimes is modeled as a normal distribution, which is a commonly used function for approximating battery failure probabilities (Harris et al., 2017; Mouais et al., 2021), reflecting the stochastic variability of battery lifetimes. The lifetime of the batteries differs for both applications and for the first and second life in stationary energy storage systems.

Since only first life batteries are used for electric vehicles, the material requirement $m^T_{EOL,EV,b}$ is derived from the capacity addition of electric vehicle batteries $P^{T-\tau_{1st,EV}}_{cap,EV,b}$ in year $(T - \tau_{1st,EV})$, where $\tau_{1st,EV}$ is the first life of electric vehicle batteries. This is multiplied by the specific material load of the battery type w^T_b (see Eq. (3a)). For stationary energy storage, two terms must be considered. The first term,

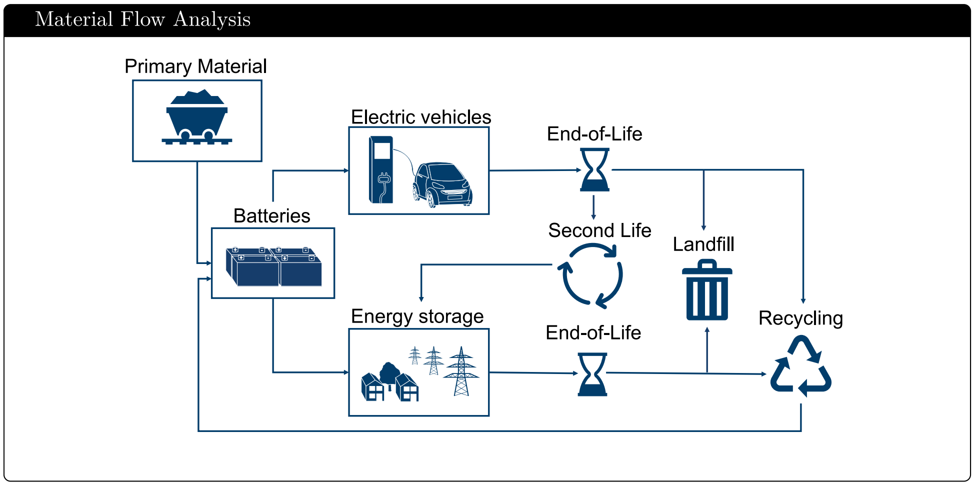


Fig. 1. Material flow analysis: Battery life cycle including second life use of electric vehicles batteries in stationary energy storage and their subsequent end-of-life treatment.

is analogous to the material demand due to the end-of-life replacement of electric vehicle batteries. The second term $P_{cap,EV,b}^{T-(\tau_{1st,EV}+\tau_{2nd,ESS})}$ describes the required replacement of second life stationary energy storage batteries, with lifetime $\tau_{2nd,ESS}$, which were previously used in electric vehicles (see Eq. (3b)).

$$m_{EOL,EV,b}^{T} = P_{cap,EV,b}^{T-\tau_{1st,EV}} \cdot w_b^T \tag{3a}$$

$$m_{EOL,ESS,b}^{T} = \left(P_{cap,ESS,b}^{T-\tau_{1st,ESS}} + P_{cap,EV,b}^{T-(\tau_{1st,EV}+\tau_{2nd,ESS})} \cdot z \cdot q^T \right) \cdot w_b^T \tag{3b}$$

Next, the amount of secondary material available through recycling is calculated. $m_{Recycling,a,b}^{T}$ can be calculated from the material requirement for newly installed batteries from capacity expansion targets $m_{new,a,b}^{T-\tau_{1st,a}}$ and the replacement requirement $m_{EOL,a,b}^{T-\tau_{1st,a}}$, each at time $(T - \tau_{1st,a})$, as shown in Eqs. (4a) and (4b). The amount of material is then multiplied by the technical recycling efficiency γ^T for the material and the application-dependent collection rate x_a^T, which reflects the differences in collection systems, traceability of battery stocks and end-of-life treatment in the different applications. The recycling efficiency reflects the technical recovery rate of each material and is defined as the ratio of the recycled output mass to the input mass of used batteries. The only distinction between the applications made here is in the case of the recycling of electric vehicle batteries, as only the fraction $(1-q^T)$ of material is recycled, as described in Eq. (4a).

$$m_{Recycling,EV,b}^{T} = (m_{new,EV,b}^{T-\tau_{1st,EV}} + m_{EOL,EV,b}^{T-\tau_{1st,EV}}) \cdot (1 - q^T) \cdot \gamma^T \cdot x_{EV}^T \tag{4a}$$

$$m_{Recycling,ESS,b}^{T} = (m_{new,ESS,b}^{T-\tau_{1st,ESS}} + m_{EOL,ESS,b}^{T-\tau_{1st,ESS}}) \cdot \gamma^T \cdot x_{ESS}^T \tag{4b}$$

The total amount of materials required for different battery types is calculated using several key parameters, as described previously. These include the expansion capacity $P_{cap,a,b}$ measured in GWh, and the specific material load w_b of each battery type in kg/GWh. Battery lifetimes are represented by $\tau_{1,a}$ and $\tau_{2,ESS}$ in years for electric vehicles and stationary energy storage systems, respectively, as well as for their first and second life cycles. The remaining battery capacity in second life applications is given by $z \in [0,1]$, while the second life rate $q \in [0,1]$ represents the share of batteries reused in a second life. Material recovery is further influenced by the technical recycling efficiency $\gamma \in [0,1]$, and the collection rate $x_a \in [0,1]$ after the batteries' first use phase in electric vehicles or stationary storage.

2.2. Drivers of material demand of batteries

The scenarios and sensitivities effecting demand for battery materials investigated in this study are described in this subsection and shown schematically in Fig. 2. First, the projected expansion of battery capacity under different development paths is discussed. The various battery types considered here and their assumed market shares are then presented, reflecting expected developments and introduction trends in the coming decades. Additionally, the analysis examines various sensitivities covering key factors that may affect material demand, such as battery lifetime, remaining capacity after first life, the share of batteries allocated to electric vehicles and stationary energy storage, second life and collection rates. All of these parameters were included in the sensitivity analysis to ensure a comprehensive assessment. As shown in the SI, variations in these parameters affect material demand. However, their influence remains limited to less than 12% within the examined ranges, which is far outweighed by the dominant effects of large-scale drivers, such as overall capacity expansion scenarios and the recycling process. Among all scenarios and sensitivity variations, we selected the combination highlighted in green in Fig. 2 as the first scenario to present in the results section. This scenario contains the most favorable assumptions in this study and represents the most optimistic case. Further material scenarios with more constraining assumptions are then discussed.

2.2.1. Capacity expansion variations

To calculate the material demand for batteries the in-stock use of materials in existing batteries and the future expansion of batteries are required. Historical values are taken from Avicenne Energy (Pillot, 2021) for 2011 to 2020 and from reports of the International Energy Agency (IEA) (International Energy Agency, 2023, 2024b) for 2021 to 2023. Future projections of the battery capacity expansion are based on three of the five Shared Socioeconomic Pathways (SSP). The *Sustainability* scenario (SSP1) was considered, which has a strong focus on sustainable development and thus leads to a significant expansion of battery capacity. The expansion of batteries in this scenario was compared to that in the *Middle of the Road* (SSP2) and *Fossil-fueled Development* (SSP5) scenarios. The *Middle of the Road* scenario represents the middle path, in which current social, economic, and technological trends continue largely unchanged. The *Fossil-fueled Development* scenario focuses on economic growth driven by the intensive use of fossil fuels. Data on global battery expansion in the three Shared Socioeconomic Pathways for 2030, 2035, and 2040 were taken from (Degen et al., 2023) and extrapolated linearly to 2050 following the trend. Three variants were developed for allocating future battery capacity between electric vehicles and stationary energy storage systems. The variants cover a range of sectoral battery allocations between 85%–90% for electric vehicles and 5%–10% for stationary energy storage, including both constant-share and time-varying cases. These scenarios align with current market data and long-term projections

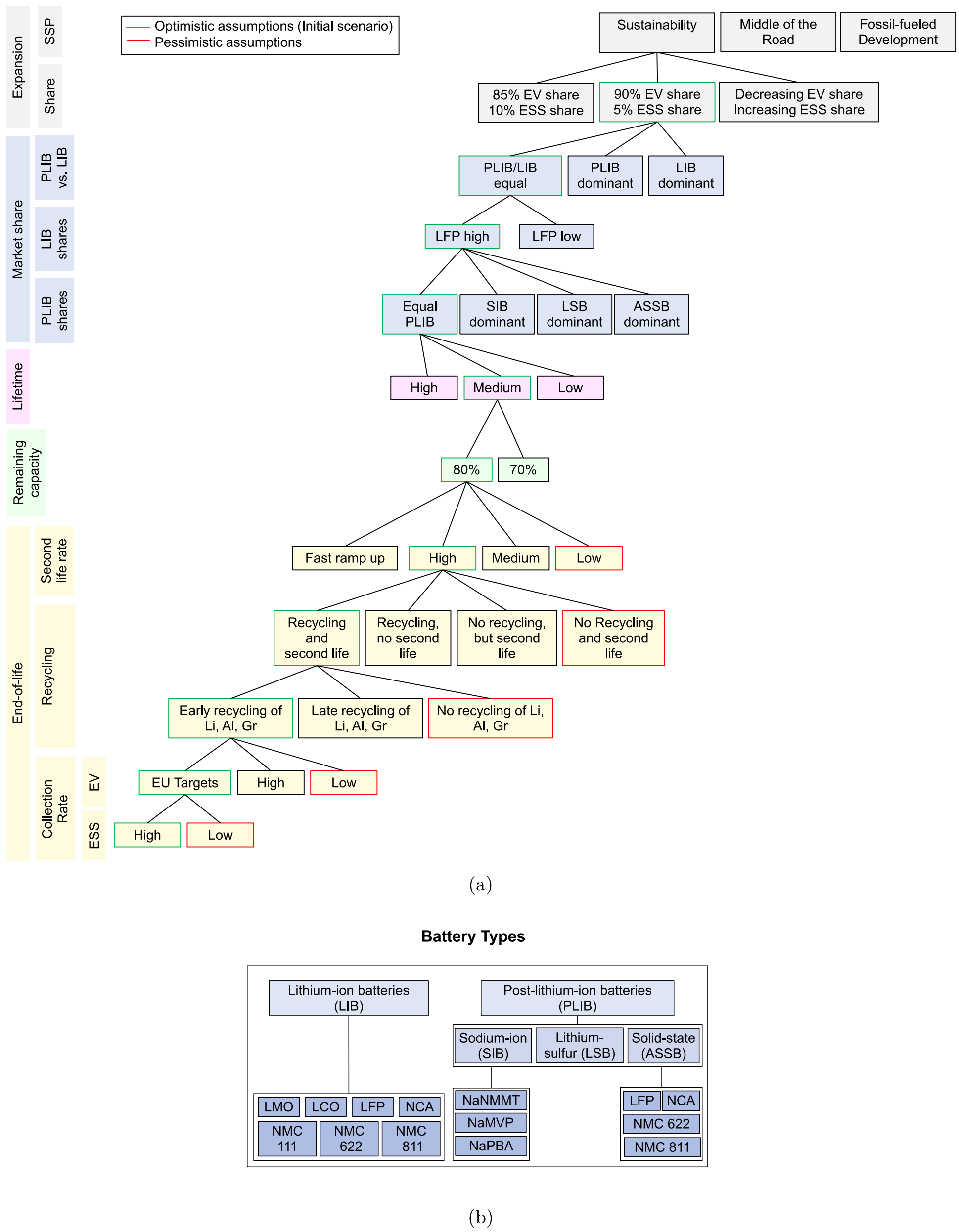


Fig. 2. Scenarios and Sensitivities: Panel (a) provides an overview of the assumed scenarios and parameter variations. The *Sustainability* scenario is illustrated in detail with the same set of variations being applied to the *Middle of the Road* and *Fossil-fueled Development scenarios*. Panel (b) shows the different battery types considered in the analysis.

from the International Energy Agency (International Energy Agency, 2023, 2020), Avicenne Energy (Pillot, 2021), McKinsey (McKinsey & Company, 2023), and the Rocky Mountain Institute (Rocky Mountain Institute, 2024). Collectively, these sources suggest that stationary storage will account for 5%–10% of total battery capacity between today and 2050. Further methodological details and the underlying assumptions regarding the expansion and application share can be found in the SI, Sec. 3.2.

2.2.2. *Selection of battery types and market shares*

Battery types differ substantially in their material composition. Hence, covering most relevant current and future battery types as well as their market shares is crucial to reveal potential material bottlenecks. For this purpose, LIB and Post-LIB technologies are considered, each of which is further distinguished by its most common cathode types, as described in the SI, Sec. 3.1, and shown in Fig. 2. In terms of market shares three variations with further sub-differentiation of cathode types are considered ranging from a historical based exponential growth of Post-LIB batteries to 90% in 2050, *PLIB dominant*, across equal market shares in 2050, *PLIB/LIB equal*, to the opposite with a remaining market share of 90% for LIB batteries in 2050, *LIB dominant*. How those are derived is explained in more detail in the SI, Sec. 3.3. Finally, this results in 24 different model runs.

2.2.3. *Recycling variations*

To reduce the demand for primary resources, effective recycling strategies for battery materials are essential. Current methods include pyrometallurgical and hydrometallurgical recycling, often combined to recover cathode materials and elements such as cobalt, copper, iron, manganese and nickel (Jacob et al., 2024). The material-specific technical recycling efficiencies applied in this study are based on data from Argonne National Laboratory's EverBatt model (Dai et al., 2019;

Xu et al., 2020) and are detailed in the SI, Table 4. Although existing LIB recycling approaches provide a foundation, Post-LIB strategies require further adaptation due to differences in chemistry and material composition. Details on these adaptations are provided in the SI, Sec. 3.7. As the recycling of lithium, aluminum, and graphite is not yet economically viable, this paper describes three variants that consider the timing at which the recycling of these materials may become economic. These variants are not predictions, but rather assumptions to test sensitivities. There is one variant in which recycling never becomes economically viable, one with an early entry point in 2031, and one with a later entry point in 2041. These allow us to investigate how different assumptions about market entry of recycling affect material demand trajectories.

2.3. Supply assumptions for battery materials

To evaluate the future supply of primary and secondary raw materials for batteries, and given that the primary focus of this study lies on modeling material demand rather than detailed supply forecasting, simplified assumptions about mining production and recycling capacities were made while aiming to cover a meaningful range of potential future developments. Three trend-based mining production scenarios were considered: constant production at 2023 levels, linear extrapolation of historical growth from 2000 to 2023, and linear extrapolation of recent trends from 2020 to 2023. However, these scenarios should not be interpreted as predictions because actual mining capacity is influenced by complex factors, such as permitting times, capital expenditures, geopolitical risks, and market expectations (International Energy Agency, 2021; The International Renewable Energy Agency, 2023). Rather, they provide a parametric, historically grounded variation approach to capture a plausible range of potential supply developments and assess the sensitivity of emerging material constraints (see SI Sec. 3.8 for further details). For recycling, current and historical capacities together with announced expansion targets through 2030 were used to create a linear extrapolation of global capacity through 2050. This trajectory includes both LIB and post-LIB chemicals and should be interpreted as indicative rather than predictive (see SI Sec. 3.8).

3. Results

This analysis shows and evaluates the resulting material demands for batteries in terms of resources and reserves, mining and recycling capacities, and criticality. This analysis aims to evaluate the feasibility of planned battery expansion, identify potential material shortages, and assess the resilience of the material supply from both primary raw material extraction and secondary recycling sources. While a broad range of variations were examined, this analysis focuses on those with a significant impact on the results. All other variations can be found within the SI.

3.1. Material demands exceed global supply in more climate ambitious scenarios

The cumulative material demand from 2023 to 2050 (see Fig. 3) indicates that the planned expansion in the *Sustainability* scenario would not be feasible. In this scenario, the currently known cobalt reserves would be exceeded by about 36% (60% global resources) and the global lithium reserves would almost be depleted. This holds true even under the optimistic assumptions of the initial scenario and without considering competing demand from other sectors. The cumulative material demand of the other two capacity expansion scenarios, *Middle of the Road* and *Fossil-fueled Development*, does not exceed current global reserves. However, the annually resolved material demand would be constrained in the *Middle of the Road* scenario as well; especially in the short-term until 2030 (see Fig. 4).

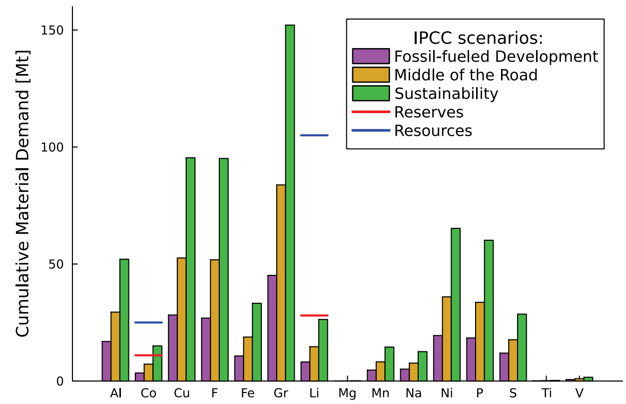
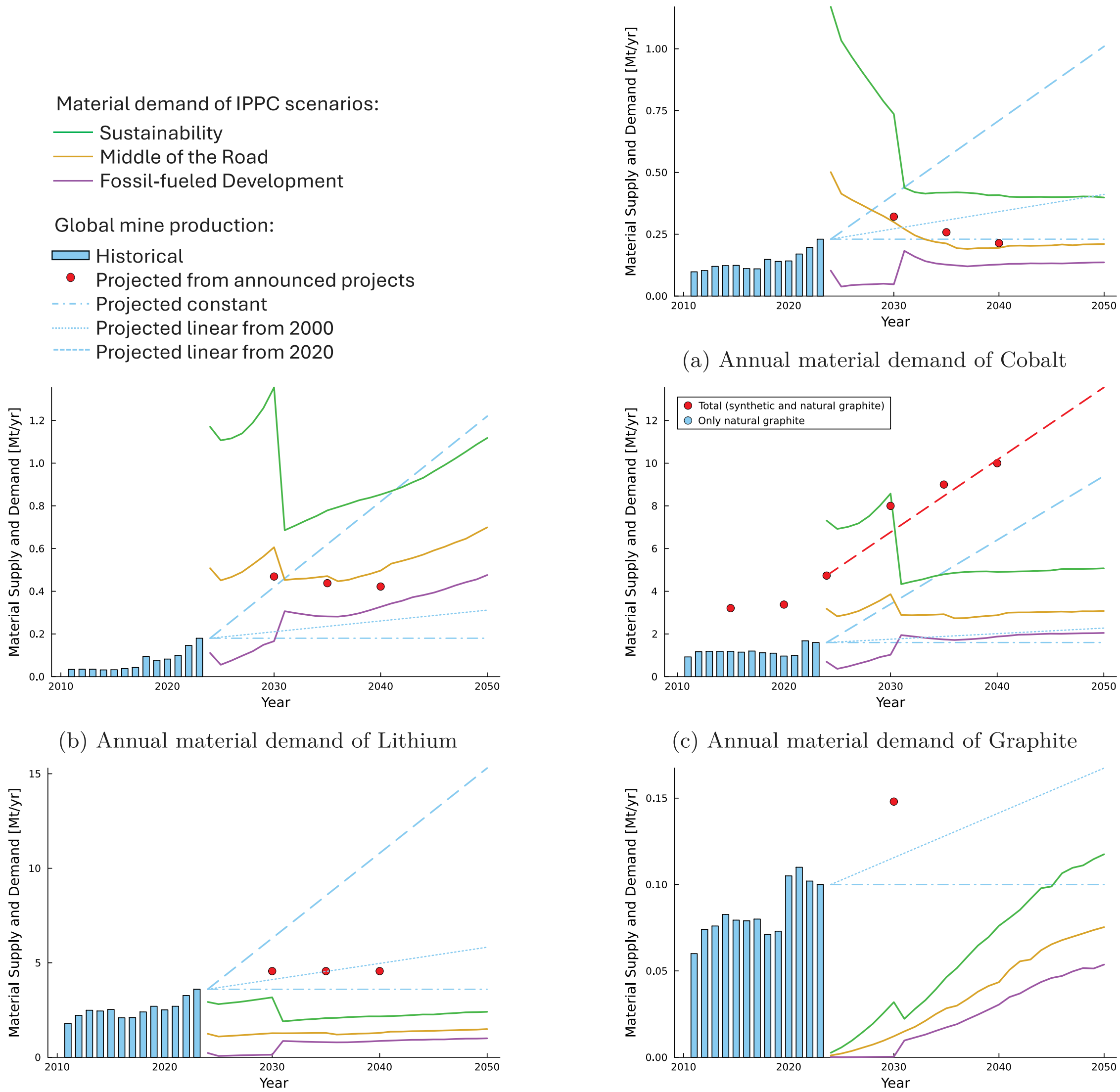


Fig. 3. Cumulative material demand in initial scenario: Cumulative material demand (from 2023 to 2050) for all battery materials in the capacity expansion scenarios, compared to current reserves and resources (United States Geological Survey, 2011–2024).

Development of material demands In 2024, the deployment trajectories specific to each scenario diverge, resulting in significant differences in material demand between the scenarios, as illustrated in Fig. 4. This is consistent with the sharp discontinuity in annual battery expansion between 2023 and 2024 (see SI Fig. 2b), marking the transition from historical data to scenario-based trajectories. As the model calculates material demand based on new capacity additions, the increase in annual deployment is reflected directly in the observed rise in material demand in the *Sustainability* scenario, and the observed decline in the *Fossil-fueled Development* scenario. The demand for materials such as nickel, lithium, graphite, and cobalt declines noticeably around 2030 in the *Sustainability* scenario. This is primarily due to the anticipated slowdown in annual battery expansion after 2030 (see SI Fig. 2b). In contrast, the *Fossil-fueled Development* scenario shows continued battery growth beyond 2030, driving further material demand. Demand for cobalt begins to decline earlier, around 2023, since a shift toward low-cobalt chemistries such as NMC811 and LFP is assumed in the initial scenario (see market share assumptions SI Sec. 3.3). In contrast, demand for lithium and graphite continues to rise until 2030, reflecting the assumption that recycling remains economically infeasible during this period. Consequently, spent batteries are not recovered, and primary material demand remains high due to replacement and continued growth. In the *Middle of the Road* scenario, a drop in demand for lithium and graphite is observed in 2030, as recycling is assumed to become viable from this point onward, thereby reducing the need for primary material input. After 2030, capacity expansion stabilizes, which flattens the demand curves for nickel, cobalt, and graphite. However, lithium demand continues to rise due to its role in nearly all battery chemistries, including emerging types such as LSB and ASSB, which require more lithium per unit of capacity. Demand for vanadium is linked to the adoption of SIB, which is expected to grow alongside Post-LIB technologies. Accordingly, vanadium shows a steadily increasing trend through 2050. The projected material demand for nickel and vanadium remains below current production capacity, and in the case of vanadium, slightly above, from around 2045. However, these estimates do not account for competing demand from other sectors, which could exacerbate potential supply constraints. Therefore, supply risks cannot be eliminated, even in these cases. For the other battery materials considered in this analysis, the annual and cumulative material requirements from 2023 to 2050 remain well below current production volumes and within known reserves. Therefore, these materials are only presented in the SI Fig. 6 as they pose no critical supply risks under the considered scenarios. The assumptions for the projection of the increase in production capacity are explained in more detail in the SI, Sec. 3.8.



(a) Annual material demand of Cobalt

(b) Annual material demand of Lithium

(c) Annual material demand of Graphite

(d) Annual material demand of Nickel

(e) Annual material demand of Vanadium

Fig. 4. Annual material demand in initial scenario: Projected annual material demand in the capacity expansion scenarios compared to historical mine production (United States Geological Survey, 2011–2024) and projected supply from 2024 onwards. The supply projections are based on three linear extrapolation assumptions: constant production; continuation of long-term trends from 2000 to 2023; and continuation of the steeper post-2020 trend, which is linked to the recent acceleration in battery deployment. This range spans supply developments consistent with historical dynamics. Red markers indicate the expected supply from projects announced by the (International Energy Agency, 2025) for 2030, 2035, and 2040 (the production forecast for vanadium in 2030 is taken from Rogers and Banerjee, 2025). These projects lie predominantly within the projected supply range. One exception is graphite. Blue bars and lines show natural graphite supply only, while red points and lines indicate total graphite (natural and synthetic) historical, expected, and projected supply.

Significant production shortfalls in mine production capacity are expected in the *Sustainability* and *Middle of the Road* scenarios for cobalt, lithium and graphite. These deficits persist even under the most optimistic assumptions about supply developments, which are significantly higher than the expected supply volumes reported by the (International Energy Agency, 2025) suggesting that short-term demand peaks cannot be met. These shortfalls cannot be fully compensated by 2050 unless mining capacity grows at least as rapidly as it has over the past three years. With this level of growth, the cobalt supply could catch up by 2045 in the *Sustainability* scenario and by 2032 in the *Middle of the Road* scenario. However, the lithium and graphite gaps would only close in the *Middle of the Road* scenario before 2040. For graphite, this supply constraint only applies when considering natural graphite. Once synthetic and natural graphite are aggregated (see red line in Fig. 4), the shortfall is limited to the Sustainability scenario, which is expected to be offset by around 2035. Further details are provided in the SI (Fig. 9, Table 5–6).

Additionally, we examined annual material requirements and criticality scores across various market share scenarios. The analysis shows that material demand, particularly in the short term, does not fall below the available supply of lithium, cobalt, and graphite, even under these variations. Due to averaging effects between materials with high criticality and low demand and materials with low criticality and high demand, the criticality analysis indicates that the overall criticality scores show only minor deviations across the different scenarios. A detailed examination of the criticality assessment is presented only in the SI (Sec. 1 and 4.2.3).

3.2 Limitations on recycling and second life applications worsen material constraints substantially

Recycling and second life applications can substantially reduce the demand for primary materials. Our results show that the amount of

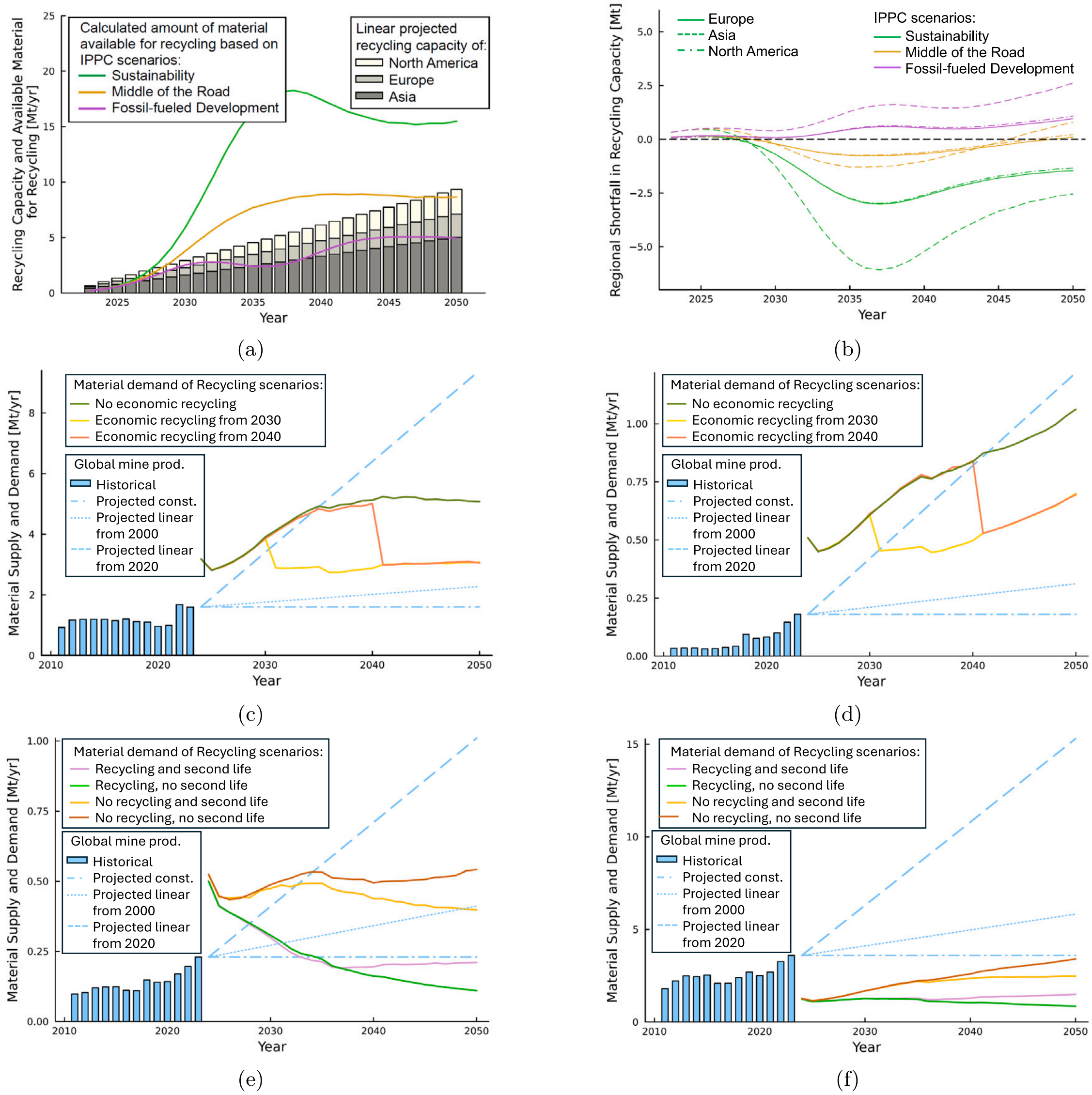


Fig. 5. Impact of recycling and end-of-life strategies: (a,b) Global and regional recycling capacities in relation to projected material flows from end-of-life batteries. (c, d) Annual material demand of the *Middle of the Road* scenario for graphite and lithium under different recycling viability scenarios. (e, f) Demand variations for cobalt and nickel across different end-of-life treatment strategies in the *Middle of the Road* scenario.

recyclable battery materials in the *Sustainability* and *Middle of the Road* scenarios will exceed the projected global recycling capacities as shown in Fig. 5(a) (for assumptions on the recycling capacity projections see SI Sec. 3.8). This mismatch is primarily driven by the sharp increase in battery deployment between 2023 and 2030, with an expected typical lifetime of about 12 years in electric vehicle applications. As a result, a significant wave of battery retirements is anticipated between 2035 and 2042 (*Sustainability*) and between 2023 and 2040 (*Middle of the Road*), respectively. This will lead to a pronounced peak in recycling demand. The temporary oversupply of end-of-life battery materials in the *Sustainability* and *Middle of the Road* scenarios would result in significant processing delays. Specifically, an estimated backlog of approximately 44 Mt would accumulate in the *Middle of the Road* scenario and 195 Mt in the *Sustainability* scenario. Regionally, especially China shows, due to both its high material demand and its largest share of global recycling capacity, a high sensitivity to changes in parameters (see Fig. 5(b)) and thus consistently represents the extreme case in all scenarios. In contrast to periods of delays in recycling, we observe periods of under-utilization of recycling capacities as well, which can question their economic viability. Especially in the *Fossil-fueled Development* scenario during the peak recycling period between 2038 and 2039, the utilization of the available recycling infrastructure would only reach about 45%–50%.

Delays in market entry of recycling The market entry of different recycling technologies can vary fundamentally because some recycling technologies, particularly those for aluminum, lithium, and graphite, are not economically viable or are still in development. This will impact the primary material demand. Based on our calculations of material demand, aluminum does not appear to pose a risk of exceeding global production capacities or available reserves in the considered scenarios. Therefore, we focus on lithium and graphite here, while aluminum is only covered in the SI. The results (see Figs. 5(c) and 5(d)) show that the absence of recycling of lithium and graphite would lead to a substantial increase in cumulative material demand, requiring up to 6.37 Mt more lithium and 40.63 Mt more graphite in the *Middle of the Road* scenario than with early implementation of economically viable recycling technologies. In the case of delayed recycling, the resulting increase in material demand is reduced by about half. Further details and materials can be found in the SI Fig. 19.

End-of-life variations The end-of-life path of batteries in form of recycling and second life applications also has a significant impact on

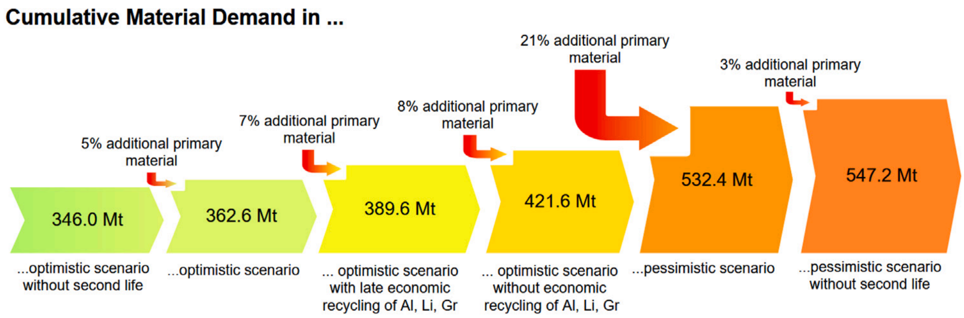


Fig. 6. End-of-life scenario comparison: Cumulative material demand from 2023 to 2050 depending on the end-of-life scenario, shown here for the *Middle of the Road* battery capacity expansion scenario. The additional material required is represented by the arrow.

the overall material demand. This is illustrated in Figs. 5(e) and 5(f), which show the annual material demand for cobalt and nickel under different end-of-life scenarios (results for other materials are shown in the SI Fig. 20). For cobalt, scenarios without recycling result in a significantly higher material demand than the current level of global mining production throughout the study period. In contrast, when recycling is introduced from around 2033–2034, annual demand falls below the current production capacity as secondary materials from spent batteries are reintroduced into the supply chain. A similar pattern emerges for nickel, with the projected demand for recycling reaching the limits of current production capacity by 2050, even in the *Middle of the Road* scenario. An interesting observation emerges when comparing the role of second life applications in different recycling scenarios. Without recycling, second life significantly reduces the primary material demand. However, in scenarios where recycling already takes place, the introduction of second life leads to a slightly higher primary material demand. This is due to the capacity degradation of second life batteries, which may require additional capacity installations, and the delayed availability of end-of-life batteries for recycling as they remain in second life applications. Finally, the lack of recycling induces additional primary material demand of about 21% and in case of the most pessimistic assumptions of this study even up to 32% (see Fig. 6). This would further exacerbate the already critical pressure on mining production capacities and the near depletion of known reserves discussed earlier. While this numbers were derived for the *Middle of the Road* scenario, similar trends can be observed in the *Sustainability* and *Fossil-fueled Development* scenarios presented in the SI Fig. 21.

4 Discussion

The growing demand for batteries, particularly for electric mobility and renewable energy storage, will create significant supply challenges for raw materials in the coming years. It is of paramount importance to ensure a stable and sustainable supply of critical materials. Traditional markets and new technological developments are competing for the same raw materials, which adds to the complexity of ensuring a stable supply. This discussion will analyze the key challenges revealed by this study and the solutions that have arisen from the growing demand for battery materials.

Postponement of the battery expansion capacity Even under optimistic assumptions, the analysis indicates that shortages of key battery materials —particularly graphite, lithium, and cobalt—combined with limited recycling capacity, will likely delay the deployment of battery storage technologies. These constraints could have far-reaching implications for the broader energy system, as batteries play a central role in balancing the temporal mismatch between electricity supply and demand. Batteries play a central role in balancing this mismatch. Limited storage capacity, especially for variable renewable energy sources such as solar and wind, could reduce the ability to integrate high shares of renewables into the grid. This could lead to increased curtailment of renewable energy production, reduced system stability, and greater reliance on fossil fuels. Overall, this would slow the pace of decarbonization. To mitigate these risks, it is crucial to accelerate the expansion of primary extraction and recycling infrastructure and to diversify the energy storage technology portfolio. Integrating alternative storage systems could reduce dependence on critical battery materials and enhance overall system resilience. Furthermore, this diversification could ensure that renewable expansion targets remain achievable, even under material supply constraints.

Competitive markets In this study, the supply situation was estimated based on total production capacity, reserves, and resources, regardless of their sectoral distribution. In reality, however, many critical raw materials used in batteries are also important to other industries, such as steel production, electronics, and the chemical sector (Government of Canada, 2024). This competing demand can significantly impact material availability and must be considered when evaluating long-term supply security. Nevertheless, allocating materials for battery production based on historical values would be misleading because future demand is expected to exceed historical trends. Similarly, allocating materials for battery production based on historical shares would be misleading because future demand is expected to far exceed past trends. This approach fails to consider the transformative role of batteries in the energy transition and the sector's expected growth, which is driven by electrification and the integration of renewable energy sources.

Second life The analysis shows that the impact of second life batteries on material demand varies depending on the recycling infrastructure. In scenarios without recycling, using second life batteries reduces cumulative primary material consumption by up to 2% by extending battery life and delaying the need for new production. However, in scenarios with recycling systems, second life batteries delay the return of valuable materials to the recycling loop. This can lead to bottlenecks in material availability during times of high demand, increasing primary material requirements by up to 5%. This trade-off underscores the importance of strategically managing the use of second life batteries in coordination with recycling capacity. An optimal approach balances expanding battery use to reduce immediate material extraction with the timely recovery of materials through recycling. Managing the timing and volume of second life use to avoid overloading recycling facilities and synchronizing material flows with peaks in demand could minimize the need for primary materials and maximize recycling throughput.

Second life batteries have the potential to be offered for as little as 20%–80% of the cost of new batteries (Dong et al., 2023), making them an attractive storage option. At the same time, the economic benefits that can be realized depend heavily on a number of factors, including logistics, storage, testing, sorting and maintenance (Hantanasirisakul and Sawangphruk, 2023). In practice, the use of second life has so far mostly been at a pilot level, and it is the subject of ongoing discussions as to whether economically viable second life concepts can be realized on an industrial scale (Hantanasirisakul and Sawangphruk, 2023). From an environmental perspective, however, second life use can offer notable advantages (Tao et al., 2021). By extending battery lifespan, it can reduce the overall carbon footprint by around 8%–17% compared to direct recycling, while the total energy required over the battery's lifecycle can be lowered by 2%–6% (Tao et al., 2021). Moreover, second life use supports circular economy principles by maximizing the utility of materials already extracted and processed.

However, the large-scale deployment of second life batteries is currently limited by several technical and safety challenges. One major concern is the risk of thermal runaway caused by internal short circuits, which is a critical safety issue even after the initial use phase (Yang et al., 2022). This risk is exacerbated by the insufficient tracking of a battery's aging history, which is essential for evaluating its suitability for reuse (Haram et al., 2021; Yang et al., 2022). Overall, the lack of standardized procedures for remanufacturing, testing, and integrating second life batteries hinders their efficiency in secondary applications (Haram et al., 2021).

5. Conclusion

The results of this study show that, even under optimistic assumptions and without taking into account competing sectors, the expansion of battery capacity in line with the IPCC's *Sustainability* scenario is not feasible due to insufficient availability of critical reserves, especially cobalt and almost lithium. In addition to these reserve constraints, current and projected mining capacities for cobalt, lithium and graphite are insufficient to meet demand until at least 2030, even under favorable capacity growth trajectories. Recycling emerges as a key strategy for reducing primary resource demand. However, under linear projections of historical recycling capacity, both the *Sustainability* and *Middle of the Road* scenarios show significant capacity constraints. These results highlight the need for a comprehensive expansion of recycling, second life, and production infrastructures, as well as the development of a diversified technology strategy. In addition to technical scaling, a functioning recycling system requires standardized take-back systems, efficient logistics, and investments in automated dismantling and sorting technologies to accommodate the variety of battery types. Second life applications can also keep materials in the utilization system longer and relieve production and recycling capacities during peak times. However, key technical challenges, such as ensuring safe integration, establishing reliable diagnostic procedures, and making recycling economical, must be overcome to achieve this. Additionally, a greater diversification of energy storage technologies is necessary to increase supply security and reduce dependence on lithium-ion batteries. Although the analysis considered alternative battery types, such as SIB, LSB, and ASSB, the results show that these technologies alone are insufficient to reduce material dependency to the extent necessary to avoid bottlenecks. Alternative storage solutions with comparable properties for short- to medium-term storage requirements, such as redox flow batteries, high-temperature batteries, and supercapacitors, offer the potential to mitigate material shortages and strengthen the resilience of the energy system. While these technologies may incur higher costs in the short term, they enhance resilience against resource constraints in the long term and mitigate the risk of storage delays jeopardizing the progress of the energy transition. Future research should focus on integrating sectoral competition for battery materials while emphasizing the crucial role of alternative energy storage technologies in achieving an optimal technology mix. This diversification is necessary to prevent systemic delays and ensures the energy transition proceeds without depleting critical reserves or overwhelming production and recycling capacities.

CRediT authorship contribution statement

Lana Söltzer: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Conceptualization. **Bernhard Wortmann:** Validation, Software, Methodology. **Detlef Stolten:** Supervision. **Jochen Linßen:** Supervision. **Heidi Heinrichs:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT and DeepL to improve the language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resconrec.2025.108745.

Data availability

Data will be made available on request.

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