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Future energy demand for automotive and stationary lithium- and sodium-ion battery production towards a European circular economy

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Europe is currently heavily dependent on imports for the critical raw materials needed for lithium-ion battery (LIB) production, as most of these resources are distributed outside the region. Despite this dependency, Europe accounts for around 25% of global electric vehicle (EV) sales. This creates an indirect form of energy dependency, as much of the energy used in battery cell production is embedded in imported materials and cells. Persistent supply chain bottlenecks have made battery access a strategic priority for automakers, prompting efforts to build more resilient domestic supply chains. However, this shift also means that a significant amount of energy will need to be sourced within Europe itself, raising concerns about energy consumption amid surging European battery capacity demand – an important factor that will shape strategic decisions in both industry and policy. This work addresses the future energy demand of LIBs and their potential near-term competitors, sodium-ion batteries, by quantifiying the cradle-to-gate and cradle-to-cradle cumulative energy demand for large-format prismatic cells, using primary machinery data on gigafactory scale. The European energy demand forecast until 2070 is conducted using a novel circular economy simulation model, considering recycling, second use and the use phase of EVs and stationary energy storage (SES) applications. We show that the local European energy demand to establish a domestic battery cell production and to be self-sufficient by 2050 will rise to 250 TWh annually. Including the use phase of EVs and SES, a total of 450–500 TWh will be needed within Europe starting in 2040, offset by savings of approx. 90 TWh from reduced fossil fuel upstream energy. The comprehensive analysis provides a quantitative framework for understanding the energy flows associated with large-scale battery cell production in Europe. We highlight processes with significant reduction potential, while also identifying factors that could increase energy demand in the future.

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Broader context

The transition to electric vehicles (EVs) and stationary energy storage (SES) is accelerating battery demand in Europe. However, battery cell production depends on critical raw materials, which are predominantly sourced from outside the region. This leaves Europe heavily reliant on imports and creates an indirect form of energy dependency, due to the substantial embedded energy in imported materials and cells. Recent European Union policies, including the Critical Raw Materials Act and the Net-Zero Industry Act, aim to strengthen local battery cell production. However, this shift also raises concerns about rising energy demand in Europe, necessitating access to affordable, abundant and reliable energy to enable a successful transition. This study quantifies the cradle-to-cradle cumulative energy demand of selected lithium-ion and sodium-ion battery cells utilising primary machine data on gigafactory scale. Going beyond previous studies, we analyse the imported and locally required energy demand along Europe's path toward battery self-sufficiency. This includes a detailed assessment of cell production, while also considering the EV and SES use phase, considering different fuel consumptions and round-trip efficiency losses at the cell level. Our findings provide critical insights for policymakers and industry leaders working at the intersection of clean energy targets, battery technology and industrial resilience.

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Introduction

Lithium-ion batteries (LIBs) are the dominating energy storage technology applied to decarbonize the transportation sector and to store fluctuating, renewable energy.[1,2] The annual

European electric vehicle (EV) sales reached nearly 3.2 million in 2023[3] and are predicted to reach 8.3 million in 2030.[4] Furthermore, the European Union (EU) has declared the ban of combustion engine vehicles (ICEVs) starting by 2035.[5] In addition, the EU targets the integration of at least 40% of renewable energy in the EU's energy mix by 2030.[6] Hence, the battery capacity demand for EVs and stationary energy storage (SES) applications is predicted to grow from 185 GWh year^{-1} in 2023[3] to 600–1400 GWh year^{-1} in 2030,[7–9] resulting in a significant energy demand increase for battery cell production in Europe.

To meet this growing demand, companies are ramping up their battery production capacity, which requires critical raw materials such as lithium, nickel, cobalt and graphite. For European companies, this primarily results in reliance on other countries, primarily on China, due to concentrated distribution of resources.[10,11] Moreover, the ownership distribution along the LIB value chain further reinforces China's influence.[12] Amid rising geopolitical tensions, the risk of supply disruptions is increasing. Consequently, Europe is strengthening local battery production and promoting circular economies.[13–15] However, expanding its own LIB supply chain will also result in a significant increase in energy demand, as most of the energy currently used for mining, refining and cell manufacturing is required outside of Europe. As part of the European Green Deal, the EU submitted the Critical Raw Materials Act (CRMA) in 2023, which aims to achieve an extraction capacity of 10% of the EU's annual demand for strategic raw materials, a domestic processing and refining capacity of 40% for battery materials and a recycling capacity of 25% by 2030 to ensure access to a secure and sustainable supply.[13] Furthermore, the Net Zero Industry Act (NZIA) was proposed, aiming for 40% local battery cell and cathode and anode active material (CAM/AAM) production by 2030.[15] Understanding the European local energy requirements, which inevitably involve CO_2-emissions and costs, is therefore central to achieving this goal and to guide strategic decisions in industry and policy. Existing life-cycle assessment (LCA) research focusing on cumulative energy demand (CED) typically concentrates on the energy requirements associated with gate-to-gate battery manufacturing[16–18] or provides cradle-to-gate energy assessments at the cell level.[19–21] Forecast-oriented studies, often focus on material demands[22–25] or battery cost projections.[26–29] This study aims to bridge the gap between cell-level energy demand analyses and forecasting approaches by predicting the cradle-to-cradle energy demand across the entire battery value chain accumulated for the European market. The analysis is categorized into several key stages, ranging from mining and refining of lithium hydroxide (LiOH), lithium carbonate (Li_2CO_3), nickel sulfate ($NiSO_4$), cobalt sulfate ($CoSO_4$) and manganese sulfate ($MnSO_4$) to CAM and AAM synthesis, metals and non-active materials production, gate-to-gate battery cell manufacturing and scrap generation, while also considering the use phase of EVs and SES applications.

Therefore, the energy consumption per kWh_{cell} of selected state-of-the-art LIBs, sodium-ion battery (SIB) cells and next-generation materials are determined by applying a (1) battery cell model, a (2) battery cell production model and an (3) LCA model. The production model, based on primary gigafactory-scale machine data,[16] calculates energy usage and material needs. These outputs, alongside results from the battery cell model, feed into a cradle-to-gate LCA focused on CED. The energy requirements for cells based on secondary materials are modeled, considering the recycling of lithium, nickel, cobalt, manganese, aluminum and copper. In addition, we go beyond previous studies by applying a (4) circular economy simulation model (see Fig. 1) to develop a forecast of the European energy demand, with a detailed breakdown into cell production and the use phase of EVs and SES. The EV and SES battery capacity demand is determined based on European EV sales, sales-weighted battery size data and SES capacity projections.

For the first time, this analysis approach quantifies the local European energy demand required to develop domestic battery cell production, aiming to strengthen national capabilities and to be self-sufficient by 2050. Additionally, the energy demand associated with imported materials required to meet Europe's overall battery capacity demand is determined, considering three dominant technology scenarios: lithium nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP) and SIB. Moreover, the study examines the use phase of EV and SES applications and models the annual electricity demand for EV charging in Europe by taking into account the varying fuel efficiencies of different battery technologies and factoring in round-trip efficiency losses at the cell level.

Methods

Model overview

The energy demand analysis resulting from the need for battery cells for the electrification of the transportation sector and the energy transition in Europe, was performed with a novel, in-house developed circular economy simulation model, which represents a simplified battery circular economy and is based on prior work by Wesselkämper *et al.*[22] Key innovations of the model and their motivation used in this work are summarized in Table 1.

Technical setup of the model

Based on market and forecast input data, batteries are created by the production function each year. For storage and transformation of the battery stocks, the Python framework pandas[30] is used, while the stochastic assignment of battery properties is enabled by the SciPy framework.[31] Subsequently, the active battery stocks age continuously, until they reach their life expectancy, when another function moves them from the active to the retired battery stock. The different battery stocks, *i.e.* active stock, recycled stock and second use battery stock are implemented as pandas data frames. Depending on the input scenario, retired EV batteries are assigned to either of the latter two battery stocks. This sequence of functions is triggered annually with updated input data. Over the

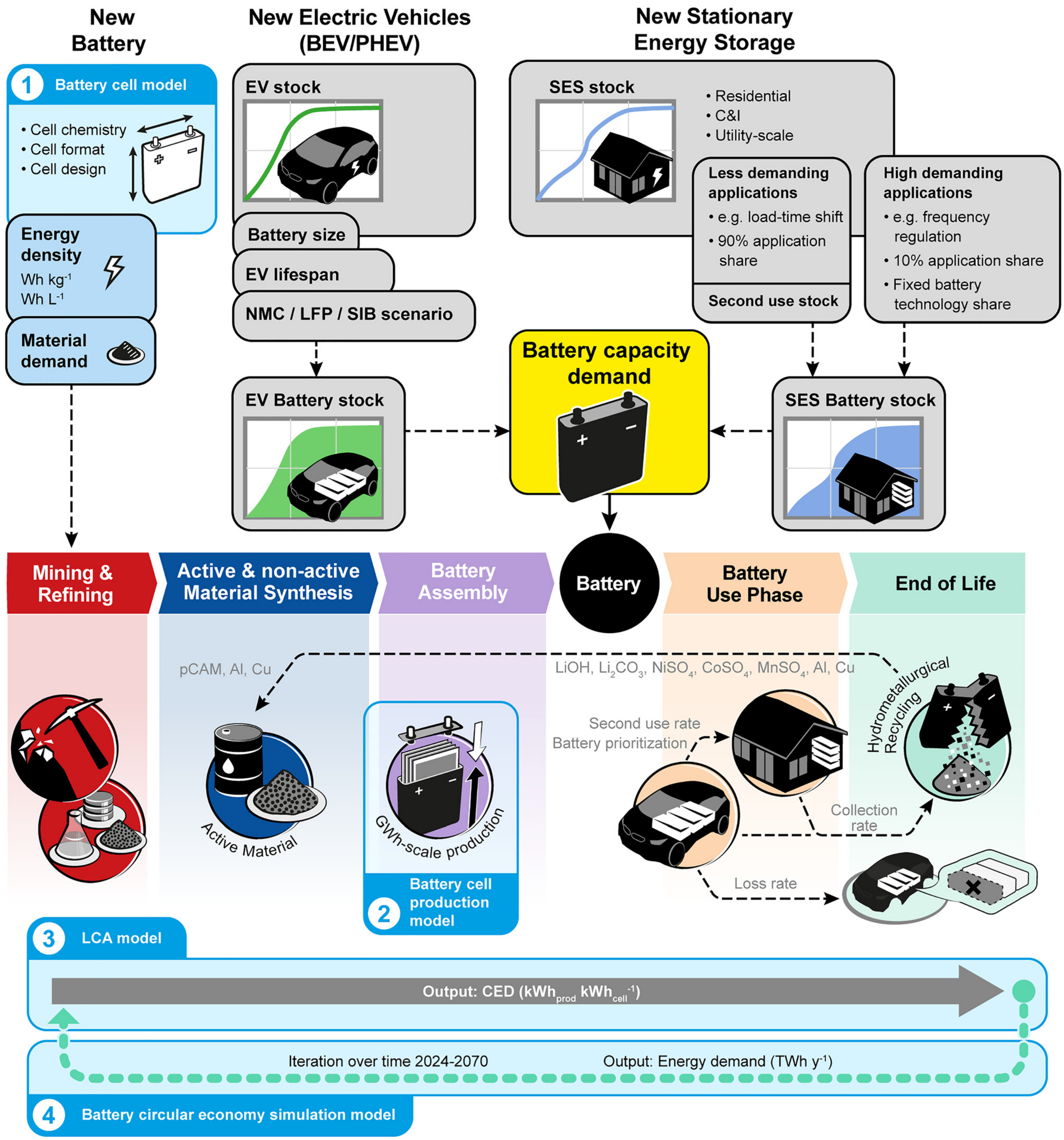

Fig. 1 Modeling framework of the (1) battery cell model, (2) battery cell production model, (3) life-cycle assessment model and (4) circular economy simulation model to determine the energy consumption across the entire battery value chain in Europe until 2070. By combining the models (1), (2) and (3), the CED at cell level is determined for various state-of-the-art and next-generation cells. The annual battery capacity demand is derived from EV and SES battery demand forecasts. Over the entire forecast period, battery cells are generated according to the input parameters using the (4) Circular economy simulation model, while at the same time battery cells reach the end of their use phase each year and are either recycled or repurposed. pCAM: precursor cathode active material, C&I: commercial & industrial.

course of the simulation, the battery stock is saved each year. Afterwards, this data is analysed to return the desired output. In this study, the output represents the European energy demand that must be produced locally from 2024 until 2070 to be self-sufficient in 2050 and the energy that needs to be imported in terms of battery materials and cells to meet the European battery capacity demand. In contrast to other energy impact studies,[20] this model also accounts for the EV charging energy demand, considering fuel efficiency and round-trip efficiency losses in the EV and SES use phase.

Table 1 Innovations and motivations of the applied circular economy simulation model

Innovation	Motivation
The entire EV fleet and SES "battery stock", which refers to all existing batteries in the economy, is modelled, including both primary and secondary battery materials.	This allows analyzing the quantity and properties of the various battery stocks at any given point in time, such as their technological constitution, material flows or energy throughputs.
The market segmentation for EVs and SES batteries in small and large EVs and low- and high-demanding SES applications and the technology roadmap is taken into consideration.	The application of the battery is expected to influence technological choices and the battery size. The influence of such market-driven effects can thus be analysed.
A market-driven perspective on the demand for second use batteries is employed, compared to a fixed share of EV batteries deployed in second use applications in other studies.[22,23]	Due to the supply of used EV batteries significantly exceeding projected SES demands, saturation effects can be expected to occur rapidly. This setup ensures that such effects are considered.
Combination of market-driven perspective with technology dependent prefiltering of potential second use batteries.	The technology constitution of second use batteries can be expected to differ from that of all retired EV batteries. This influences system properties such as the recycled material streams or round-trip efficiencies of the SES sector.

Cell level energy consumption

The energy consumption of selected LIBs and SIBs at the cell level was calculated by a cradle-to-gate approach. Therefore, three distinct models were combined, namely a (1) battery cell model, a (2) battery cell production model and an (3) LCA model. The battery cell model specifies material input, cell format (prismatic cell), cell design and cell parameters and as output produces the cell energy density and a bill of materials (BOM) for all cell components. The production model is based on Degen *et al.*[16,32] and simulates the manufacturing process at a gigafactory scale (GWh $year^{-1}$) for the selected cell, providing an in-depth quantification in terms of energy consumption and material use. The production model is based on primary machinery data from the research battery cell factory in Münster, Germany operated by Fraunhofer FFB. These BOMs, along with the cell energy density and production energy consumption, serve as inputs for the LCA model. A more detailed description of these models and the applied cell, component and material parameters is given in Voß *et al.*,[33] who focused on the Global Warming Potential of SIBs.

This study focuses on the CED of LIB and SIB cell chemistries that are either commercially relevant or considered promising next-generation batteries. For LIBs, the battery cells examined include LFP|Graphite (Gr), NMC|Gr, $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA)|Gr and 0.33 Li_2MnO_3·0.67 $LiNi_{0.27}Mn_{0.6}Co_{0.13}O_2$ (LMR-NMC)|Gr. NMC622, NMC811 and NMC955 are also analysed with 5 wt% and 20 wt% silicon containing anodes. For SIBs, O3-$NaNi_{1/3}Fe_{1/3}Mn_{1/3}O_2$|hard carbon (NFM111|HC), $Na_3V_2(PO_4)_2F_3$ (NVPF)|HC and $Na_2Mn[Fe(CN)_6]$ (Mn-PBA)|HC are considered. The lithium and sodium layered oxide CAMs are modeled by the precursor synthesis *via* co-precipitation and calcination.[34] The polyanionic type CAMs (LFP[35] and NVPF[36]) are modeled *via* a solid-state synthesis and for Mn-PBA, a solvent based precipitation synthesis is modeled based on primary industrial data.[37] For the synthetic graphite synthesis process, the energy intensive calcination and graphitization steps are considered. The calcination step is based on a new modeling approach to produce needle coke, considering condensable volatiles for energy generation.[33] In contrast to existing LCA studies, the graphitization is modeled using an Acheson powder process based on recent industrial primary data, which is published by Carrére *et al.* to produce battery grade graphite.[38] Previous studies, which mainly refer to the carbon footprint, have significantly underestimated the CO_2-emissions of graphite.[21,39,40] Additionally, the graphite modeling includes milling, micronizing, coating and packaging steps, whereby the packaging steps are excluded in this study.

For SIBs, HC synthesis from petroleum pitch is considered, as this supply chain offers the highest potential for large-scale production.[41] Alternative HC precursors are lignin, phenolic resin and coconut shells.[41,42]

For silicon containing anodes, the production of metallurgical grade silicon is modeled based on the life cycle inventory data by Frischknecht *et al.* (SI Table S10).[43] In the manufacturing process, it is assumed that the co-utilization of graphite and silicon is carried out by blending silicon with graphite in the electrode fabrication process,[44] resulting in the same energy consumption as for the graphite AAM production process. To enable a more accurate modeling of silicon containing anodes, comprehensive industrial synthesis data is essential. The raw material mining and refining are modeled globally. The output is the produced energy consumption (kWh_{prod}) per specific cell energy (kWh_{cell}) and is shown in Fig. 4. For all battery cells the same prismatic cell housing is modeled. The resulting life cycle inventory data is provided in the SI. The functional unit for this analysis is defined as 1 kWh of battery cell energy produced. Ecoinvent 3.9.1 is used as the underlying life cycle inventory database.

EV market: current state and forecast

The current state of the European EV market was determined by the sales of battery electric vehicles (BEVs), which are collected from the Marklines database[45] and plug-in electric vehicles (PHEVs)[46] from 2011–2023 (SI Table S1). The projected future EV fleet and the annual EV sales are shown in Fig. 2 and SI Fig. S2, respectively. The battery size (kWh), fuel efficiency (km kWh^{-1}), weight (kg) and battery chemistry were spezified for each BEV model in 2023. We further classified BEV models into two market segments, small and large BEVs, based on the median battery size of 67.7 kWh (see SI Table S1). For the existing BEV fleet, the sales-weighted battery capacity is 47 kWh.[47] For PHEV, battery sizes are expected to grow from 10 kWh (2011) to 17 kWh (2034).[48] The average kilometers driven per year in Germany in 2023 (12 440 km $year^{-1}$)[49] are projected onto Europe with a 2000 km $year^{-1}$ standard deviation. The battery lifespan of EVs that were sold before 2020 was assumed to be 8 years based on the battery warranty of EV manufacturers.[50] Despite longer service life of EVs, no battery replacement is considered. After 2020, in line with assumptions made in Xu *et al.*,[51] batteries will have the same or even longer lifetime than EVs. In the EU, vehicle lifespan ranges from 8–17 years, with an average lifetime of 12.3 years, presented using a Weibull distribution (SI Fig. S3).[52] Despite the extended battery service life, reusing batteries from one EV to another is not considered, primarily due to uncertainties around consumer acceptance and warranty issues.

The yearly EV sales result in the battery demand $d_{\mathrm{n,EV}}(y)$. The EV battery production is based on $d_{\mathrm{n,EV}}(y)$ and the battery size ($E_{\mathrm{bat}}(y)$), that are defined by the input scenario. Multiplying $d_{\mathrm{n,EV}}(y)$ and $E_{\mathrm{bat}}(y)$ yields the demand of EV batteries in units of capacity ($d_{\mathrm{E,EV}}(y)$), as described by eqn (1).

$$d_{\mathrm{E,EV}}(y) = E_{\mathrm{bat}}(y)\cdot d_{\mathrm{n,EV}}(y) \tag{1}$$

Additionally, an EV loss rate of 1%, which defines the loss of active batteries as a fraction from the entire battery stock, is applied in this study, based on grey exports, primarily to Africa, which prevent the battery cells from being recycled in Europe.[53]

SES market: current state, forecast and second use

The European SES market capacity from 2014–2023 is sourced from a SolarPower Europe report.[54] The capacity forecast until 2050 is based on the persistence scenario from Sterchele *et al.*[55] for Germany and is scaled up for Europe according to the regions electricity consumption, as it can be assumed that the flexibility demand scales with overall electricity demand.[56–60] We assume that the SES capacity demand of 1600 GWh will remain constant from 2050 onwards. Additionally, we differentiate between less-demanding and high-demanding applications. Less-demanding application batteries are utilized for continuous energy supply over extended periods (*e.g.* storage of renewable energy), while high-demanding application batteries, are only needed to store or supply energy for a short amount of time (*e.g.* frequency regulation).[61] Hence, it is estimated that 90% of SES batteries are less-demanding application batteries, while 10% are high-demanding application batteries. We also considered second use of end-of-life batteries from the automotive sector, as these batteries typically retain 80% of their original capacity, making them well-suited for less-demanding applications.[62,63] We consider a 75% second-use rate for NMC|Gr, NCA|Gr and NFM|HC and a 100% second-use rate for LFP|Gr and NVPF|HC.[51] Further, second life batteries (SLB) are only used in less-demanding application, as these repurposed batteries are not suitable for performance critical applications.[64] For all SES batteries, we modeled 250 cycles per year.[65,66] As for EV batteries, the lifetime is modeled using a Weibull distribution. The most likely service life is derived from Xu *et al.* with 19 years for new LFP|Gr, NVPF|HC and PBA|HC and 14 years for new NMC|Gr, NCA|Gr and NFM|HC battery cells.[51] For SLB, the most likely lifetime is assumed to be 13 years (LFP|Gr and NVPF|HC) and 8 years (NMC|Gr, NCA|Gr and NFM|HC) as shown in SI Fig. S4.[67] In contrast to this work, previous studies[22,23] defined the extent of second use from the supply perspective as a share of available end-of-life batteries. This model investigates second use from a demand-based perspective. Therefore, the demand ($d_{\mathrm{E,SES}}(y)$) for new SES installations in year y is calculated as given by eqn (2), with $E_{\mathrm{SES}}(y)$ representing the existing capacity of SES batteries. $E_{\mathrm{SES}}(y)$ is the sum of purpose-built capacity $\left(E^{*}_{\mathrm{SES}}(y)\right)$ and the sum of SLB in service ($E_{\mathrm{SES,SLB}}(y)$) as given by eqn (3). $d_{\mathrm{SES,total}}$ is the defined total SES demand. If there is an oversupply of end-of-life batteries, LIBs containing pure graphite and SIBs are prioritized for second use. Overall, second use is modeled to the fullest possible extent, defined by the availability of end-of-life batteries and the less demanding SES demand (see SI Fig. S10).

$$d_{\mathrm{E,SES}}(y) = d_{\mathrm{SES,total}}(y) - E_{\mathrm{SES}}(y) \tag{2}$$

$$E_{\mathrm{SES}}(y) = E^{*}_{\mathrm{SES}}(y) + E_{\mathrm{SES,SLB}}(y) \tag{3}$$

Production scrap

Battery production scrap is produced at different stages in the manufacturing process and therefore scrap rates are included as a factory-specific property.[68] Utilising the total battery production demand ($d_{\mathrm{E,bat}}(y)$) and the existing production capacity ($d_{\mathrm{E,fs}}(y)$), the number of new factories required in the current year ($d_{\mathrm{n,f}}(y)$) can be calculated using eqn (4), where the average production capacity of a factory is denoted as E_{f}. E_{f} is defined as 20 GWh $year^{-1}$.

$$d_{\mathrm{n,f}}(y) = \frac{d_{\mathrm{E,bat}}(y)\cdot d_{\mathrm{E,fs}}(y)}{E_{\mathrm{f}}} \tag{4}$$

The ages of factories created are continuously increasing. New factories are created when the existing factories are not able to meet production volumes. The resulting total factory number and annual new installed battery production plants are depicted in SI Fig. S9. Their scrap rate ($f_{\mathrm{scrap}}(x)$) is a function of the factory age and is determined by combining the scrap rates of all battery production plants generated in a certain year. The scrap rate is a function of the factory age starting at 18% and dropping to 4%. Scrap is treated like a complete battery and is recycled after one year. This is based on assumptions by Mauler *et al.*[69,70] and Wesselkämper *et al.*[22]

Hydrometallurgical recycling

Recycling of LIBs and SIBs from EVs and SES applications is considered an important way to tackle the future supply risks of primary materials, especially for Europe, to decrease reliance on other countries.[71] This study examines the impact of battery recycling on primary material demand and energy consumption in battery cell production, assuming a 97% recycling collection rate of end-of-life battery cells.[48] The energy consumption of hydrometallurgical recycling was modeled according to Jiang *et al.*[72] Their data is based on two Chinese recycling

Table 2 Fuel efficiency and round-trip efficiency of the selected cells that are applied in the energy demand calculations for the use phase

Type		Fuel efficiency [km kWh^{-1}]		Round-trip efficiency [%]	
Cathode	Anode	Small BEVs	Large BEVs	0.2C[a]	Ref.
NMC532	Gr	7.81	7.04	96	79
NMC622	Gr	7.82	7.05	96	79
NMC622	Gr+ 5 wt% Si	7.90	7.13	95	76 and 79
NMC622	Gr+ 20 wt% Si	7.99	7.21	91	76 and 79
NMC811	Gr	7.86	7.09	96	79
NMC811	Gr+ 5 wt% Si	7.94	7.17	95	76 and 79
NMC811	Gr+ 20 wt% Si	8.03	7.25	91	76 and 79
NCA	Gr	7.86	7.09	96	85
LFP	Gr	7.67	6.91	98	79
LMR-NMC	Gr	7.90	7.13	87	85
NMC955	Gr+ 5 wt% Si	7.96	7.18	95	76 and 79
NMC955	Gr+ 20 wt% Si	8.04	7.27	91	76 and 79
NFM111	HC	7.58	6.82	92	82
NVPF	HC	7.59	6.83	95	80
PBA	HC	—	—	98	83

[a] Extrapolated to 0.2C. The round-trip efficiency of NMC811|Gr is also assumed for NMC955|Gr, NMC622|Gr and NMC532|Gr. Gr: graphite, HC: hard carbon, Si: silicon.

companies with a NMC and LFP recycling capacity of 100 kt $year^{-1}$ and 25 kt $year^{-1}$, respectively. In Europe, hydrometallurgical recycling is emerging as the main recycling process involving both chemical and mechanical processes.[73] The mechanical process includes disassembly, crushing and drying, followed by a filtration and separation step. This process yields a black mass, along with aluminum and copper scrap. The further processing of the black mass produces CAM precursor materials, which are assumed to be battery-grade by the end of the recycling process. Graphite recycling was not considered, as currently graphite is not recycled at a commercial scale.[74] Aluminum and copper scrap are further processed (see SI for details). The energy consumption (kWh_{rec}) per kWh_{cell} is depicted in SI Fig. S8. The recycling of NFM|HC was modeled after that of NMC|Gr, whereas Mn-PBA|HC and NVPF|HC were modeled analogously to LFP|Gr. A recycling yield of 90% was assumed for lithium, aluminum and copper and 98% for nickel, cobalt and manganese (see SI Tables S2 and S3).[51]

Fuel and round-trip efficiencies

Since this model also accounts for charging energy consumption during the use phase, fuel and round-trip efficiency are important parameters that must be considered. The specific energy (Wh kg^{-1}) of battery cells based on different technologies leads to variations in battery weight. Lower specific energies result in heavier battery cells, which increase overall vehicle weight and reduce fuel efficiency. For this study it was assumed, that a 10% reduction in vehicle weight improves fuel efficiency by 6%.[75] For small and large BEVs, the calculated battery cell weights are approx. 235 kg and 314 kg, respectively. Combined with the determined vehicle weight without battery the total vehicle weight is calculated (see SI Table S1). The fuel efficiency is then calculated for each battery chemistry based on the vehicle weight differences. In 2023, the fuel efficiency at cell level is 7.82 km kWh^{-1} and 7.05 km kWh^{-1} for small and large BEVs, respectively. It is noteworthy that fuel efficiency on pack level is lower, necessitating more charging energy.

The round-trip efficiency is defined as the ratio of energy that can be used relative to the energy that went into charging the battery. Ideally, discharging energy should be the same as charging energy, but in practice a part of the energy is lost, which is affected by the voltage hysteresis between the charge and discharge curves.[76] The round-trip efficiency is also highly sensitive to operating parameters such as C-rate, depth-of-discharge, temperature and voltage range, which makes the comparability of round-trip efficiencies difficult in existing studies.[76–79] In this model, round-trip efficiency values are based on a C-rate of 0.2C (see Table 2). In addition, an annual degradation factor of 0.2% was considered in this study. It is crucial to note that the round-trip efficiency is evaluated at the cell level. For silicon containing graphite anodes, however, it is assessed at the material level due to the limited available data.[76,79–85]

Results and discussion

EV and SES fleet growth

In Fig. 2, the projected EV fleet (a) and SES capacity (b) development in Europe until 2070 are depicted. The EV stock forecast is based on UBS estimates from 2025–2030[4] and the full electrification scenario.[5] To achieve the goal of climate neutrality by 2050, only vehicles that produce zero CO_2 emissions will be permitted for sale starting in 2035. From that point on, 13 million BEVs are expected to be sold annually thereafter (see SI Fig. S2).[86,87] The total EV fleet, consisting of small and large BEVs, as well as PHEVs, indicates that the overall number of EVs is expected to grow significantly, reaching a fleet size of 140 million by 2045. Based on 2024 sales data, the EV fleet is projected to increase by a factor of 3.2 by 2030 and by a factor of 9.2 by mid-2040. The small BEVs (sales-weighted average battery capacity of 53.6 kWh) and large BEVs (76.4 kWh) were determined by the median battery size of 67.7 kWh (SI Table S1) and have a sales distribution of approx. 50 : 50 in 2023, which is predicted to remain constant until

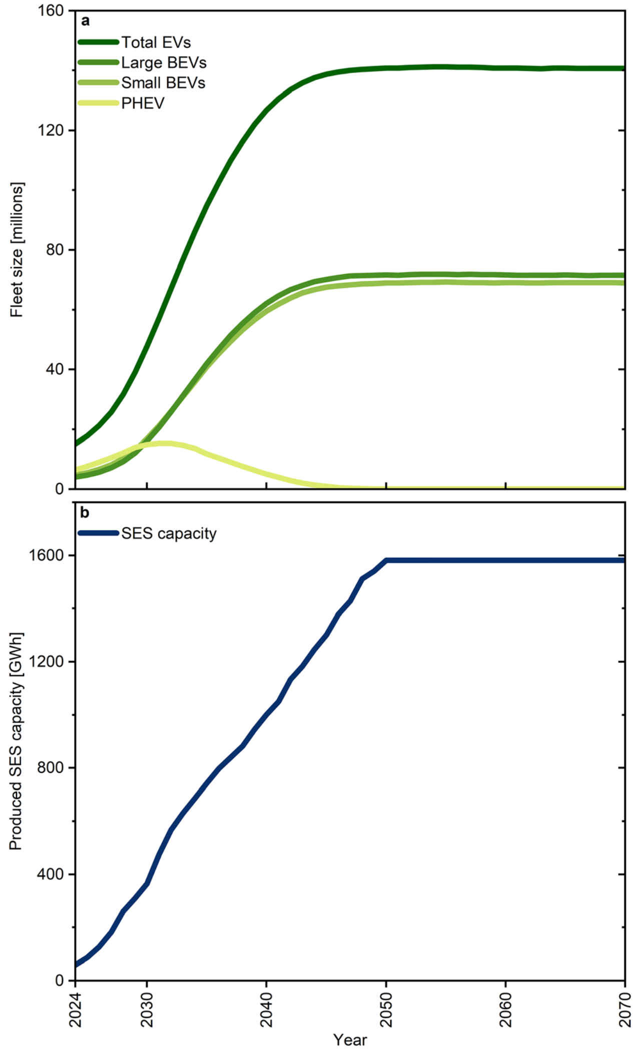

Fig. 2 European EV stock development projected until 2070 subdivided in small and large BEVs and PHEVs (a) and the produced SES capacity forecast (b).

2070. Therefore, large BEVs peak around 72 million and small BEVs at 69 million vehicles by 2050. PHEVs are expected to grow to 15 million vehicles by 2030, but then decline sharply due to the ban of ICEV sales.[5]

In 2023, Europe installed 17.2 GWh of new SES capacity, reaching about 36 GWh installed capacity in total.[54] By 2050, about 1600 GWh of SES battery capacity are forecasted.[55–60]

Battery capacity demand and technology shares

Due to uncertainties of future developments in battery technologies, the EV and SES battery capacity demand is represented in this work by three backcasting scenarios: High LFP (Fig. 3a), high NMC (Fig. 3b) and high SIB (Fig. 3c). The market shares of battery technologies in 2023 were determined for small and large BEVs, based on the collected BEV battery chemistry and sales data (SI Fig. S1). These figures serve as the forecast projection starting points. To improve clarity, Fig. 3 presents the SES battery capacity demand without differentiating between battery technologies, with a detailed breakdown provided in the SI (Fig. S7). It is important to note that this work focuses primarily on short-duration energy storage systems, as the majority of newly installed capacity belong to this category.[88–90] For short-duration energy storage systems, LIBs and SIBs are particularly well suited. Nevertheless, long-duration energy storage systems are also crucial for managing extended periods of low wind or solar generation.[89,91] A variety of technologies are being explored for long-duration energy storage, including redox-flow and high-temperature batteries.[92] However, long-duration energy storage system development has progressed slowly and these systems currently represent only a small fraction of overall stationary energy storage. The Faradion Institution forecasts that redox-flow batteries will account for approx. 5% of the United Kingdom SES market by 2030.[89] Overall, redox-flow and high-temperature batteries were not considered in this study due to the limited availability of industrial synthesis and manufacturing data.[93,94]

The LFP scenario (Fig. 3a) projects that LFP-based LIBs will dominate the EV and SES market over the next decades. Starting in 2040, approx. 1000 GWh year^{-1} of battery capacity will be required, with the LFP scenario projecting that the share of LFP|Gr will continuously increase, reaching 570 GWh year^{-1} for EVs and 75 GWh year^{-1} for less-demanding SES applications by 2070. As in the NMC scenario, SIBs are considered for small BEVs and less demanding SES applications reaching a share of 20% and 30%, respectively, by 2070. For small BEVs, NVPF|HC and NFM111|HC are considered due to their high volumetric energy density compared to other SIB chemistries,[71,95] while Mn-PBA|HC[96] accounts for the majority of SIBs in SES applications. NMC|Gr is expected to capture a market share of 10% for small BEVs and 30% for large BEVs by 2070.

NMC remains the dominant cathode chemistry in the NMC scenario (Fig. 3b), capturing a market share of 75–95% for EVs (750 GWh year^{-1}) and 60–85% for SES (98 GWh year^{-1}) in the forecast period from 2024 until 2070. Within this scenario, NMC811|Gr has the largest share for small BEVs and SES, while high-nickel and silicon-rich batteries are dominant for large BEVs. The share of LFP|Gr is projected to steadily decline starting from 2024.

SIBs are considered in this analysis as a compelling near-term challenger to LIBs with 240 GWh of battery capacity globally announced.[27] The high SIB scenario (Fig. 3c) is largely driven by elevated lithium carbonate prices and lithium supply chain risks, leading to an increased market share for SIBs,[27] particularly as an alternative to LFP|Gr cells. By 2070, the battery capacity demand of SIBs is projected to reach up to 205 GWh year^{-1} for small EVs and up to 220 GWh year^{-1} for large EVs. In the SES market, SIBs are expected to be even more dominant, accounting for 72 GWh year^{-1} of SES installations.

It is noteworthy that, compared to existing literature, our battery capacity demand analysis represents a relatively conservative scenario. Many studies project between 0.7–1.4 TWh year^{-1} by 2030.[7] Nevertheless, our forecast of 0.55 TWh year^{-1} by 2030 aligns closely with BloombergNEF's base case[8] and the accelerated ambition scenario by Yang *et al.*[97]

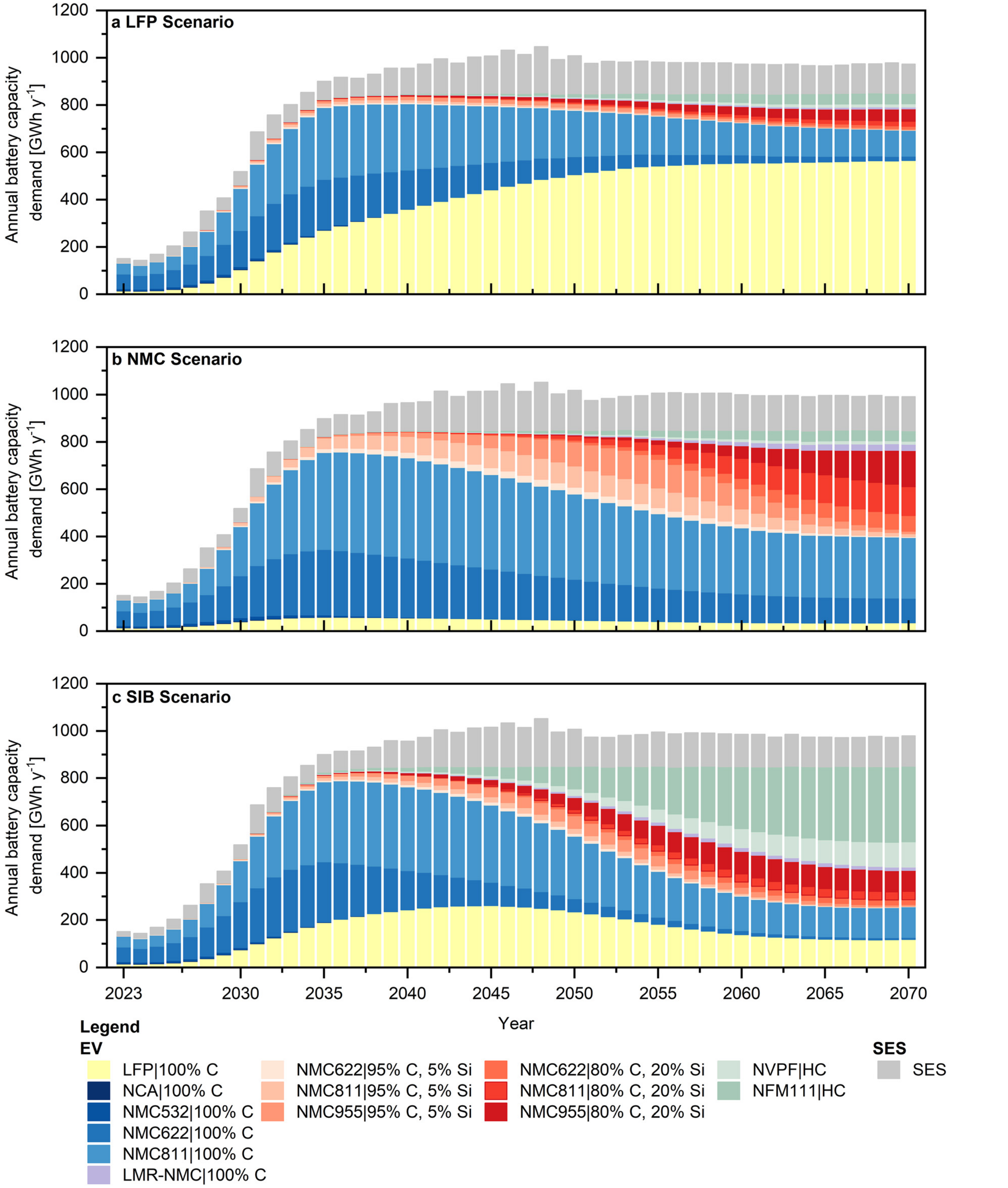

Fig. 3 Annual battery capacity demand forecast by battery technology for the LFP (a), NMC (b) and SIB (c) scenarios until 2070 considering small and large EVs and less-demanding and high-demanding SES applications. To improve clarity, the SES battery capacity demand is not differentiated by each battery technology in this figure. However, a detailed breakdown is provided in the SI (Fig. S7). In addition, the technology shares (in %) are also shown in Fig. S5 and Fig. S6 in the SI. C: synthetic graphite, Si: silicon, HC: hard carbon.

Cumulative energy demand

CED analysis is a consistent method for quantifying the total primary energy required over the life cycle of a product or service. It considers both direct and indirect energy use, covering all renewable and non-renewable energy inputs.[98,99] The energy mix in the mining industry is dominated by electricity and diesel fuel, both accounting for about one third of overall energy use.[100–102] Refining includes chemical and thermal treatments to purify the raw materials into battery-grade precursors which requires more energy than mining. According to GREET data, the refinement steps energy use is primarily based on natural gas and electricity, whereby the extraction method has a crucial influence. For nickel (sulfide ore), cobalt and manganese the share is around 50 : 50. Copper (sulfidic ore) and aluminum (wrought) refinement is mainly based on electricity and for lithium natural gas predominates (Brine production in Chile).[103] For the active material (AM) synthesis steps, powered by electricity and heat, the breakdown is shown in the SI. For the gate-to-gate battery cell production electricity and natural gas are required (∼50 : 50), with the formation step being the largest electricity consumer.[16,32]

The results of the CED of primary and secondary materials for prismatic cells are depicted in Fig. 4, with a cathode thickness of 90 μm, showing the sustainability in terms of energy consumption. On the anode side, LIBs were modeled with pure synthetic graphite as well as with 5 wt% and 20 wt% silicon. Natural graphite production is less energy intensive than synthetic graphite synthesis but was not considered in this study due to the increasing share of synthetic graphite as an anode material.[104,105] For SIBs, pitch-based HC was considered. A major difference in graphite and HC production is the graphitization step, where needle coke powder is heated above 3000 °C for several weeks,[38] while HC carbonization process typically occurs at temperatures between 1100–1700 °C.[106] This results in significantly higher energy consumptions for the graphite synthesis process, as shown in Fig. 4a, where the anode CED for LFP|Gr exceeds that of SIB cells by more than a factor of two. The anode impact decreases with increasing silicon content, as silicon production requires 28.7 kWh kg_{AAM}^{-1}, compared to 147.1 kWh kg_{AAM}^{-1} for graphite (HC: 57.3 kWh kg_{AAM}^{-1}) and further amplified by an increased energy density. Accordingly, the energy consumption for anode production accounts for 22.8–31.7% of the total energy consumption for NMC|Gr cells, 53.4% for LFP|Gr cells and between 19.2–21.2% for SIBs. For NMC|Gr + 20 wt% silicon, the anode impact drops to just 12–15%.

The largest driver of energy consumption for all cells, except LFP|Gr, is the cathode. This is primarily due to the mining and refining processes of $CoSO_4$ (321.4 kWh kg^{-1}) and $NiSO_4$ (71.8 kWh kg^{-1}). Further, the co-precipitation and calcination steps to produce NMC, NCA and NFM111 cathode materials are highly energy intensive (see SI).[34,39] LFP shows the lowest cathode contribution to the total energy impact among all selected cells, with a share of 16.5%, since less-energy intensive materials (Fe, PO_4) are required. Cell mechanics impact both LFP|Gr and SIB cells more than NMC|Gr battery cells, particularly due to their lower energy densities. The impact is notable because this model considers a large commercial prismatic cell, where the majority of the 330 g housing weight comes from high impact material aluminum (42.95 kWh kg^{-1}). For pouch and cylindrical cells, the impact is significantly lower. Pouch cells require less cell housing (per kWh_{cell}), while for cylindrical cells the cell housing is based on nickel-plated steel, which has a reduced impact (6.97 kWh kg^{-1}).

The gate-to-gate cell production has a relatively small impact on the overall energy consumption, ranging between 25–28 $kWh_{prod.}$ kWh_{cell}^{-1} for NMC|Gr and NCA|Gr based on today's production technology and know-how for LIB production. Owing to significantly lower energy densities, the cell production accounts for 36 $kWh_{prod.}$ kWh_{cell}^{-1} for LFP|Gr and 32–50 $kWh_{prod.}$ kWh_{cell}^{-1} for SIBs, underlying the importance of increasing energy density.

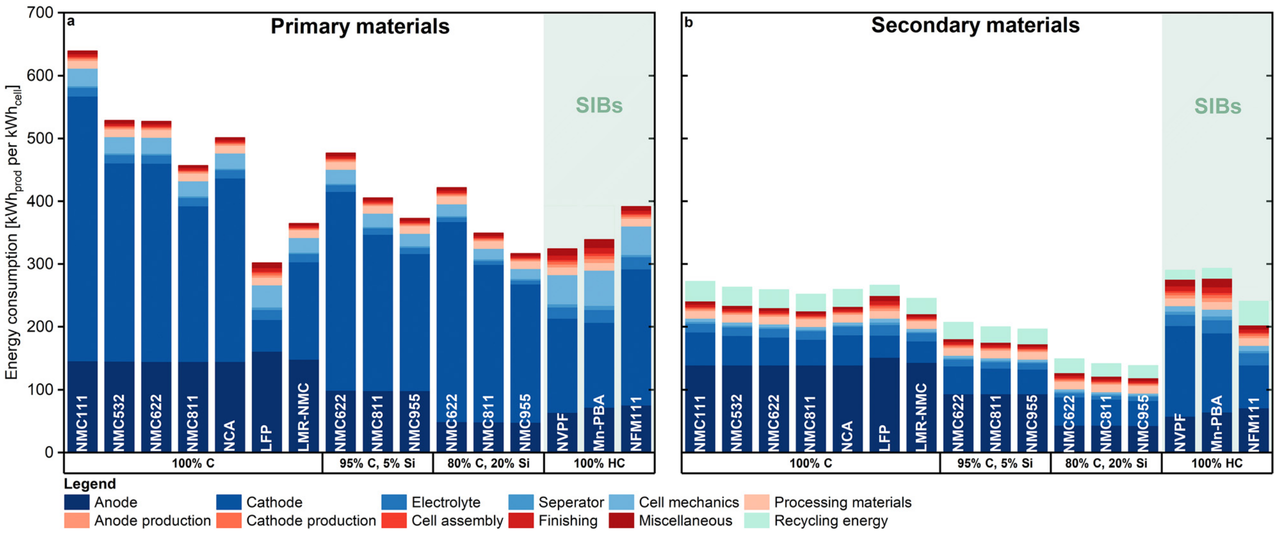

Fig. 4 Cradle-to-gate (a) and cradle-to-cradle (b) CED of selected LIB and SIB cells in a prismatic cell format based on primary and secondary materials. The underlying cell parameters are applied in the SI Table S8. Processing materials includes solvents for mixing, as well as compressed air, argon and nitrogen. The miscellaneous category includes material handling operations during cell production, dry rooms (dew point: 40 °C) and the NMP recovery system. Hydrometallurgical recycling recovers nickel, cobalt, manganese (98% recovery rate) and lithium, aluminum and copper (90% recovery rate). The cathode thickness is set at 90 μm.

Combined, LFP|Gr emerges as the most energy-efficient to produce at cell level with approx. 300 $kWh_{prod.}$ kWh_{cell}^{-1}, which is nearly half of the CED of NMC622|Gr. Following LFP|Gr, NVPF|HC has the second-lowest CED, closely followed by PBA|HC. NFM|HC has a slightly higher energy consumption due to the $NiSO_4$ precursor. Overall, SIBs are therefore competitive with NMC|Gr and NCA|Gr in terms of energy consumption, but the production per kWh_{cell} requires 20–90 kWh more than LFP|Gr cells, which are considered the competing technology. For pure graphite cells, LMR-NMC stands out regarding the CED, achieving a high energy density due to its high practical capacity of 250 mAh g^{-1} and the utilization of the low impact material $MnSO_4$ (3.7 kWh kg^{-1}). The use of silicon-rich anodes would further reduce energy consumption.

Since a large part of the mining and refining of important battery materials takes place outside of Europe,[101] recycling of battery cells is important for Europe to reduce dependence on other countries and in transition to a circular economy, to reduce pressure on natural resources. In Fig. 4b, the CED of cells based on secondary materials is shown. The recycling energy was modeled utilizing a hydrometallurgical process according to Jiang *et al.*,[72] based on industrial data for NMC|Gr and LFP|Gr recycling. For the recycling process 15–38.4 kWh kWh_{cell}^{-1} are needed, in line with the advanced process by Düsenfeld, which is published by Mohr *et al.*[107] In contrast to the CED of battery cells based on primary materials, SIB and LFP|Gr cells exhibit the highest CED for secondary cells, as only less energy intensive materials are recovered (LFP: Li_2CO_3 and NFM: $NiSO_4$). For NVPF|HC and PBA|HC, only aluminum is recovered. In case of NVPF|HC cells, significant potential for energy reduction originates from vanadium recycling, as energy intensive vanadium pentoxide (105 kWh kg^{-1})[108] is used in CAM synthesis. In general, processes need to be developed for SIBs that are tailored for SIB recycling to be competitive in terms of CED of battery cells based on secondary materials. Nevertheless, recycling can further mitigate battery life cycle impacts for cells with low elemental value. In the assumptions made in this work, the reduction potential of secondary NVPF|HC and PBA|HC cells are still 10.5% (−34 kWh) and 13.6% (−46 kWh), respectively. The savings potential for LFP|Gr is in the same order of magnitude (11.9%). Significant energy savings can be achieved for NMC and NCA-based LIBs and NFM111|HC cells. The savings range from approx. 119 kWh (LMR-NMC|Gr) to 367 kWh (NMC111|Gr), with most being over 50% (NFM111|HC: 151 kWh, 38%). Overall, the CEDs of secondary cells containing pure graphite are in the same range (252–272 kWh kWh_{cell}^{-1}). As the silicon content increases, the CED decreases significantly. For NMC955|Gr + 20 wt% silicon, the CED drops to just 139 kWh kWh_{cell}^{-1}, representing a 52.2% reduction compared to LFP|Gr. Compared to cells produced from primary materials, the percentage contribution of cell production based on secondary materials gains increasing relevance in the transition to a circular economy. Most of the energy consumption of secondary cells is attributed to the anode, indicating that at least in terms of energy consumption, graphite recycling is of great interest.

European cell production energy demand

Fig. 5 depicts the energy demand for electrifying Europe (a–c), as well as the energy that must be supplied within Europe to achieve self-sufficiency by 2050 (d–f, marked areas). These results represent the base case, derived from three backcasting scenarios, namely NMC, LFP and SIB, selected in light of uncertainties related to technological developments, market dynamics and geopolitical conflicts. As shown in Fig. 5a–f, a significant share of the cradle-to-cradle energy demand in the initial forecast years orginates from mining and refining of highly energy intensive NMC precursors (LiOH, Li_2CO_3, $NiSO_4$, $CoSO_4$ and $MnSO_4$). CAM synthesis includes all other required precursors in addition to LiOH, Li_2CO_3, $NiSO_4$, $CoSO_4$ and $MnSO_4$, as well as the energy needed for producing the CAM. AAM synthesis energy includes the production of graphite, silicon and HC. Additionally, the energy demand also accounts for metals, non-active materials and battery cell and scrap production. The model predicts that in 2030 520 GWh $year^{-1}$ and after 2040 1 TWh $year^{-1}$ of battery capacity are needed annually.

In 2024, the energy demand for producing LIB cells for 2.5 million EVs and approx. 22.4 GWh of SES capacity across all three scenarios is around 50 TWh. Almost 45% of this energy is required for the mining and refining of LiOH, Li_2CO_3, $NiSO_4$, $CoSO_4$ and $MnSO_4$ and a significant share also arises from CAM and AAM synthesis. The peak energy demand is projected to be reached in 2035 and will increase by a factor of 7.7 in the NMC scenario, 7.2-fold in the LFP scenario and 7.3-fold in the SIB scenario. In the NMC scenario, energy demand is projected to reach 378 TWh by 2035, primarily due to the energy intensive production of NMC|Gr cells based on primary materials (see Fig. 4a). In total, the production of CAM and AAM (including mining, refining and synthesis) represents 80% of the energy requirements in 2035, while gate-to-gate battery cell production contributes only about 6.4%. Although the EV battery capacity demand remains steady in the following years and SES demand rises, the energy consumption in the NMC scenario decreases significantly starting from 2035 and reaches a steady state by 2050. This decline is primarily attributed to recycling, as valuable and energy intensive precursors for NMC production are recovered. By 2070, it is forecasted that the energy demand drops to 206 TWh, a reduction of 45%, with recycling accounting for 10.4% of the total energy demand.

The LFP scenario (Fig. 5b and e) has the lowest peak energy demand compared to the NMC (Fig. 5a and d) and SIB (Fig. 5c and f) scenarios. The model predicts approx. 340 TWh in 2035, which is 11% lower than in the NMC scenario (see Fig. 6). This difference is due to significantly less energy intensive production of LFP|Gr, highlighting substantial short-term reduction potentials from CAM materials that do not use critical raw materials such as nickel and cobalt. However, the total energy demand from 2024–2070 is only 3.7% lower and will require more energy beyond the forecast period (see Fig. 6). The lower energy savings that come with recycling are the main reasons for this. Furthermore, the production of AAM, metals, non-active materials and battery cells has a higher impact, resulting

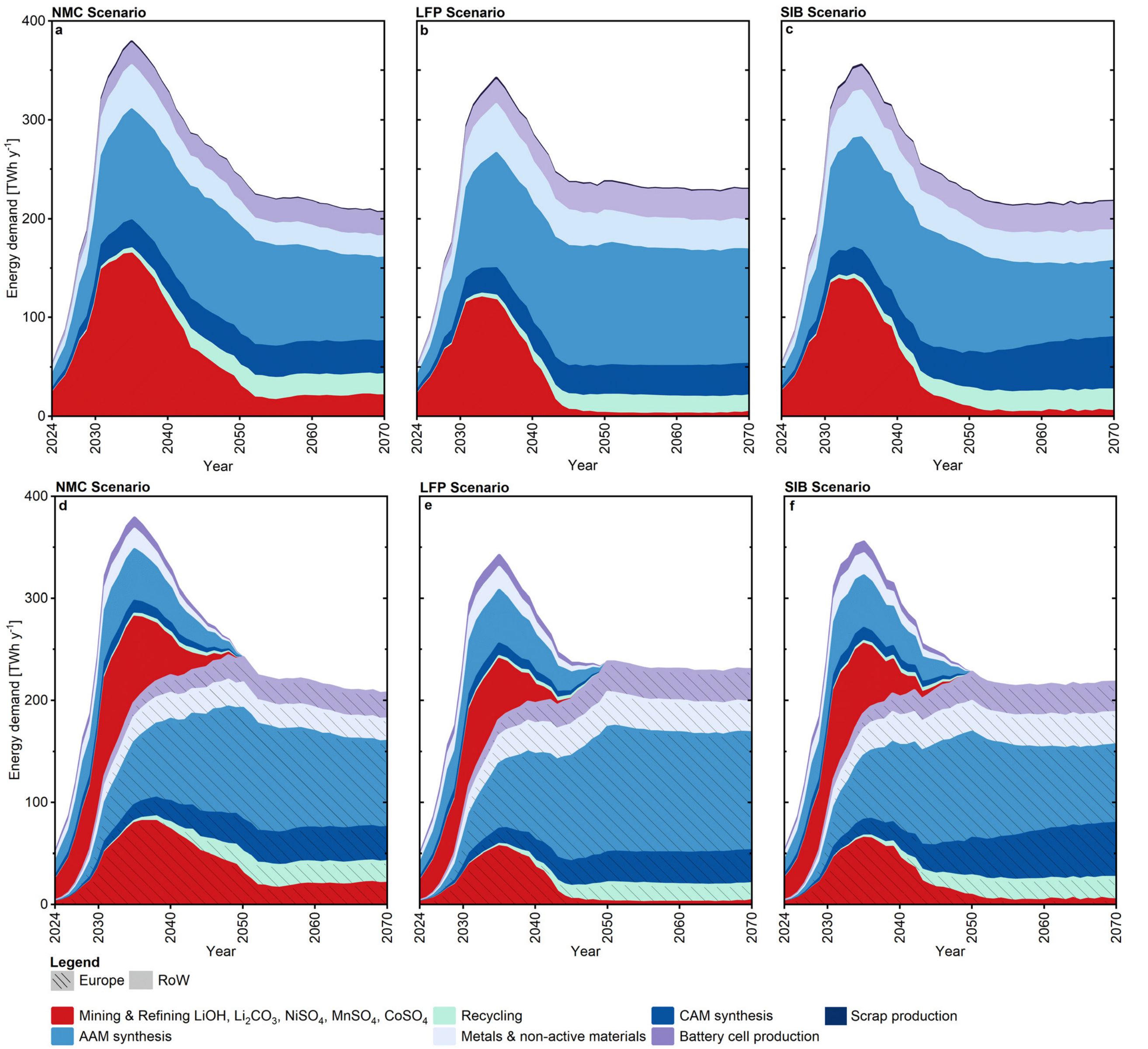

Fig. 5 Cradle-to-cradle energy demand projections for electrifying Europe (a)–(c) and the distribution of the energy in local required energy in Europe (marked areas) and imported energy (RoW) (d)–(f). The determination of local energy requirements in Europe is based on the current global market shares of the battery value chain, as well as the CRMA and NZIA targets for 2030. For 2050, we modeled that Europe would be self-sufficient. The values from 2030 to 2050 were linearly extrapolated. Three scenarios are applied, namely NMC (a) and (d), LFP (b) and (e) and SIB (c) and (f). For clarity, the battery scrap production is not shown in (d)–(f). TWh 10^9 kWh.

from their lower energy density. The proportion of AAM synthesis increases from 30% to 50%, the share of gate-to-gate cell production is predicted to increase from 6% to 14%, while the share of metals and non-active materials will remain relatively constant in the range of 12–15% throughout the forecast period. The SIB scenario (Fig. 5c and f) represents a combination of the LFP and NMC scenarios in the initial years, as SIBs are predicted to enter the European market in 2030–2035. As in all scenarios, CAM and AAM synthesis are the main energy drivers, but the more energy intensive CAM synthesis compared to LFP-based LIBs is offset by the less energy intensive HC synthesis, resulting in an overall lower energy demand. The impact of cell production and metals and non-active materials is in the same order of magnitude compared to the LFP scenario. Total energy consumption from 2024–2070 is 4.5% and 0.7% lower than in the NMC and LFP scenarios, respectively. However, it should be noted that a substantial SIB share is projected towards the end of the forecast period and that SIBs have the highest energy consumption (kWh kWh_{cell}^{-1}) for secondary cells. As a result, the influence of SIBs based on secondary materials only become apparent from 2070 onwards.

While the base case provides a reference point, future energy demand will depend on a range of variables whose evolution remains uncertain. One major factor is the emergence of

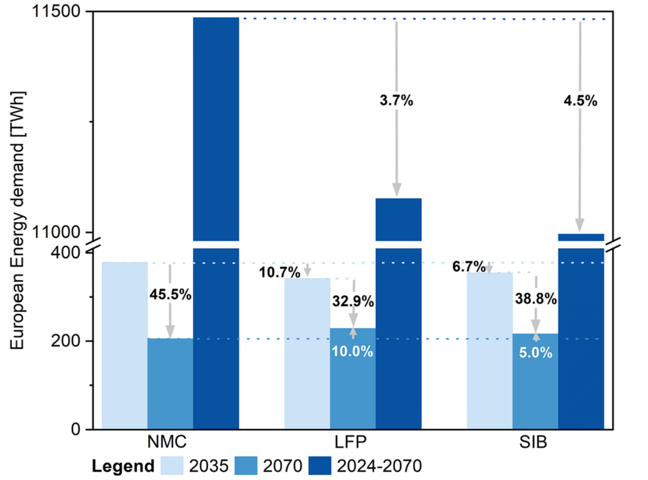

Fig. 6 European energy demand comparison for the NMC, LFP and SIB scenarios (based on Fig. 5a–c). The peak energy demand in 2035, the last year of the forecast (2070) and the overall energy demand from 2024–2070 are depicted.

post-lithium-ion technologies. Solid-state batteries have the potential to reduce the gate-to-gate cell production energy demand to 10.6–17.5 $kWh_{prod.}$, lithium–sulfur batteries to 13.4 $kWh_{prod.}$ and lithium air batteries to 20.9 $kWh_{prod.}$.[16] This contrasts substantially with present large-scale LIB technologies such as LFP|Gr (36 $kWh_{prod.}$) and NMC811|Gr (25 $kWh_{prod.}$), highlighting potential energy reductions. However, to assess the impact of these post-lithium-ion technologies, the materials are of crucial importance, requiring cradle-to-gate CED analyses with large-scale synthesis data. A recent study models a high CED of 493–655 kWh kWh_{cell}^{-1} for oxide-based solid-state batteries,[109] significantly higher than for silicon-containing NMC cells. Furthermore, it remains uncertain if and when these technologies will achieve market penetration and their adoption would necessitate modifications to existing manufacturing lines.[16] By contrast, SIBs are considered in this analysis as they represent a drop-in technology and are on the verge of large-scale commercialization.[27] Further improvements may arise from advances in the gate-to-gate production processes, as demonstrated by Degen *et al.*,[16] including dry coating, integration of heat pumps and efficiency improvements from learning effects and economies of scale, with potential savings of up to 66%. Nevertheless, as the gate-to-gate cell production is only projected to account for around 5–6% of total energy consumption in the base case by 2040, substantial overall reductions can only be achieved by significantly improving the energy efficiency of raw material mining and refining. A key focus is the optimization of comminution processes, where crushing and grinding represent the largest opportunities for energy savings.[110–112] Emerging technologies such as high-pressure grinding rolls and stirred mills have the potential to substantially contribute to these reductions. Additionally, adopting advanced combustion technologies[110] and optimizing the energy supply can further enhance overall efficiency, with one study reporting that the U.S. metal mining sector could reduce its energy consumption by about 61% by shifting from current practices to the best-estimated practical minimum energy use.[113] In the refining stage, considerable energy savings can be achieved by implementing new metallurgical processes. For nickel production, for instance, these include ore pre-concentration, transitioning to bath smelting technology and utilizing bioleaching in hydrometallurgical processing.[111]

However, this technological progress is offset by several factors that are expected to drive higher energy inputs in the mining industry in the future. Declining ore grades for metals such as copper, nickel, cobalt and lithium mean that larger volumes of rock must be mined, crushed and processed, leading to an increased energy consumption.[102,113] Furthermore, the development of more challenging deposits, characterized by deeper orebodies, remote locations, and more complex mineralogy, is anticipated to raise energy intensity.[102,113] Hence, energy inputs in mining have already risen substantially in the 21st century and are expected to continue increasing in the coming decades as these trends persist.[113]

The largest potential for reducing energy demand of LIBs is derived from AAM synthesis, as illustrated in Fig. 5. This is driven by improved material recovery for synthetic graphite,[38] increased utilization of silicon and natural graphite[105,114] and especially by graphite recycling. The concept of recycling anode materials back into the battery supply chain is still a relatively new process and remains largely in the research and development phase.[115] This is primarily because graphite[116,117] has received less attention in LIB recycling compared with high-value cathode metals such as cobalt,[118] nickel[119] and lithium.[120] Furthermore, concerns over the purity and electrochemical performance of recycled materials have hindered commercial utilization. Hence, graphite anodes have been downcycled or used in lower-value applications.[121] Significant innovations are required to establish a profitable and sustainable industrial-scale recycling process that meets the high-performance requirements for LIB anode materials[122] (see SI for details). In Europe, political incentives are still lacking: the EU's Battery Regulations set mandates for recycled content in new batteries, yet graphite was notably excluded despite being designated a critical mineral under the CRMA.[123] This exclusion is particularly striking given that recycling graphite also presents a strategic opportunity to reduce dependence on China.

Furthermore, there is a growing need for more tailored recycling processes for SIB recycling, such as recovering vanadium pentoxide from NVPF cathodes. Reduction potential also exists through increasing the energy density of battery cells. For example, the specific energy density of LIBs has doubled over the past decades, rising from around 150 Wh kg^{-1} to approx. 300 Wh kg^{-1}.[18] In the case of SIBs, further improvements are expected primarily through increases in the specific capacity of HC anodes, which could exceed 400 mAh g^{-1}.[27]

Future energy demand could increase significantly if circular economy strategies, such as recycling and second use, are implemented less extensively than modeled in this study. The analysis assumes sufficient recycling capacities and a collection rate of 97% (additional 1% EV loss rate). Failure to meet these recycling rates and recovery efficiencies would lead to a substantial rise in energy demand. Under the study's assumptions, recycling in the NMC scenario saves approx. 5100 TWh of energy, averaging 118 TWh annually throughout the forecast period. Fig. 4 demonstrates that recycling is environmentally attractive even for cathode materials with lower elemental value, contributing to annual energy savings of 67 TWh and 84 TWh in the LFP and SIB scenarios, respectively. Moreover, if recycled raw materials fail to meet battery-grade quality and necessitate additional energy-intensive refining, overall energy demand will further increase.

The presented base case is also based on strong EV fleet growth until 2035, which is uncertain, especially if the ban on ICEV sales in the EU is lifted.

Local European cell production energy demand

In Fig. 5a–c and Fig. 6, the energy demand for electrifying Europe is depicted, whereby the question arises how much energy will be needed within Europe with a focus on implications for the European battery value chain. Europe has only significant capacities in manganese mining (5%) and in the refining of cobalt (19%), nickel (11%) and manganese (8.4%).[11] Additionally, Europe only accounts for the global production of 3% CAM, 2% AAM, 4% electrolyte and 2% seperator.[124] Battery production represents 8.5% of cells that are globally produced, meaning that nearly all the energy for battery production is sourced abroad, whereby China dominates the supply chains of all materials.[11] To strengthen national capabilities and to reduce reliance on other countries, the EU proposed the CRMA in 2023, which aims to achieve an extraction capacity of 10% of the EU's annual demand for strategic raw materials, a processing capacity for 40% and recycling capacity for 25% by 2030. For battery manufacturing, these strategic raw materials include lithium, nickel, cobalt, manganese, silicon, aluminum, copper and graphite.[13] Furthermore, as stated in the NZIA, the EU targets 40% local production of CAM, AAM and battery cells.[15] Starting from 2050, we modeled, that Europe will be self-sufficient. The individual shares were linearly extrapolated from 2030 to 2050 (SI Table S5).

In 2024, only about 3 TWh of energy used for cradle-to-cradle battery cell production is sourced domestically in Europe, despite the region representing nearly 25% of the global EV market.[11] This indicates that almost all the energy needed for electrification is imported currently, leading to significant energy dependency. By ramping up the local LIB and SIB supply chains, dependency on other countries is reduced, but the energy demand is consequently shifted to Europe. This model projects that local energy demand will rise to 83–87 TWh annually by 2030 in the base case to meet the stated CRMA and NZIA targets, representing approx. 35% of the total energy required for battery cell production. In order to achieve self-sufficiency by 2050, the annual domestic energy demand would still need to triple to around 250 TWh, assuming that circular economy approaches are prevalent by then (see Fig. 5d–f and 7). The use of SLB in the less-demanding application SES sector leads to energy savings of 9–11 TWh

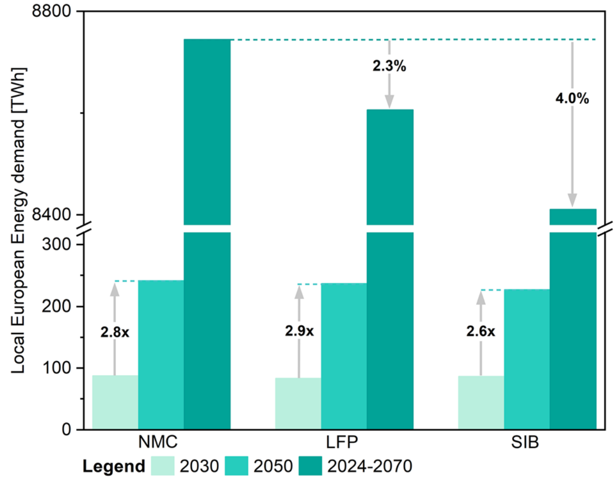

Fig. 7 Local European energy demand comparison for the NMC, LFP and SIB scenarios (based on Fig. 5d–f). The comparison includes the year 2030, for which targets have been set through the CRMA and NZIA regulations, the year 2050, in which we assume self-sufficiency for Europe and the entire forecast period from 2024 to 2070.

annually on average across the three scenarios. Furthermore, the recycling supply of end-of-life batteries is postponed, resulting in more time to build up recycling capacities. Overall, it is crucial for Europe to minimize the electric vehicle loss rate, maximize the recycling collection rate and build up the recycling infrastructure.

Local European energy demand considering use phase

The EV lifetime (calendric and cycle), fuel efficiency and round-trip efficiency of a battery have a strong influence on the environmental impacts related with its use phase. The sales-weighted fuel efficiency was calculated at cell level, shown in SI Table S1 for both small and large BEVs resulting in 7.82 km kWh^{-1} for small and 7.05 km kWh^{-1} for large BEVs. The cell-specific fuel efficiencies are shown in Table 2. Additionally, Table 2 presents initial round-trip efficiency values, which are also based at the cell level, for which there is limited literature available, particularly for EV-relevant C-rates of ≤ 0.4C.

Fig. 8 illustrates the projected local European energy demand for domestic cradle-to-cradle cell production, EV charging and the efficiency losses (for both EV and SES) in the NMC (a), LFP (b) and SIB (c) scenarios. The European energy demand for battery cell production is derived from Fig. 5 (marked areas). The model projects that by 2045 the charging energy demand for approx. 140 million EVs in Europe will reach around 210–215 TWh in all scenarios. This represents a tenfold increase from 2024 levels and a threefold rise in EV energy consumption between 2030 and 2045. These trends are consistent across all three scenarios, despite variations in fuel efficiency among the different battery technologies. While NMC|Gr cells demonstrate the highest fuel efficiency, resulting in the lowest energy consumption in the NMC scenario, the differences are relatively minor. Over the entire forecast period, the EV charging energy demands for the LFP and SIB scenarios are only 109 TWh and 83 TWh higher,

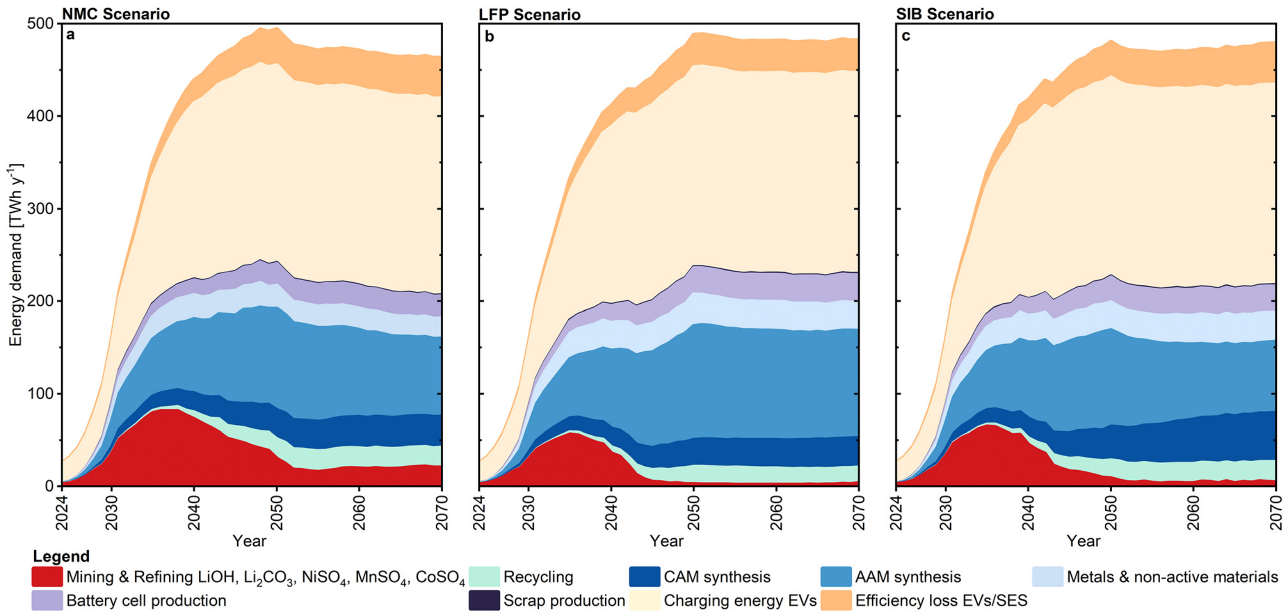

Fig. 8 European energy demand projections for the NMC (a), LFP (b) and SIB (c) scenarios until 2070 divided into cradle-to-cradle battery cell production and the EV and SES use phase. The use phase includes EV charging energy and EV and SES inefficiency losses.

respectively. Variations in round-trip efficiency led to overall losses that are approx. 165 TWh and 148 TWh higher for the NMC and SIB scenarios, respectively, in contrast to the LFP scenario. Overall, efficiency losses have a significant impact resulting in efficiency losses during the EV use phase ranging from 4% to 7%. This impact is even more dominant for SES batteries, which undergo 250 discharge cycles per year (SI Fig. S12). Additionally, because SES batteries have a longer service life and are reused from the automotive sector, the influence of the annual degradation factor of 0.2% on the energy efficiency becomes more substantial. Combined, efficiency losses are projected to increase from around 7 TWh in 2030 to over 35 TWh in 2070, underscoring an essential area of battery research. Minimizing future efficiency losses could be achieved through thermal management and optimization of charging and discharging rates by using advanced charging algorithms and implementing smart charge/discharge control systems.[125] Further, potential reduction arises from improvements in material properties, electrode characteristics and operating conditions.[76] Large voltage hysteresis occurs for silicon-containing anodes, which can be attributed to the significant kinetic resistance experienced during the lithiation/delithiation process,[126] as well as the compressive stress that arises during lithiation.[127] The issues of low coulombic efficiencies are related to the substantial volume changes of silicon and ongoing solid electrolyte interphase formation and electrolyte decomposition.[128,129] Future developments addressing these issues could improve energy efficiency. Similarly, LMR-NMC cathodes exhibit large voltage hysteresis and potential decay, which could be addressed by surface treatments.[85] For SIBs, potential efficiency improvements exist through cycling at high states of charge, as demonstrated by Rehm *et al.* for NFM|HC cells.[130] For next-generation battery technologies, targeted research to minimize such inefficiency losses will be critical for future system performance and sustainability. Developing new electrode materials with huge overpotentials are therefore not of great practical interest.[78] It is important to note that we consider round-trip efficiencies at the cell level. In practice, the remaining components of a battery system (*e.g.*, pack and module casing, inverter and battery management systems) contribute additionally to lower overall efficiencies.

The local energy demand in Europe for battery cell production, EV charging and inefficiency losses (EV and SES) is projected to increase sixfold from 2024 to 2030 and twentyfold until 2050. To achieve self-sufficiency starting in 2050, Europe must supply 450–500 TWh annually in all three scenarios, sourced primarily from electricity. McKinsey predicts an average growth in electricity demand of 1.1% per year from 2020 to 2050 in Europe, which is 0.4% lower than the average annual growth observed between 1990 and 2007.[124] This corresponds to an energy increase of approx. 1400 TWh, reaching around 4900 TWh by 2050. This is equivalent to an average rise of 45 TWh per year or about 66 TWh annually between 2023 and 2030 (460 TWh in total).[131] Based on our calculations, the average annual growth rate of battery-related electricity demand is projected at +35% from 2024 to 2030, averaging around 22 TWh per year. An average annual growth rate of +12.9% is projected until 2050, thus expanding disproportionately compared with overall electricity demand. Consequently, based on assumptions made in this study, batteries account for roughly one-third of McKinsey's projected additional electricity demand in both 2030 and 2050. Meeting the additional energy demand would be feasible for Europe but entails considerable uncertainties and challenges. To meet the increasing demand with natural gas power plants, Europe would need to double electricity generation from natural gas (450 TWh in 2023[132]).

To produce the energy entirely from solar panels, an area of ~2300 km^2 would be required, based on the assumption that one m^2 of solar panels generates 220 kWh $year^{-1}$.[133] That correspond approx. to the size of US state Rhode Island or 2.5 times the area of Berlin. Furthermore, approx. 250–300 TWh of electricity will be required for EV charging alone by 2040, with demand occurring largely in a decentralized manner. This necessitates the large-scale deployment of charging infrastructure. Additionally, capacity issues in the power grid, including long lead times for grid connections, highlight the urgency of expanding distribution networks.[134] Substantial investments will be needed in generation assets, transformers, local grids and charging points. At the same time, the continued expansion of renewable energy capacity is essential to meeting climate targets. However, permitting procedures and slow build-out speeds remain critical bottlenecks and the increasing share of renewables tends to drive higher overall system costs.[135] These developments underscore the dual challenge of decarbonizing the power system while maintaining affordability and system stability.[136] Nevertheless, large-scale electrification combined with clean domestic power generation offers significant benefits for Europe's security of energy supply. Reducing dependence on imported fossil fuels not only strengthens resilience but also represents a key step toward achieving long-term climate goals. Although Europe may not have a classical comparative advantage in large-scale battery cell production due to higher costs compared to Asia, strategic factors are crucial. Advanced recycling technologies could give Europe a comparative advantage by enabling the more efficient use of critical raw materials and reducing reliance on imports. Integration with the local automotive industry and the growing renewable energy sector can further enhance system-level efficiency and innovation. Together, these factors enable Europe to optimize resource allocation, strengthen energy security and reduce economic dependency. This avoids a shift from reliance on fossil fuels to another form of energy and economic vulnerability.

The substantial growth in electricity demand driven by electrification also results in a considerable decline in fossil fuel consumption, as illustrated in Fig. 9, which quantifies the potential savings in both locally produced and imported energy. The modeling accounts for the upstream energy demand associated with the production of petroleum-based products for use in ICEVs, as well as for electricity generation from natural gas, coal and oil, including both upstream energy and energy losses during the electricity generation process. It is important to note that this refers solely to the energy required for these processes and not to the embedded energy of fossil fuels. Gasoline and diesel are produced from crude oil, only about 23% of which is sourced locally in Europe.[137] By 2045, the transition to EVs is projected to reduce local upstream energy for petroleum fuels by 35 TWh per year, while avoiding around 120 TWh of energy imports. For electricity generation, SES systems with a capacity of 1600 GWh are expected to store and release approx. 500 TWh of electricity per year by 2050 (see SI Fig. S12). Between 2050 and 2070, this saves 90–110 TWh of upstream fossil fuel energy, about half of which is locally produced. Overall, local energy savings would amount to 21 TWh by 2030, rising to around 90 TWh in 2050, considering current shares of locally produced and imported fossil fuels.

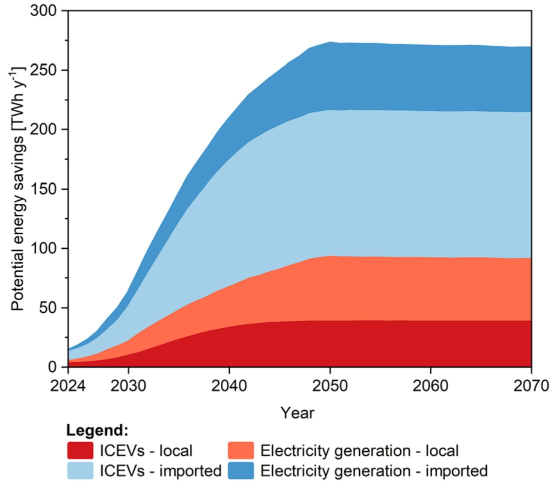

Fig. 9 Potential upstream energy savings from fossil fuels in ICEVs, as well as from electricity generation during the transition to EVs and SES systems, with energy divided into local and imported sources.

Conclusions

Europe's current dependence on foreign resources for battery production arises from the concentrated distribution of critical materials. Despite accounting for nearly 25% of global EVs in 2024, Europe relies on a mere 6.8% of domestically sourced energy for battery cell production, importing most of the required energy in terms of materials and battery cells. Strengthening local supply chains is crucial for reducing energy dependency, but it also necessitates supplying a substantial amount of energy from within Europe.

This study quantifies the energy demand associated with large-scale battery cell production to electrify Europe, divided into locally required and imported energy. The model projections indicate that, for the NMC scenario, the cradle-to-cradle battery cell production to electrify Europe will demand approx. 380 TWh of energy by 2035. Similar estimates for the LFP (340 TWh) and SIB scenarios (355 TWh) underscore the substantial rise in overall energy demand. However, only a limited share of approx. 35% would be produced locally within Europe based on the forecast. To achieve self-sufficiency by 2050, Europe's local energy demand for battery cell production is projected to rise to approx. 250 TWh. An additional 200–250 TWh will be needed to power EVs and to compensate for efficiency losses during the discharge of EVs and SES applications, reflecting the unique approach of this model, which incorporates both EV fuel efficiency and round-trip efficiency losses. Combined, a projected 450–500 TWh annually will be needed from 2038 until 2070, highlighting significant amounts of energy thus need to be supplied for the transition to EVs and renewable energy storage (see Fig. 8). This is offset by 90 TWh of upstream fossil fuel energy. The European battery industry will require access to affordable, abundant and reliable energy in order to successfully achieve the transition toward self-sufficiency.

Mining and refining processes for lithium, nickel, cobalt and manganese are projected to account for nearly half of the total energy demand of battery cell production in the initial years, while recycling is significantly less energy intensive. It should be noted that sufficient recycling capacities are assumed in the base case (800 GWh $year^{-1}$ by 2050), although the recycling infrastructure is still in very early stages (SI Fig. S11). The assumption of a 50% collection rate of end-of-life batteries would increase the energy demand in the NMC scenario by 2500 TWh, adding an average of additional 54 TWh annually for the entire forecast period. For Europe, maximizing collection rates and recycling efficiencies will be essential, while graphite recycling and tailored recycling processes for SIBs offer further potential to reduce energy demand.

Building on this extended portfolio, future work could analyse the potential factors influencing the overall energy intensity of battery manufacturing, as outlined in this study. These factors include the impact of next-generation batteries and improvements in energy efficiency, particularly in the mining and refining industries. Additionally, the associated abatement costs could be examined further. It can be concluded that European policymakers need to implement effective and supportive regulations that enable companies to develop viable, sustainable recycling capabilities. Such measures will be instrumental in mitigating future energy demand, reducing dependence on imports and ensuring a stable, long-term supply of critical battery materials. Meeting these goals will also require substantial investment in renewable electricity and supporting infrastructure. Ultimately, large-scale electrification combined with clean domestic power generation will strengthen Europe's energy security and mark a decisive step towards achieving long-term climate goals.

Author contributions

L. I.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, visualization and writing – original draft, A. S.: conceptualization, formal analysis, investigation and methodology, M. G.: writing – review & editing, S. L.: conceptualization, funding acquisition, software, resources, supervision and writing – review & editing.

Conflicts of interest

There are no conflicts to declare. The author's utilized ChatGPT to enhance readability during the preparation of this work. After employing this tool, we thoroughly reviewed and edited the content as necessary, assuming full responsibility for the final publication.

List of abbreviations

AAM	Anode active material
AM	Active material
BEV	Battery electric vehicle
BOM	Bill of material
CAM	Cathode active material
CED	Cumulative energy demand
C&I	Commercial & industrial
CRMA	Critical raw material act
EU	European Union
EV	Electric vehicle
Gr	Graphite
HC	Hard carbon
ICEV	Internal combustion engine vehicle
LCA	Life-cycle assessment
LIB	Lithium-ion battery
LFP	Lithium iron phosphate
LMR	Lithium- and manganese-rich
Mn-PBA	Manganese-Prussian blue analogue
NCA	Lithium nickel cobalt aluminum oxide
NFM	Sodium nickel iron manganese oxide
NMC	Lithium nickel manganese cobalt oxide
NVPF	Sodium vanadium fluorophosphate
NZIA	Net Zero Industry Act
pCAM	Precursor cathode active material
PHEV	Plug-in electric vehicle
RoW	Rest of World
SES	Stationary energy storage
SIB	Sodium-ion batteries
SLB	Second life batteries

Data availability

The data supporting this article have been included as part of the SI. See DOI: **https://doi.org/10.1039/d5ee02287h**.

The production model used in this study is primarily based on the framework developed by Degen *et al.*, available under "Source Data Fig. 3" at **https://doi.org/10.1038/s41560-023-01355-z**.

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References

1 J. Xie and Y.-C. Lu, *Nat. Commun.*, 2020, **11**, 2499.
2 A. Masias, J. Marcicki and W. A. Paxton, *ACS Energy Lett.*, 2021, **6**, 621–630.

3 International Energy Agency, Trends in electric cars. Global EV outlook 2024, https://www.iea.org/reports/global-ev-outlook-2024/trends-in-electric-cars, accessed 18 November 2024.
4 Neil Winton, Europe To Buy Nearly 9 Million Fewer EVs By 2030 Than Expected: Report, https://www.forbes.com/sites/neilwinton/2024/04/08/europe-to-buy-nearly-9-million-fewer-evs-by-2030-than-expected-report/, accessed 14 August 2024.
5 European Parliament, EU ban on the sale of new petrol and diesel cars from 2035 explained, https://www.europarl.europa.eu/topics/en/article/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained, accessed 22 February 2025.
6 Council of the EU & European Council, Fit for 55, https://www.consilium.europa.eu/en/policies/fit-for-55/, accessed 18 November 2024.
7 S. Link, L. Schneider, A. Stephan, L. Weymann and P. Plötz, *Nat. Energy*, 2025, **10**, 526–534.
8 BloombergNEF, Lithium-Ion Batteries: State of the Industry 2023, 2023.
9 International Energy Agency, Global EV Outlook 2023. Catching up with climate ambitions, 2023.
10 European Commission, Study on the critical raw materials for the EU 2023, 2023.
11 A. L. Cheng, E. R. H. Fuchs, V. J. Karplus and J. J. Michalek, *Nat. Commun.*, 2024, **15**, 2143.
12 T. Greitemeier, A. Kampker, J. Tübke and S. Lux, *J. Power Sources Adv.*, 2025, **32**, 100173.
13 Regulation (EU) 2024/1252 of the European Parliament and of the Council, establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020, 2024.
14 Regulation (EU) 2023/1542 of the European Parliament and of the Council, concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC, 2023.
15 European Comission, The Net-Zero Industry Act: Accelerating the transition to climate neutrality, https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en, accessed 17 March 2025.
16 F. Degen, M. Winter, D. Bendig and J. Tübke, *Nat. Energy*, 2023, **8**, 1284–1295.
17 S. Davidsson Kurland, *Environ. Res. Commun.*, 2020, **2**, 12001.
18 Y. Liu, R. Zhang, J. Wang and Y. Wang, *iScience*, 2021, **24**, 102332.
19 Q. Dai, J. C. Kelly, L. Gaines and M. Wang, *Batteries*, 2019, **5**, 48.
20 J. B. Dunn, L. Gaines, J. C. Kelly, C. James and K. G. Gallagher, *Energy Environ. Sci.*, 2015, **8**, 158–168.
21 J. B. Dunn, C. James, L. Gaines, K. Gallagher, Q. Dai and J. C. Kelly, *Material and Energy Flows in the Production of Cathode and Anode Materials for Lithium Ion Batteries*, 2015.
22 J. Wesselkämper, L. Dahrendorf, L. Mauler, S. Lux and S. von Delft, *Resour., Conserv. Recycl.*, 2024, **201**, 107218.
23 C. Xu, P. Behrens, P. Gasper, K. Smith, M. Hu, A. Tukker and B. Steubing, *Nat. Commun.*, 2023, **14**, 119.
24 F. Maisel, C. Neef, F. Marscheider-Weidemann and N. F. Nissen, *Resour., Conserv. Recycl.*, 2023, **192**, 106920.
25 R. Jiang, C. Wu, W. Feng, K. You, J. Liu, G. Zhou, L. Liu and H.-M. Cheng, *Sci. Rep.*, 2025, **15**, 2267.
26 L. Mauler, F. Duffner, W. G. Zeier and J. Leker, *Energy Environ. Sci.*, 2021, **14**, 4712–4739.
27 A. Yao, S. M. Benson and W. C. Chueh, *Nat. Energy*, 2025, **10**, 404–416.
28 H. Bajolle, M. Lagadic and N. Louvet, *Energy Res. Soc. Sci.*, 2022, **93**, 102850.
29 G. Berckmans, M. Messagie, J. Smekens, N. Omar, L. Vanhaverbeke and J. van Mierlo, *Energies*, 2017, **10**, 1314.
30 W. McKinney, *pandas: a foundational Python library for data analysis and statistics. Python for high performance and scientific computing*, 2011, pp. 1–9.
31 P. Virtanen, R. Gommers, T. E. Oliphant, M. Haberland, T. Reddy, D. Cournapeau, E. Burovski, P. Peterson, W. Weckesser, J. Bright, S. J. van der Walt, M. Brett, J. Wilson, K. J. Millman, N. Mayorov, A. R. J. Nelson, E. Jones, R. Kern, E. Larson, C. J. Carey, İ. Polat, Y. Feng, E. W. Moore, J. VanderPlas, D. Laxalde, J. Perktold, R. Cimrman, I. Henriksen, E. A. Quintero, C. R. Harris, A. M. Archibald, A. H. Ribeiro, F. Pedregosa and P. van Mulbregt, *Nat. Methods*, 2020, **17**, 261–272.
32 F. Degen and M. Schütte, *J. Cleaner Prod.*, 2022, **330**, 129798.
33 P. Voß, B. Gruber, M. Mitterfellner, J.-D. Plöpst, F. Degen, R. Schmuch and S. Lux, *Energy Environ. Sci.*, 2025, **18**, 8104–8129.
34 Q. Dai, J. C. Kellly, J. Dunn and P. T. Benavides, *Update of Bill-of-Materials and Cathode Materials Production for Lithium-ion Batteries in the GREET® Model*, 2018.
35 J. Quan, S. Zhao, D. Song, T. Wang, W. He and G. Li, *Sci. Total Environ.*, 2022, **819**, 153105.
36 Commissariat Energie Atomique, Centre Nat Rech Scient and Univ de Picardie Jules Vernes, US2018297847 (A1), 2016.
37 S. Wickerts, R. Arvidsson, A. Nordelöf, M. Svanström and P. Johansson, *J. Ind. Ecol.*, 2024, **28**, 116–129.
38 T. Carrère, U. Khalid, M. Baumann, M. Bouzidi and B. Allard, *J. Energy Storage*, 2024, **94**, 112356.
39 R. Iyer and J. Kelly, *Updated Production Inventory for Lithium-Ion Battery Anodes for the GREET® Model, and Review of Advanced Battery Chemistries*, 2022.
40 D. Surovtseva, E. Crossin, R. Pell and L. Stamford, *J. Ind. Ecol.*, 2022, **26**, 964–979.
41 H. Liu, M. Baumann, X. Dou, J. Klemens, L. Schneider, A.-K. Wurba, M. Häringer, P. Scharfer, H. Ehrenberg, W. Schabel, J. Fleischer, N. von der Aßen and M. Weil, *J. Energy Storage*, 2022, **56**, 105964.
42 J. Yin, Y. S. Zhang, H. Liang, W. Zhang and Y. Zhu, *Mater. Rep.: Energy*, 2024, **4**, 100268.
43 R. Frischknecht, R. Itten, P. Sinha, M. de Wild-Scholten, J. Zhang, V. Fthenakis, H. C. Kim, M. Raugei and M. Stucki,

Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems, 2015.
44 S. Chae, S.-H. Choi, N. Kim, J. Sung and J. Cho, *Angew. Chem.*, 2020, **59**, 110–135.
45 Automotive Industry Portal MarkLines, Connect to the global automotive industry. database, https://www.marklines.com/en/, accessed 14 August 2024.
46 Statista Market Insights, *Plug-in Hybrid Electric Vehicles – Europe*, https://www.statista.com/outlook/mmo/electric-vehicles/plug-in-hybrid-electric-vehicles/europe#unit-sales.
47 S. Li, B. Wang, M. Yang and F. Zhang, The Global Diffusion of Electric Vehicles: Lessons from the First Decade, https://documents1.worldbank.org/curated/en/225111639490843204/pdf/The-Global-Diffusion-of-Electric-Vehicles-Lessons-from-the-First-Decade.pdf, accessed 12 March 2025.
48 M. Abdelbaky, J. R. Peeters and W. Dewulf, *Waste Manage.*, 2021, **125**, 1–9.
49 DAT, Durchschnittliche Fahrleistung von Personenkraftwagen-Haltern in Deutschland von 2003 bis 2023, https://de.statista.com/statistik/daten/studie/251743/umfrage/durchschnittliche-fahrleistung-von-personenkraftwagen-in-deutschland/, accessed 14 August 2024.
50 D. Nichols, EV Battery Warranties and Exclusions, https://www.greencars.com/greencars-101/ev-battery-warranties-and-exclusions, accessed 29 October 2024.
51 C. Xu, Q. Dai, L. Gaines, M. Hu, A. Tukker and B. Steubing, *Commun. Mater.*, 2020, **1**, 99.
52 European Automobile Manufacturers' Association (ACEA), Vehicles on European Roads, https://www.acea.auto/files/ACEA-Report-Vehicles-on-European-roads-.pdf, accessed 29 October 2024.
53 United Nations Environment Programme, *Used Vehicles and the Environment: A Global Overview of Used Light Duty Vehicles – Flow, Scale and Regulation*, 2020.
54 SolarPower Europe, European Market Outlook for Battery Storage 2024-2028, https://www.solarpowereurope.org/insights/outlooks/eu-market-outlook-for-solar-power-2024-2028/detail, accessed 12 January 2025.
55 P. Sterchele, J. Brandes, J. Heilig, D. Wrede, C. Kost, T. Schlegl, A. Bett and H.-M. Henning, *Wege zu einem klimaneutralen Energiesystem. Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen*, 2020.
56 Agora Energiewende, Climate-neutral power system 2035. How the German power sector can become climate-neutral by 2035, https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_11_DE_KNStrom2035/AEW_KNStrom2035_Summary_EN.pdf.
57 J. Baars, T. Domenech, R. Bleischwitz, H. E. Melin and O. Heidrich, *Nat. Sustain.*, 2021, **4**, 71–79.
58 G. Bamana, J. D. Miller, S. L. Young and J. B. Dunn, *One Earth*, 2021, **4**, 1704–1714.
59 U.S. Geological Survey, Mineral commodity summaries 2023, 2023.
60 European Court of Auditors, The eu's industrial policy on batteries: New strategic impetus needed, https://www.eca.europa.eu/ECAPublications/SR-2023-15/SR-2023-15_EN.pdf.
61 IEA, Innovation in batteries and electricity storage, 2020.
62 B. Faessler, *Energies*, 2021, **14**, 2335.
63 K. Richa, C. W. Babbitt, N. G. Nenadic and G. Gaustad, *Int. J. Life Cycle Assess.*, 2017, **22**, 66–81.
64 H. Engel, P. Hertzke and G. Siccardo, *Second-life EV batteries: The newest value pool in energy storage*, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage#/, accessed 26 August 2024.
65 J. Figgener, P. Stenzel, K.-P. Kairies, J. Linßen, D. Haberschusz, O. Wessels, M. Robinius, D. Stolten and D. U. Sauer, *J. Energy Storage*, 2021, **33**, 101982.
66 H. Engel, P. Hertzke and G. Siccardo, Breathing new life into used electric vehicle batteries. How second-life EV batteries could disrupt the power sector and create value in energy storage, https://www.mckinsey.com/capabilities/sustainability/our-insights/sustainability-blog/breathing-new-life-into-used-electric-vehicle-batteries, accessed 29 October 2024.
67 M. H. S. M. Haram, J. W. Lee, G. Ramasamy, E. E. Ngu, S. P. Thiagarajah and Y. H. Lee, *Alexandria Eng. J.*, 2021, **60**, 4517–4536.
68 L. Yu, Y. Bai, B. Polzin and I. Belharouak, *J. Power Sources*, 2024, **593**, 233955.
69 L. Mauler, F. Duffner and J. Leker, *Appl. Energy*, 2021, **286**, 116499.
70 L. Mauler, X. Lou, F. Duffner and J. Leker, *Energy Adv.*, 2022, **1**, 136–145.
71 Fraunhofer, Umfeldbericht zu Natrium-Ionen-Batterien 2023. Status Quo und Perspektiven entlang einer zukünftigen Wertschöpfungskette, https://www.ffb.fraunhofer.de/de/news/Pressemitteilungen/Umfeldbericht-Natrium-Ionen-Batterien.html, accessed 23 April 2025.
72 S. Jiang, H. Hua, L. Zhang, X. Liu, H. Wu and Z. Yuan, *Sci. Total Environ.*, 2022, **811**, 152224.
73 M. Stephan, Battery recycling in Europe continues to pick up speed: Recycling capacities of lithium-ion batteries in Europe, https://www.isi.fraunhofer.de/en/blog/themen/batterie-update/lithium-ionen-batterie-recycling-europa-kapazitaeten-update-2024.html, accessed 12 March 2025.
74 J. Mao, C. Ye, S. Zhang, F. Xie, R. Zeng, K. Davey, Z. Guo and S. Qiao, *Energy Environ. Sci.*, 2022, **15**, 2732–2752.
75 A. L. Robinson, A. I. Taub and G. A. Keoleian, *MRS Bull.*, 2019, **44**, 920–923.
76 P. Meister, H. Jia, J. Li, R. Kloepsch, M. Winter and T. Placke, *Chem. Mater.*, 2016, **28**, 7203–7217.
77 S. Farhad and A. Nazari, *Int. J. Energy Res.*, 2019, **43**, 931–944.
78 A. Eftekhari, *Sustainable Energy Fuels*, 2017, **1**, 2053–2060.
79 Y. Preger, H. M. Barkholtz, A. Fresquez, D. L. Campbell, B. W. Juba, J. Romàn-Kustas, S. R. Ferreira and B. Chalamala, *J. Electrochem. Soc.*, 2020, **167**, 120532.
80 J. F. Peters, M. Baumann, J. R. Binder and M. Weil, *Sustainable Energy Fuels*, 2021, **5**, 6414–6429.

81 Battery Archieve, https://www.batteryarchive.org/, accessed 14 November 2024.
82 Faradion UK, Strong Performance, https://faradion.co.uk/technology-benefits/strong-performance/#:~:text=The%20(round%20trip)%20energy%20efficiency,energy%20efficiency%20of%20circa%2070%25, accessed 14 November 2024.
83 Natron Energy, https://natron.energy/files/resources/natron_bp_critical_power_battery_021124_prodnameupdate.pdf.
84 N. Tapia-Ruiz, A. R. Armstrong, H. Alptekin, M. A. Amores, H. Au, J. Barker, R. Boston, W. R. Brant, J. M. Brittain, Y. Chen, M. Chhowalla, Y.-S. Choi, S. I. R. Costa, M. Crespo Ribadeneyra, S. A. Cussen, E. J. Cussen, W. I. F. David, A. V. Desai, S. A. M. Dickson, E. I. Eweka, J. D. Forero-Saboya, C. P. Grey, J. M. Griffin, P. Gross, X. Hua, J. T. S. Irvine, P. Johansson, M. O. Jones, M. Karlsmo, E. Kendrick, E. Kim, O. V. Kolosov, Z. Li, S. F. L. Mertens, R. Mogensen, L. Monconduit, R. E. Morris, A. J. Naylor, S. Nikman, C. A. O'Keefe, D. M. C. Ould, R. G. Palgrave, P. Poizot, A. Ponrouch, S. Renault, E. M. Reynolds, A. Rudola, R. Sayers, D. O. Scanlon, S. Sen, V. R. Seymour, B. Silván, M. T. Sougrati, L. Stievano, G. S. Stone, C. I. Thomas, M.-M. Titirici, J. Tong, T. J. Wood, D. S. Wright and R. Younesi, *JPhys Energy*, 2021, **3**, 31503.
85 L. Kraft, T. Zünd, D. Schreiner, R. Wilhelm, F. J. Günter, G. Reinhart, H. A. Gasteiger and A. Jossen, *J. Electrochem. Soc.*, 2021, **168**, 20537.
86 ACEA, Economic and Market Report Global and EU auto industry: Full year 2023, https://www.acea.auto/files/Economic_and_Market_Report-Full_year_2023.pdf.
87 VDA, Passenger car market: VDA adjusts forecasts, https://www.vda.de/en/press/press-releases/2023/230502_PM_Passenger-car-market_VDA-adjusts-forecasts.
88 N. Nsitem, Y. Sekine and A. Leach, Headwinds in Largest Energy Storage Markets Won't Deter Growth, https://about.bnef.com/insights/clean-energy/headwinds-in-largest-energy-storage-markets-wont-deter-growth/, accessed 13 August 2025.
89 J. J. Marie, *Batteries in Stationary Energy Storage Applications*, https://www.faraday.ac.uk/wp-content/uploads/2024/11/Faraday_Insights_21_FINAL.pdf, accessed 13 August 2025.
90 Mordor Intelligence, Europe Battery Energy Storage System Market Research On Size, Growth Trends, Segments, Regions & Competition (2025–2030), https://www.mordorintelligence.com/industry-reports/europe-battery-energy-storage-system-market, accessed 13 August 2025.
91 M. Staadecker, J. Szinai, P. A. Sánchez-Pérez, S. Kurtz and P. Hidalgo-Gonzalez, *Nat. Commun.*, 2024, **15**, 9501.
92 T. M. Gür, *Energy Environ. Sci.*, 2018, **11**, 2696–2767.
93 S. Weber, J. F. Peters, M. Baumann and M. Weil, *Environ. Sci. Technol.*, 2018, **52**, 10864–10873.
94 M. Hiremath, K. Derendorf and T. Vogt, *Environ. Sci. Technol.*, 2015, **49**, 4825–4833.
95 M. He, A. E. Mejdoubi, D. Chartouni, M. Morcrette, P. Troendle and R. Castiglioni, *J. Power Sources*, 2023, **588**, 233741.
96 K. Hurlbutt, S. Wheeler, I. Capone and M. Pasta, *Joule*, 2018, **2**, 1950–1960.
97 H. Yang and L. Fulton, *Werkst. Ihre Veredl. J.*, 2023, **14**, 347.
98 R. Frischknecht, F. Wyss, S. Büsser Knöpfel, T. Lützkendorf and M. Balouktsi, *Int. J. Life Cycle Assess.*, 2015, **20**, 957–969.
99 H.-J. Althaus, C. Bauer, G. Doka, R. Dones, R. Frischknecht, S. Hellweg, S. Humbert, N. Jungbluth, T. Köllner, Y. Loerincik, M. Margni and T. Nemecek, *Implementation of Life Cycle Impact Assessment Methods. Data v2.2*, St. Gallen, 2010.
100 K. R. Rábago, A. B. Lovins and T. E. Feiler, *Energy and sustainable development in the mining and minerals industries*, 2001.
101 BNEF, Miners turn to clean energy: Costs and key strategies. database.
102 T. Igogo, T. Lowder, J. Engel-Cox, A. Newman and K. Awuah-Offei, *Integrating Clean Energy in Mining Operations: Integrating Clean Energy in Mining Operations: Opportunities, Challenges, and Enabling Approaches*, JISEA, 2020.
103 R. Iyer and J. Kelly, *Updated Production Inventory for Lithium-Ion Battery Anodes for the GREET® Model, and Review of Advanced Battery Chemistries*, Argonne National Laboratory, 2022.
104 Yano Research Institute Ltd., Current Status and Future Prospects Current Status and Future Prospects of LIB Material Market. Major Four Materials.
105 P. Engels, F. Cerdas, T. Dettmer, C. Frey, J. Hentschel, C. Herrmann, T. Mirfabrikikar and M. Schueler, *J. Cleaner Prod.*, 2022, **336**, 130474.
106 Z. Huang, X. Qiu, C. Wang, W. Jian, L. Zhong, J. Zhu, X. Zu and W. Zhang, *J. Energy Storage*, 2023, **72**, 108406.
107 M. Mohr, J. F. Peters, M. Baumann and M. Weil, *J. Ind. Ecol.*, 2020, **24**, 1310–1322.
108 H. He, S. Tian, B. Tarroja, O. A. Ogunseitan, S. Samuelsen and J. M. Schoenung, *J. Cleaner Prod.*, 2020, **269**, 121740.
109 F. Degen, M. Mitterfellner and A. Kampker, *J. Ind. Ecol.*, 2025, **29**, 113–128.
110 M. Azadi, S. A. Northey, S. H. Ali and M. Edraki, *Nat. Geosci.*, 2020, **13**, 100–104.
111 T. Norgate and N. Haque, *J. Cleaner Prod.*, 2010, **18**, 266–274.
112 S. Lezak, C. Cannon and T. Koch Blank, *Low-carbon Metals for a low-carbon World: a new Energy Paradigm for Mines*, Rocky Mountain Institute, 2019.
113 U.S. Department of Energy, *Mining Industry Mining Industry Energy Bandwidth Study*, 2007.
114 R. Istrate, A. Mas-Fons, A. Beylot, S. Northey, K. Vaidya, G. Sonnemann, R. Kleijn and B. Steubing, *Joule*, 2024, **8**, 2992–3016.
115 S. Natarajan and V. Aravindan, *Adv. Energy Mater.*, 2020, **10**, 2002238.
116 SMM Information & Technology Co., Ltd., High-End Artificial Graphite For NEV Price, USD/mt, https://www.metal.com/Carbon-Anode/202409020006, accessed 11 August 2025.

117 SMM Information & Technology Co., Ltd., High-End Artificial Graphite For ESS Price, USD/mt, https://www.metal.com/Carbon-Anode/202409020003, accessed 11 August 2025.
118 SMM Information & Technology Co., Ltd., Refined Cobalt Price, USD/mt, https://www.metal.com/Cobalt/201102250375, accessed 11 August 2025.
119 SMM Information & Technology Co., Ltd., SMM #1 Nickel Price, USD/mt, https://www.metal.com/Nickel/201102250239, accessed 11 August 2025.
120 SMM Information & Technology Co., Ltd., Battery-Grade Lithium Metal (Weekly) Price, USD/mt, https://www.metal.com/Lithium/202304250002, accessed 11 August 2025.
121 M. Zhou, B. Li, J. Li and Z. Xu, *ACS EST Eng.*, 2021, **1**, 1369–1382.
122 R. Chenitz, E. Pajootan and A. Mokrini, *ACS Sustainable Resour. Manage.*, 2025, **2**, 1337–1339.
123 European Commission, Commission Delegated Regulation (EU) 2025/606, supplementing Regulation (EU) 2023/1542 of the European Parliament and of the Council by establishing the methodology for calculation and verification of rates for recycling efficiency and recovery of materials from waste batteries, and the format for the documentation, 2025.
124 McKinsey & Company, The battery cell component opportunity in Europe and North America, 2024.
125 Energy Development GmbH, What is Battery Energy Storage System (BESS) Optimization? https://enery.energy/en/what-is-battery-energy-storage-system-bess-optimization/, accessed 16 August 2025.
126 V. A. Sethuraman, V. Srinivasan and J. Newman, *J. Electrochem. Soc.*, 2013, **160**, A394–A403.
127 B. Lu, Y. Song, Q. Zhang, J. Pan, Y.-T. Cheng and J. Zhang, *Phys. Chem. Chem. Phys.*, 2016, **18**, 4721–4727.
128 E. Moyassari, T. Roth, S. Kücher, C.-C. Chang, S.-C. Hou, F. B. Spingler and A. Jossen, *J. Electrochem. Soc.*, 2022, **169**, 10504.
129 P. Li, J.-Y. Hwang and Y.-K. Sun, *ACS Nano*, 2019, **13**, 2624–2633.
130 M. Rehm, M. Fischer, M. Rubio-Gomez, M. Schütte, D. U. Sauer and A. Jossen, *J. Power Sources*, 2025, **633**, 236290.
131 A. Weiss, D. Hernandez Diaz, T. Grüenewald and M. Subbu, *Electricity demand in Europe: Growing or going?* https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/electricity-demand-in-europe-growing-or-going, accessed 18 August 2025.
132 World Energy Council, *Energie in der Europäischen Union. Zahlen & Fakten*, 2024.
133 J. Koch, Tabelle: So viel Ertrag kann deine PV-Anlage bringen, https://1komma5.com/de/solaranlage/ertrag-pv-anlage/, accessed 19 March 2025.
134 European Commission, Implementation dialogue on permitting for renewable energy projects and related infrastructure, https://energy.ec.europa.eu/events/implementation-dialogue-permitting-renewable-energy-projects-and-related-infrastructure-commissioner-2025-06-11_en#:~:text=Overall%2C%20the%20discussion%20highlighted%20a,are%20important%20challenges%20to%20tackle., accessed 18 August 2025.
135 McKinsey & Company, Transformaion of Europe's power system until 2050, including specific considerations for Germany.
136 Federal Ministry for Economic Affairs and Energy, Electricity 2030. Long term trends – Tasks for the coming years, 2016.
137 International Energy Agency, Europe. Oil supply, https://www.iea.org/regions/europe/oil, accessed 19 August 2025.