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Analysis of the Li-ion battery industry in light of the global transition to electric passenger light duty vehicles until 2050

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Abstract

The decarbonization of the transport sector requires a rapid expansion of global battery production and an adequate supply with raw materials currently produced in small volumes. We investigate whether battery production can be a bottleneck in the expansion of electric vehicles and specify the investment in capital and skills required to manage the transition. This may require a battery production rate in the range of 4–12 TWh/year, which entails the use of 19–50 Mt/year of materials. Strengthening the battery value chain requires a global effort in many sectors of the economy that will need to grow according to the battery demand, to avoid bottlenecks along the supply chains. Significant investment for the establishment of production facilities (150–300 billion USD in the next 30 years) and the employment of a large global workforce (400k–1 million) with specific knowledge and skillset are essential. However, the employment and investment required are uncertain given the relatively early development stage of the sector, the continuous advancements in the technology and the wide range of possible future demand. Finally, the deployment of novel battery technologies that are still in the development stage could reduce the demand for critical raw materials and require the partial or total redesign of production and recycling facilities affecting the investment needed for each factory.

1. Introduction

Electric light duty vehicles (LDVs) are becoming increasingly popular among consumers. As of 2020, the electric vehicle (EV) stock surpassed 10 million units, or 1% of the total LDV stock, with 65% being battery electric vehicles (BEVs) and the remainder plug-in hybrid EVs [1]. The scope of the ambitious climate targets entails that EVs, coupled with renewable energy sources, become the dominant technology in the road transport sector. The widespread adoption of EVs can bring several benefits, with the most notable positive effects being the reduction of greenhouse gases and particulate matter released into the atmosphere. However, the future uptake of electric LDVs is dependent on the ability of the battery market to sustain the future high demand for EVs. Current EVs rely on Li-ion batteries (LIBs) for energy storage, which is a technology already widely used in portable electronics. The size of LIBs in EVs is significantly larger than the current LIBs in electronic devices. Hence, the full (or partial) replacement of the current LDV fleet with EVs will require the quick expansion of the production capacity of the battery industry, which in turn requires robust value chains for primary raw material mining and processing. The likely future raw material demand and the challenges related to the supply required for the transition to electric mobility have been covered in several reports and peer-reviewed articles [2–15]. Current estimates on the global installed production capacity for LIBs span from 250 GWh/year [16] to 640 GWh/year [6]. This wide range suggests significant uncertainty due to the lack of accessible, up-to-date

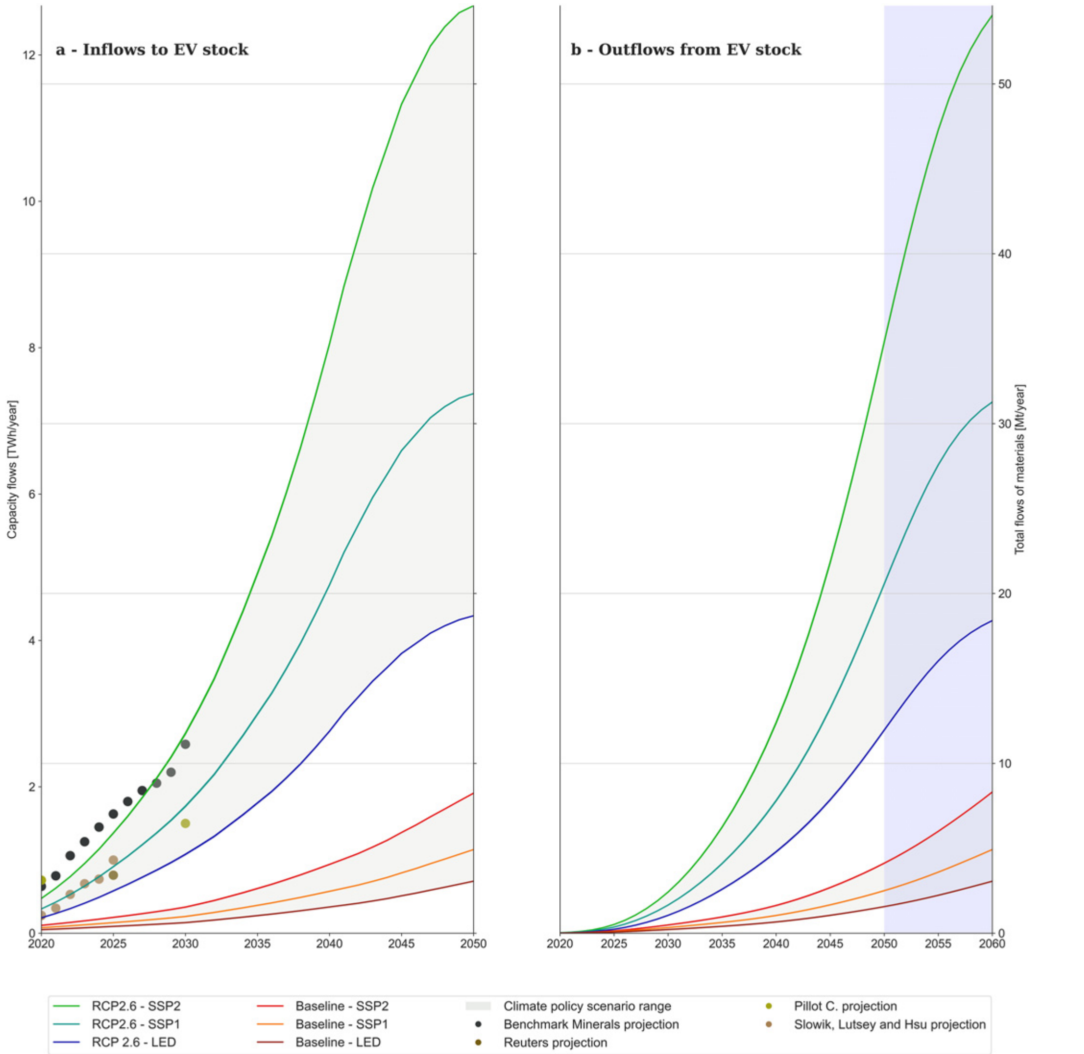

Figure 1. Capacity and material flows of LIBs in EVs. (a) Inflows to the EVs stock until 2050 in each scenario. Scatter plots identify reported forecasts of future manufacturing capacity in TWh installed to 2030. Primary *y*-axis depicts capacity inflows in TWh/year, while the secondary *y*-axis, with values from (b) depicts yearly material inflows in Mt. (b) Outflows of LIBs from EV stock until 2060 in light of the survival curve created for this study, assuming an average lifetime of EVs of 11 years.

and transparent data. Furthermore, several reports present forecasts on the planned production capacity in 2025 or 2030, but the reported values differ considerably (figure 1) [6, 16, 17]. The scattered reported values highlight how the possible future gaps between LIB supply and demand can occur under the quick adoption of EVs.

To ensure the required supply of raw materials and batteries, it is important to quantify likely future LIB demand and in-/out-flows, to identify the industrial and economic requirements for a smooth and rapid transition from fossil-fueled vehicles to EVs. Given the current evolution of the LIB as a technology and economic sector, deep electrification scenarios can potentially introduce challenges within the area of (1) capital investment for the construction of manufacturing facilities; (2) potential million-ton demand for primary materials requiring a quick ramp-up in mining activities; and (3) recycling plants ready to efficiently process the future outflows of LIBs reaching end-of-life (EOL) to reduce the pressure on the primary supply sector.

To the best of our knowledge, the peer-reviewed literature has not yet provided an assessment of the combined economic implications and industrial challenges of the quick transition to EVs needed to attain the ambitious transport electrification targets set. Here, we present an analysis of future battery demand and its possible implications under deep electrification scenarios of the passenger vehicle sector. The scenarios assessed are aligned with the mitigation of the global temperature rise target, commonly known as the 2 °C target.

This study builds upon the scenarios defined by the authors of the open dynamic material systems model for the resource efficiency-climate change nexus (ODYM-RECC) [18–21], also used by the

International Resource Panel [22]. The ODYM-RECC model encompasses six socioeconomic-climate policy scenarios. To be precise, there are two climate policy scenarios (Baseline and the Representative Concentration Pathway—RCP2.6—with the latter that ensures reaching the 2 °C target [23, 24]) and three socioeconomic pathways (SSP1, SSP2 and LED) [25–28], which together provide a combination of climate policy and socioeconomic pathway. In RCP2.6, the atmospheric concentration of greenhouse gases reaches around 490 parts per million CO_2-equivalent, which corresponds to 2.6 W m^{-2} by 2100, before declining again [23, 24]. The shared socioeconomic pathways (SSPs) describe a range of possible future developments, on a societal level, that lead to either high or low socioeconomic challenges for mitigation and adaption in the context of climate change [29]. In this context, in the SSP1 narrative, the adaptation and mitigation to climate change pose low challenges, while the SSP2 narrative represents a 'middle-of-the-road' with respect to mitigation and adaptation challenges [25]. The low-energy demand (LED) scenario, which does not belong to the originally developed SSP narratives presented in O'Neill *et al* [29], describes a future in which the focus on energy end-use, efficiency and demand reduction allow the attainment of the climate change mitigation targets without the deployment of negative emission technologies, Carbon Capture and Storage or nuclear power [26].

Among the six scenarios assessed, three are consistent with the 2 °C target (RCP2.6 scenarios), while the remaining three scenarios follow the assumption that no new climate policies are put in place after 2020. Therefore, a business-as-usual trend is evaluated.

Hereafter, when referring to all the scenarios aligned with climate change mitigation targets (RCP2.6—SSP1, SSP2 and LED), we use the naming convention 'high-penetration scenarios' while the other scenarios are defined as 'low-penetration scenarios'. In this study, taking the inflows of EVs in the ODYM-RECC model [30] as the entry point to our calculations, we calculate the projected global demand for LIBs, key materials and economic implications of the global transition to electrified LDV technologies. The time-frame analyzed in this study starts in 2020 and ends in 2050. We show a spectrum of pathways regarding the evolution of the EV fleet and its implications for the LIB industry. Full numbers for the passenger vehicle fleet can be found in the supplementary information (http://stacks.iop.org/ERIS/2/011002/mmedia), and additional information on assumptions concerning the fleet composition can be found in the methods section.

2. Methodology and scenarios

2.1. EV fleet and battery scenario definition

The analysis for the global EV fleet (BEVs and PHEVs) presented in this article is based on the ODYM-RECC model [18, 30, 31], which uses the IAM-based narratives for the trends driving the deployment of EVs. From the publicly available ODYM-RECC output files [30, 32], we used the yearly inflows of EVs into the stock, defined in million units per year. The total size of the LDV stock varies according to the socioeconomic pathway (SSP1, SSP2 and LED), while the penetration (intended as a total share of the stock) of BEVs and PHEVs depends on the climate policy scenario (RCP2.6 or baseline). The stock, according to the projections of the model, amounts to 1.2 billion (LED), 2 billion (SSP1) and 3.4 billion (SSP2) vehicles in 2050 (table 1). Under the baseline climate policy scenarios, the share of EVs and PHEVs reach 5% and 8%, respectively, by 2050 (table 1). On the other hand, in the RCP 2.6 scenarios the share of EVs and PHEVs reaches 45% and 17%, respectively, by 2050 [30] (table 1).

To estimate the outflows of EVs from the stock, we use a Weibull distribution with an average lifetime of 11.5 years [33], based on the European average, and a maximum retirement age of 25 years. Due to the lack of statistically significant data on the current and future residence time of EVs, this assumption is based on historical data on conventional vehicles. However, as a result of developments in battery chemistry and in battery management systems, it is possible that future LIBs may achieve a longer cycle life without significant capacity fade, delaying the replacement of the vehicles. This will consequently affect both the outflows and inflows presented in this analysis. On the other hand, consumer behavior, e.g. yearly distance driven and charging patterns, and regional climate conditions can negatively affect the cycle life of LIBs and consequently the EVs [34–36].

For the definition of the different vehicle sizes, we used the European car segment classification [37], excluding the M-(multi-purpose) and S-(sport) segments. Data on the market share of each vehicle class was taken from the ICCT EU vehicle market statistics, and applied to the global fleet inflows [38], which reports the following market share for both BEVs and PHEVs: A-segment (microcars)-8%, B-segment (small cars)-21%, C-segment (medium cars)-27%, D-segment (large cars)-7%, E-segment (executive cars)-3%, F-segment (luxury cars)-0.2%, J-segment (sport utility vehicles)-35%. For simplicity, we assumed this market share applies to all the modeling years (2015–2060). Battery sizes largely vary across and within vehicle sizes available on the market. Regarding the battery size for the starting year (2015), we collected the average battery size across the vehicles belonging to each segment from the EV database website [39]. Advancements in the energy density of

Table 1. Composition of the LDV stock in 2050 by technology.

Climate policy scenario	Socioeconomic pathway	Total stock (Mln units)	EV stock (Mln units)	EV stock (%)	PHEV stock (Mln units)	PHEV stock (%)
Baseline	SSP2	3379	165	5%	260	8%
	SSP1	2005	100	5%	154	8%
	LED	1173	63	5%	92	8%
RCP2.6	SSP2	3379	1528	45%	586	17%
	SSP1	2005	900	45%	346	17%
	LED	1173	526	45%	203	17%

LIB chemistries can result in an overall increase in the battery size in each BEV segment with the same overall weight of the battery pack [12]. In this work, we assumed that in 2050 the size of the battery packs will reach the capacity forecast in Baars *et al* [12], which is an assumption corroborated by the International Council on Clean Transportation in a factsheet reporting that the average battery capacity in BEVs has been increasing over time [40]. Furthermore, given the uncertainty on the future technological development of LIBs, we assumed the same material loading throughout the entire analyzed timeframe. For PHEVs, we assumed that the battery size remains constant in the period 2015–2050.

Currently, there are three main types of LIBs used in EVs, $LiFePO_4$ (LFP), LiNiCoAl (NCA) and $LiNi_xMn_yCo_{1-x-y}$ (NMC), with the latter being the most common chemistry. However, within the realm of NMC chemistry, numerous variants exist with the main difference being the ratio of Ni, Mn and Co in the active material. Earlier generations of NMC chemistry presented the same ratio of the three elements, but the trend in recent years has been towards Ni-rich mixes, which can increase the energy density of the chemistry while decreasing the Co content [41, 42]. Furthermore, current R & D effort is towards developing novel technologies that can bring better performance and safety, such as all-solid-state batteries, lithium-air and lithium-sulphur chemistries [43]. However, the current technology readiness level of these technologies does not make them competitive with the current state-of-the-art, and it is uncertain whether these technologies will become competitive or when they will be available for large-scale deployment. Similarly, the future market share of LIBs is challenging to quantify since breakthroughs in new battery chemistries may have a profound impact on the market. Hence, our scenario for the future market share of LIBs estimates that until 2050, NMC chemistry will be the dominant technology, with an increasing trend towards Ni-rich cathodes, such as NMC 811 and NMC 955. The available literature covering the current and historical market share (2015–2020) of LIBs is rather scattered. In this work, we take an average market share for each chemistry from the sources analyzed [4, 6, 7, 44–47], for the periods 2015, 2020 and 2030, combined with interpolations for the years within this range to define yearly market share. In addition, we define two more reference years for the interpolations until 2050, more precisely defining market share for the years 2040 and 2050. Our estimates for the years 2040 and 2050 follow the assumption that NMC 811 and NMC 955 LIBs will be the reference chemistries, with NCA and LFP LIBs having a 7% share each. To evaluate the demand of materials embodied in the LIBs included in our scenario, we keep track of key materials on both a cell and pack level, namely we calculate future flows of Al, Co, Cu, graphite, Li, Mn, Ni, plastics and steel. We base the material content ($kg\ kWh^{-1}$) on the data presented in [13, 48] regarding the cathode material, on Dai *et al* [49] for the graphite content in the anode and the Li loading in the electrolyte, and we take as reference the pack design from Ellingsen *et al* [50]. With regard to the battery pack, we worked under the simplified assumption that its material composition, e.g. electronics and frame, does not change with the chemistry and over time, due to the lack of more detailed data.

Both current and historical data on the CAPEX of LIB manufacturing facilities is rather scarce. A report released in 2017 by the European Commission's Joint Research Center provides investment costs for several factories, resulting in an average specific investment cost of 144 Euro/kWh annual production capacity [51]. Similarly, the Rocky Mountain Institute assumes a CAPEX of approximately 140 USD/kWh in 2020 and a constant drop until 2040 where the capital expenditure reaches 25 USD/kWh [52]. In this work, for each scenario, we assumed a CAPEX of 140 USD/kWh in 2016, and we further calculated the CAPEX reduction (in USD/kWh) over time for each scenario using Wright's law [53] and an experience rate of 16% based on Schmidt and colleagues [54].

A report by the Faraday Institution forecasts that 130 GWh of annual production by 2040 in the UK, with 26 000 employees involved in LIB manufacturing activities [55], will lead to an average of 200 employees/GWh required to work in future LIB production facilities. In contrast, the European Commission's Joint Research Center reports an average of 106 workers/GWh. Our analysis assumed an average of 120 employees/GWh, which is the average value reported [51, 55–57]. However, LIB production holds potential for the automation of some production steps [58]. Therefore, the future employment generated may be lowered by automation and industry 4.0 trends, following the forecasts for the automotive sector as a whole [59, 60]. Here, we assume that employment demand will reduce by 25% by 2040, leading to 98 employees/GWh.

3. Results

3.1. Global demand for LIBs and their key raw materials up to 2050

Scenarios consistent with the 2 °C target show that the global demand for LIBs in 2050 can reach ∼4 TWh/yr (RCP2.6—LED scenario) to 13 TWh/yr (RCP2.6—SSP2 scenario), which consequently leads to total material inflows ranging between 19 Mton/yr and 54 Mton/yr (figure 1). Conversely, low-penetration scenarios present a significantly lower demand for LIB capacity and materials by 2050, with the maximum being 2 TWh/yr and ∼8 Mton/yr in the baseline—SSP2 scenario.

Estimates on the future installed LIB production capacity [6, 17, 61, 62] (figure 1) highlight the uncertainty surrounding the future short-term expansion of the industry and how a fast-paced deployment of EVs could be crippled due to the undersized annual LIB supply capacity. The projections in 2025 show a likely total battery production capacity ranging from 605 GWh/year to 1.6 TWh/year. The more optimistic production capacity forecast [6] is well aligned with the scenario encompassing the highest yearly addition of EVs. The possibility of supply failing to meet demand across all production capacity scenarios only occurs in two scenarios consistent with the deep decarbonization of the passenger vehicle fleet. More precisely, two production capacities reported [17, 61] an inability to sustain the growth in demand for EVs forecast in the RCP2.6—SSP2 and RCP2.6—SSP1 scenarios. In contrast, the low-penetration scenarios do not highlight any potential bottlenecks regarding installed production capacity.

The demand for several TWh/yr of LIBs, as in high EV penetration scenarios, will drive the necessity to supply high quantities of key battery raw materials to the appropriate refining sectors, which must then supply the refined battery-grade materials to the battery production facilities.

The electrodes of current state-of-the-art LIBs rely on a handful of materials, namely Co, Li, Mn, Ni (positive electrode) and graphite (negative electrode). These materials are likely to be employed in battery packs for at least the coming decade, due to the current and future market relevance of lithium nickel manganese cobalt oxide (NMC) LIBs.

The demand for LIB materials, such as Al, Cu, Ni and Mn, does not represent a significant concern in comparison to their respective current production rates. In contrast, graphite, Li and Co extraction in 2019 stood at 1.1 Mton, 82 and 144 kton, respectively [63–65]. With current and estimated future production rates, the supply of these materials may fall short of demand in 2032 (graphite), 2033 (Li) and 2041 (Co) assuming the LED scenario and the RCP2.6 climate policy, which represents the high electrification scenario characterized by the lowest demand for LIBs, and consequently materials. On the other hand, a higher number of EVs, as in the scenarios RCP2.6 SSP1 and SSP2, would significantly lower the point at which demand exceeds the current and anticipated future supply rate capabilities (figure 2). Therefore, natural graphite, Li and Co may constitute potential bottlenecks for LIB production due to the projected rapid growth in their demand and their current production rates.

High electrification scenarios require a strong expansion of the mining capacity for these materials. While the current and projected future extraction rates of graphite, Li and Co raise aconcern regarding the capacity of the virgin material market to support LIB demand, there are no threats regarding the total resources available in the ground [63, 64, 66, 67]. However, the geographical concentration of these resources, especially Co [10], may represent an obstacle to the stability of the supply chains.

Natural graphite is rather abundant and is widely used in several applications, such as lubricants and steelmaking [65]. While the European Commission includes natural graphite on its list of critical raw materials [68, 69], it is possible to produce synthetic graphite from hydrocarbon materials [67], with the downside of the cost that may be twice as high as natural graphite [13, 67]. Granted that the production cost of synthetic graphite will drop, the future demand for graphite could be fulfilled by synthetic graphite, alleviating a potential shortage of natural graphite mines. In addition, silicon is considered a strong candidate material for negative electrodes in LIBs; if the challenges associated with its application are overcome, the demand for graphite may be, partially or totally, cut with a simultaneous increase in performance of LIBs [70–72].

Li mines are currently not operating at full capacity (∼50%), and by 2025 an almost doubling of the total mining capacity installed will take place, according to forecasts [47]. Figure 2 shows that until 2025 the planned mining capacity for Li can potentially cover the demand for this material in most of the high LIB demand scenarios. However, the supply may fail to meet the demand for battery-grade Li in the highest penetration scenario (RCP2.6—SSP2). Furthermore, it is important to note that while Li is a key component in LIBs, its use is not limited to this sector [64], meaning that the entire mining capacity of this

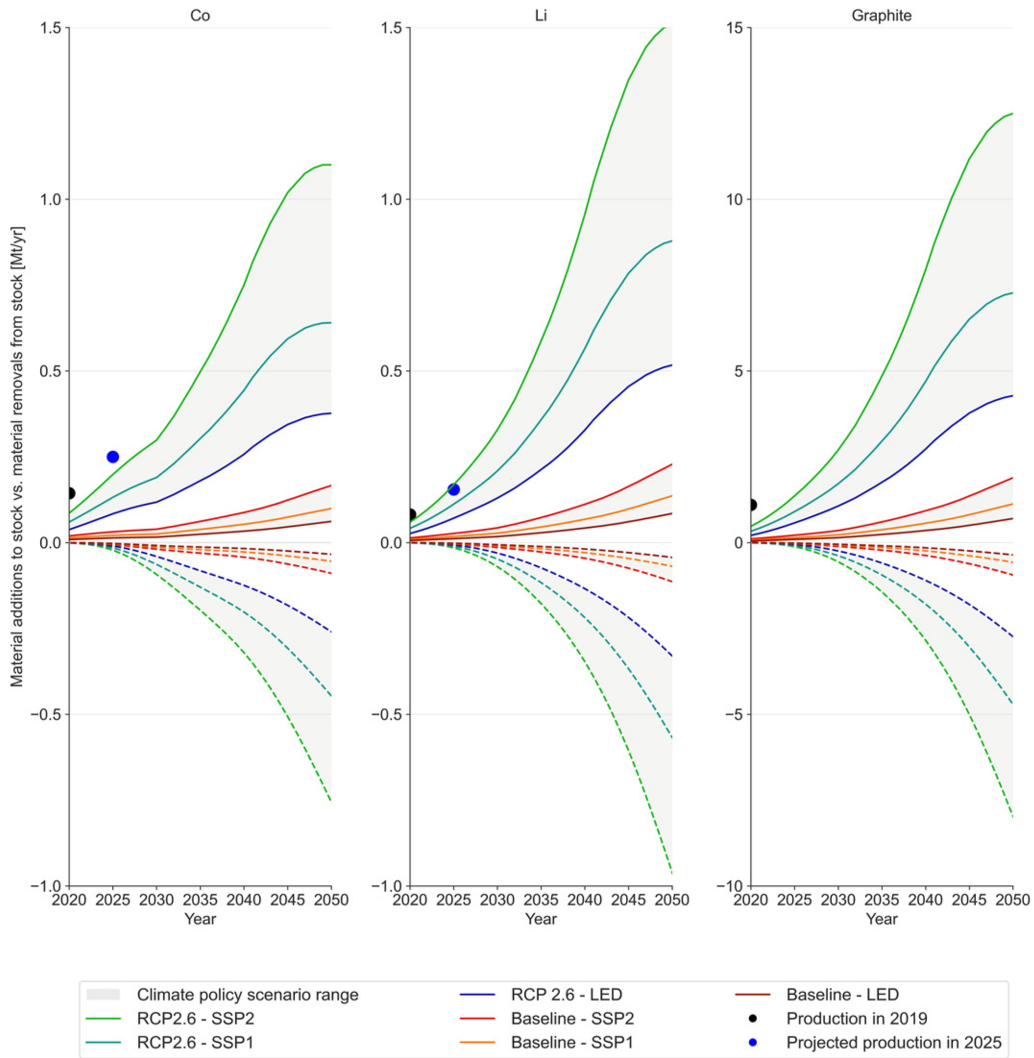

Figure 2. Li, Co and graphite flows to and from EV stock. Each line represents a different scenario while the gray area defines the climate policy scenario range. Positive *y*-axis curves represent the inflows to the stock in Mt/yr, the dots depict either the production rate in 2019 (black dot) or the forecast production capacity in 2025 [47] (blue dot). Curves across the negative *y*-axis show the outflows from the EV stock, with these materials either available for recycling or stationary applications.

material is not dedicated to LIBs. Sudden demand growth of battery-grade Li could be detrimental to the price of the commodity and subsequently to the cost of LIBs. In addition, it takes a few years to set up new Li mines. Li production from brine requires only one year from the construction of the pond to the complete evaporation of the saltwater [73]. In addition, processing plants for Li conversion to battery-grade material require up to 2 years to be installed [73, 74], leading to a total of 2–3 years of response time to establish new Li mines. However, recycled Li from LIBs reaching EOL could cover part of the future demand for the resource. Historically, Li is not recovered from spent LIBs due to its low market value, but it could become economically viable if the primary supply falls short of demand, causing a surge in the price of the commodity.

Current estimates report that by 2025 the mining capacity of Co will reach ∼230 kt, with supply coming from both the expansion of mining capacity and additional resources coming from recycling [47]. However, future Co availability is rather uncertain. Co is typically mined as a by-product of both Ni and Cu mining [13], meaning that its production rate is often closely linked to the market of these two materials [75, 76], and their future prices may indirectly affect Co supply and price. Furthermore, Co mining is mainly located in the Democratic Republic of Congo and most of the refining occurs in China [75, 76]. Therefore, a shock in the market, either due to a surge in the price of the commodity or to demand failing to meet supply may generate a rush from battery producers in securing the supply of this material. This could, in turn, cause a bottleneck in the industry’s overall output with the consequences affecting numerous EV original equipment manufacturers.

While total availability of battery-grade materials does not seem to represent a constraint to deployment trajectories of EVs, strategic planning is required to establish the appropriate mining capacity, given the possibility of facing a tremendous increase in the demand for key raw materials. The expansion from surface to underground mining may take several years. In contrast, building new mining activities requires significant time from exploration to actual extraction of the ores. Time may vary depending on the country, mainly due to permitting. However, from planning to extraction in a new mine, approximately more than 10 years may be needed [10, 77]. Similarly, the refining capacity needed to convert virgin metals to their LIB-grade counterparts needs to be in place to avoid bottlenecks along the value chain of the materials.

In addition to the supply of virgin materials, part of the future demand for LIB materials may be covered by recycled LIBs reaching EOL. The recycling infrastructure needs to grow accordingly with the deployment of LIBs to ensure the highest recovery rates possible to ensure as much coverage of the material demand as possible, and to avoid unsuitable disposal of LIBs such as landfilling. However, the yearly LIB retiring rate is somewhat uncertain to predict given the possibility of using them in 2nd life applications. Therefore, the demand for recycling facilities will follow the same logistic growth as the projected LIB demand curve (figure 1) but with a time lag due to the high residence time of LIBs in the EV stock (∼11 years). In figure 1, we show the total LIB material outflows from the EV stock and in the negative y-axis of figure 2, we show a forecast of the relevant material outflows from the EV stock, specifically Co, Li and graphite. While not all the materials may be available for recovery in the retirement year due to 2nd life applications, the LIBs produced will eventually need to be recycled, allowing partial closing of the loop for battery-grade materials. In the short-term, recycling LIBs would not suffice to cover a significant proportion of the demand for battery materials, but in the medium-/long-term a significantly higher share of demand may be supplied by recycled materials. Low-penetration scenarios present the possibility of covering a high fraction of the demand earlier than high-penetration scenarios. This is due to the low pace of deployment of EVs, which ultimately drives a rather constant demand, which could provide less stress on the supply side and allow for more robust circular economy possibilities. In high EV penetration scenarios the full implementation of circular economy practices (reuse, refurbishment, 2nd life applications and recycling) plays an even more significant role since the high demand for raw materials is substantially higher than lower-penetration scenarios. Within circular economy principles there are several possibilities to avoid the recycling phase after 1st life, and thus extend the life of LIBs, or that allow high recovery rates of active materials and their regeneration for further reuse in LIBs [78–80]. The adoption of circular economy strategies in the LIB sector (due to the decreased demand for primary materials) could reduce the vulnerability of relevant value chains and bring environmental benefits [79] to the sector. In addition, it is likely that these strategies may reduce the production costs of LIBs, due to the cost of Co [79, 80]. Nonetheless, to successfully achieve higher reuse and recovery rates, further development of the technologies, i.e. battery performance, reuse and recycle, is required and this shift needs to be supported with appropriate policies and where necessary, economic subsidies [79, 80].

3.2. Investment needed and job creation within the LIB industry

In addition to the challenges to the material supply, the transition to EVs may require the construction of several LIB manufacturing facilities, which in turn can have significant direct economic consequences both in terms of capital expenditure (CAPEX) needed to build the production facilities and concerning the skilled employees needed to run these facilities. Figure 3 presents the yearly CAPEX, measured in billion USD needed in each scenario assessed. The capital cost of transitioning to EVs in scenarios consistent with the RCP2.6 trajectory amounts to cumulative investments of 150–300 billion USD by 2050, with yearly investment required ranging from 4–10 billion USD. On the other hand, low-penetration scenarios induce a cumulative CAPEX of 41–81 billion USD by 2050, and yearly investment rather stable around 1–3 billion USD. In high-penetration scenarios, the capital cost reduction is more pronounced, due to the significantly higher manufacturing capacity installed, than in the low-penetration scenarios, leading to a steeper decrease in the CAPEX in USD/kWh. Moreover, the CAPEX in 2050 for high-penetration scenarios ranges from 21 (SSP2) to 28 (LED) USD/kWh, while in low-penetration scenarios it reaches 35–48 USD/kWh. Developments in LIBs and breakthroughs with novel technologies may affect the investment

needed in the construction of LIB facilities.

While the CAPEX of manufacturing facilities is expected to decrease over time due to increased know-how and economies of scale, the OPEX part remains rather uncertain. The active materials of an LIB represent a significant fraction of the cost of producing a battery, with estimates ranging from 20% to 50% of the total cost [81–83]. Co and Li prices fluctuate, and possible shortages in supply can generate a surge in their price driving up the production costs of LIBs. However, the increase in prices can positively affect the recycling and urban mining of materials, especially for Li.

The construction of several new battery manufacturing facilities will stimulate the demand for a skilled workforce with specific training in electrochemistry, software development and mechanical engineering.

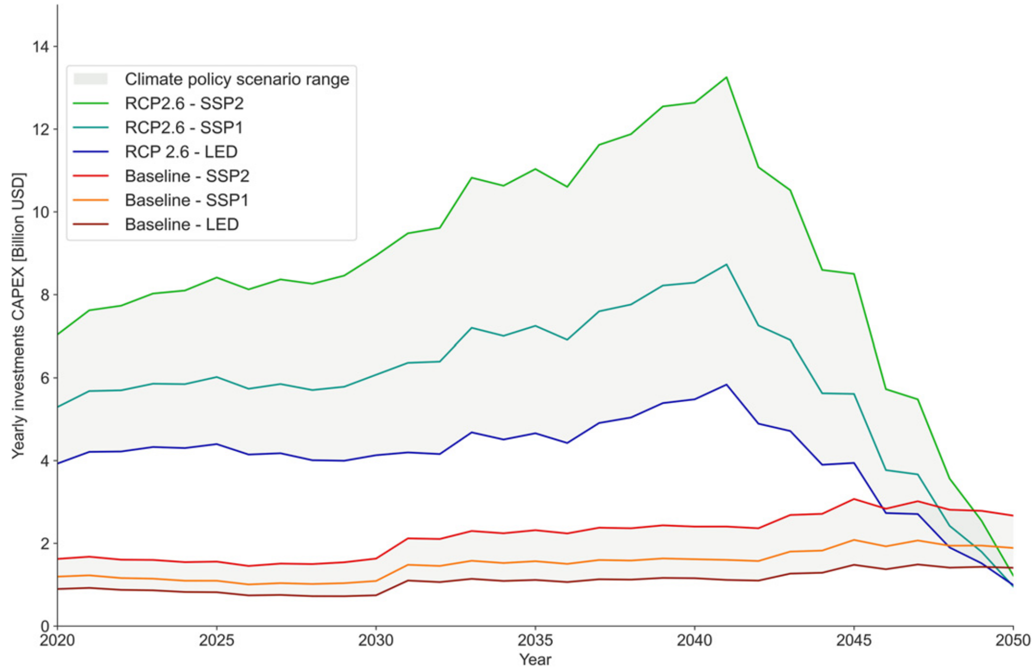

Figure 3. Estimated annual CAPEX needed to install the required LIB manufacturing facilities, in billion $, until 2050.

Numerous publications have analyzed the quantitative and qualitative effects on the job market of transitioning from non-renewable energy sources to renewable energy sources [84–88]. However, the same analysis has not yet been performed on the transition to EVs and the production of LIBs, but a similar trend as for renewables may be observed. Renewable energy sources can have net positive employment creation [84–86], under certain conditions, but at the same time due to their novelty, they require a whole new set of skills with specific training programs [87, 88]. LIB production involves a series of complex tasks, from electrode preparation to pack assembly and testing. Employees working on the design and modeling of software, electrical circuits and mechanical systems complement these positions. The latter are high- and medium-skilled positions already existing on the market. However, the former tasks represent a new set of tasks needing specific training. The race to educate employees may generate great competition amongst the largest LIB manufacturers, to get the highest number of skilled workers and gain an edge on the production and efficiency side. This in turn may lead to delay effects on other manufacturers, which may encounter a shortage of the required skilled workers needed in the LIB production lines.

As a result of the yearly growth in the establishment of battery production facilities, the direct employment generated in this economic sector can bring benefits in the areas where the facilities are located. In addition, the growth of the LIB industry will have a handful of positive side-effects on the labor market, also due to the complex value chain of LIBs. Among the strongest indirect effects on the employment market are (1) temporary employment generated for the construction phase of the production facilities; (2) additional employment generated in the surroundings of the facility for the provision of services [57, 89]; (3) employment in the recycling sector, which needs to grow according to the production sector; and, (4) employment in the mining sector to secure the supply of LIB materials. However, these additional jobs were not included in our analysis due to the challenges in their quantification.

In high-EV-penetration scenarios, we estimate that in LIB production facilities the annual employment generated grows rapidly until approximately 2040, the year in which the demand for LIB yearly addition reaches the maximum (figure 4). At its peak, the establishment of LIB production facilities can drive the demand between ∼22 thousand (RCP2.6—LED) and ∼70 thousand (RCP2.6—SSP2) person years. In 2040, employment peaks and the trend is reversed as production capacity levels off. Cumulatively, the production of LIBs in high-penetration scenarios leads to 400 thousand to 1 million permanent jobs in manufacturing facilities, for the period 2020–2050. Low-EV-penetration scenarios show slower growth in the yearly employment generated, which is also characterized by significantly lower absolute generation, with an average maximum of 3k (baseline—LED) to 10k (baseline—SSP2) reached in the periods 2045–2050. The low-penetration scenarios are estimated to generate in total 53–176 thousand jobs by 2050.

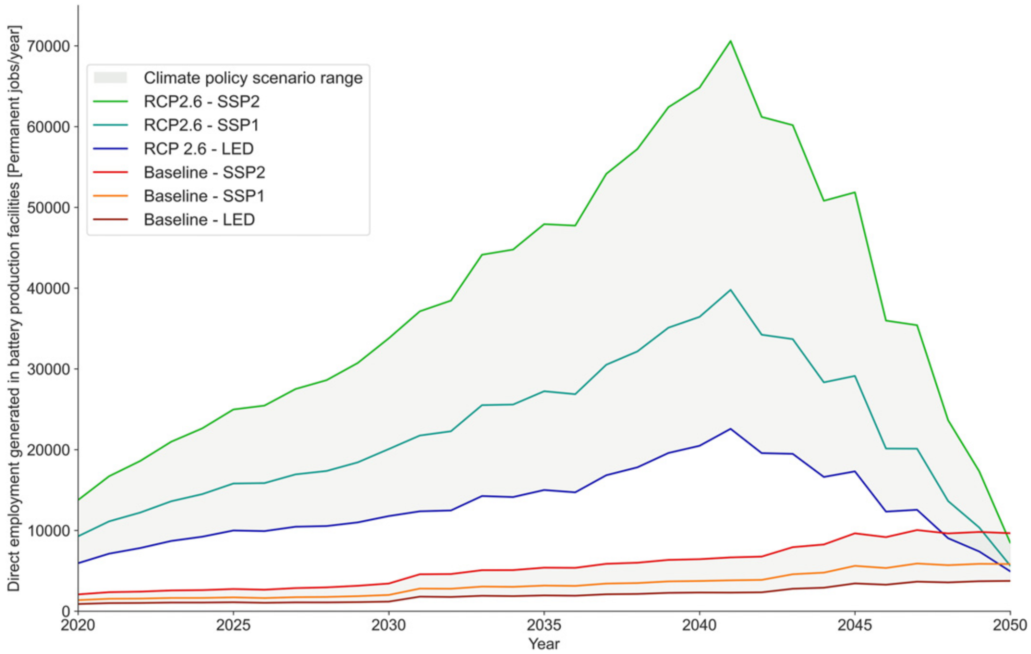

Figure 4. Annual permanent jobs generated for the operation of LIB production facilities in each scenario.

4. Discussion

The EV sector is growing quickly, providing high uncertainty regarding the future demand of LIBs and the critical raw materials needed. Furthermore, several announcements are made every year regarding the construction of new production facilities. However, as shown in this study, it is difficult to predict the long-term demand for this commodity since there is a wide range of futures in which it is possible to achieve the LDV decarbonization targets.

Compared to other key future sectors, such as wind or solar, the LIB sector does not require significantly high investment to enable the transition to EVs. Between 2010 and 2020 the investment in solar PV has been approximately 120–140 billion USD/year [90]. Annual expenditure in wind power grew from approximately 75 billion USD/year in 2010 to 144 billion USD/year, with an almost four-fold increase in the energy output [90]. In contrast, to establish the required LIB production facilities between 2020 and 2050 entails total investment up to 150–300 billion USD. Hence, the investment required in the LIB manufacturing sector can be significantly lower than the investment in the renewable energy sector that has shown fast growth similar to the growth in LIBs estimated in this analysis. In addition, our estimates only consider the improvements over time due to learning rates, but economies of scale may help to achieve stronger CAPEX reduction. However, uncertainty related to long-term demand for LIBs may represent a major concern to investors, due to the possibility of production overcapacity.

The expansion of LIB production will also generate the demand for skilled labor and this will likely follow the same trend as in the renewable sector, where the jobs generated in this sector have grown significantly in the past decade [91]. However, in the renewable energy sector it has been observed that there is a shortage of employees with the required skillset [91], and this risk may also materialize in the LIB sector. To avoid potential shortages of skilled workers, it is essential to develop skill development pathways, such as higher education programs, on-site training and core-skills transition.

Research on LIB chemistries is at an all-time high with effort to improve the current state-of-the-art chemistry NMC and develop cheaper, high-performance and environmentally friendly technologies. The current technology readiness level of the alternative chemistries is rather low, suggesting that NMC LIBs will keep dominating the market share for EV applications in the coming decade. Reaching the full theoretical performance of NMC LIBs is still an ongoing task, and the current focus is moving towards Ni-rich layers [92]. Together with NMC LIBs, $LiFePO_4$ (LFP) and LiNiCoAl (NCA) LIBs populate the current market [6]. Simultaneously, different researchers seek to develop different chemistries (e.g. Li–S, Li-air, Na-ion and all solid-state), capable of outperforming the current reference chemistry. While this analysis is mainly focused on the current reference technology and its development, i.e. NMC chemistry, the deployment of novel battery chemistries with a different material composition can transform the LIB industry. The adoption of chemistries without Li and Co could ease the concerns surrounding their value chains. At the same time, it is challenging to foresee the

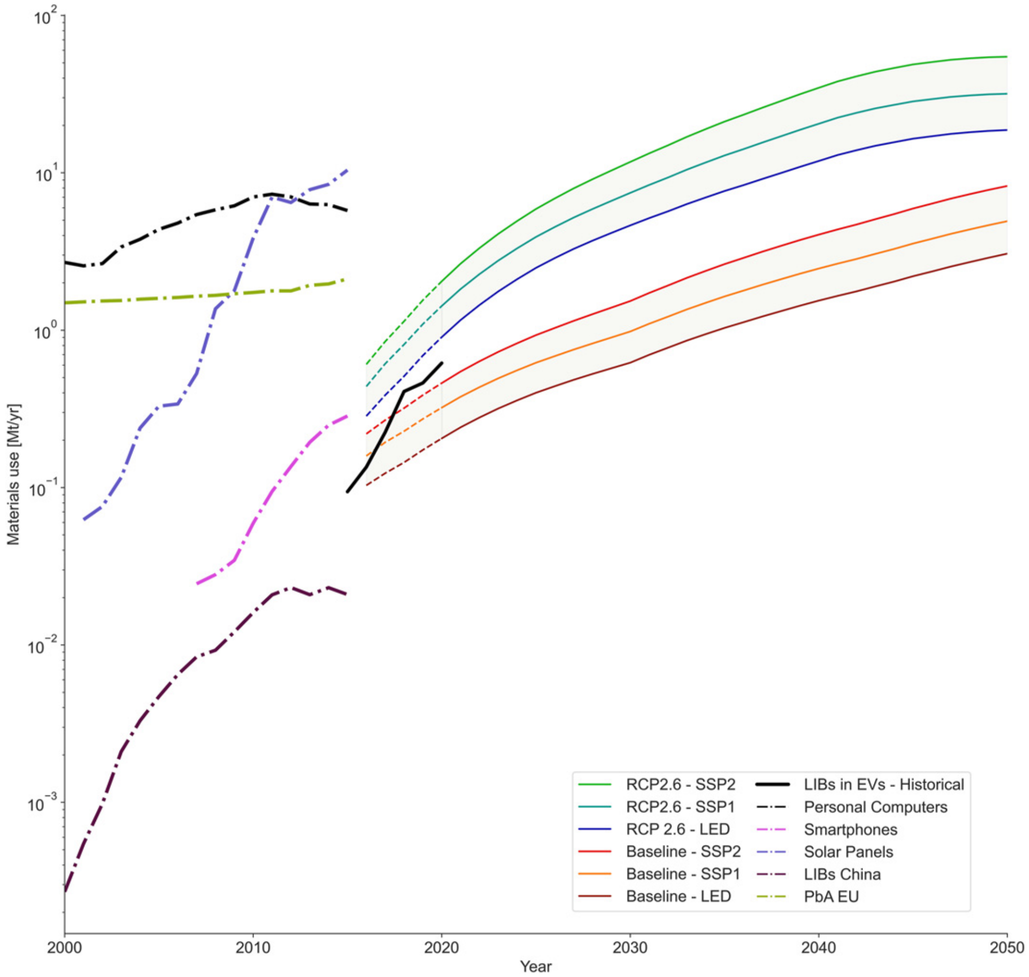

Figure 5. Evolution over time of the materials demand of the LIB industry compared to benchmark industries.

materials embodied in novel batteries and what effects these may have on the industry and its linked sectors. Moving to newly developed battery technologies can have several effects on both the production and recycling industries. As Duffner *et al* pointed out, future chemistries with higher energy densities employed in EVs can potentially drive the partial redesign of manufacturing facilities, which can lead to a net increase in the cost of the cells [61]. In spite of the challenges posed to the production and recycling sectors, new technologies can induce a reduction in the environmental impacts of LIB value chains with the possibility of reducing supply constraints due to more available materials.

In addition, since the recycling phase profitability depends on the price of the materials embodied in LIBs, the use of cheaper materials may diminish the economic viability of recycling facilities [93]. To date, the pyrometallurgical treatment of spent LIBs is the most common, due to the high recovery rates of valuable metals, such as Ni, Cu and Co [94–96], while Li is lost in the slag. Li is often recovered either through hydrometallurgical or direct recycling techniques [94, 95]. Hydrometallurgical recycling is less common due to the greater challenges posed in recovering more valuable metals such as Co, Cu, Ni and Al [95]. However, with the rise of Co and Li prices, this recycling strategy could see increasing adoption rates, together with direct recycling. LIBs will likely be used in other sectors of the economy, such as in stationary energy storage applications, and the adoption of circular economy strategies calls for more efficient recycling strategies with the possibility of reactivating the active materials for reuse within the LIB sector.

The current yearly demand for LIBs has not yet had a significant impact on automotive CO_2 emissions. However, concerns about the supply failing to meet the demand are already becoming prevalent. Recently, several automotive manufacturers stated that production delays are due to production bottlenecks in the pack assembly [58]. If the EV demand keeps growing at the rate observed in the past 5 years it is likely that other original equipment manufacturers, as they move to a larger portfolio of EVs available, may face similar issues. The competitiveness of EVs may be threatened by the shortage of key resources.

As EV adoption is quickly gaining momentum, the same is happening to the LIB market with constant announcements regarding the construction of new LIB production facilities. However, as the current plans seem promising and total installed production capacity exceeds the current and short-term forecast demand, high electrification scenarios call for significantly higher production capacity to be put in place. Figure 5 shows how quickly the demand for LIBs will grow in the short- to medium-term, compared to reference industries. Between high- and low-penetration scenarios, there are significant differences in the average yearly demand for LIB materials, which can have different effects on the upstream sectors of interest, as discussed in the previous sections of this manuscript.

Compared to similarly complex, fast-growing sectors, such as PV and smartphone production, the LIB industry may potentially require significantly more materials (figure 5). With these trends, the upcoming decade will be the cornerstone for LIB production know-how and recycling, and the establishment of strong value chains that will lay the groundwork for the future fate of the transition to electrified mobility at a pace that would allow the realization of the electrification targets of the transport sector. This rapid growth requires significant capital investment along the supply chain, with the need for a synchronized expansion of material processing activities, battery manufacturing plants and recycling facilities to avoid bottlenecks that could potentially disrupt the supply chains and slow down the deployment of EVs. The potential growth of the LIB value chain can create a multitude of jobs in various areas, from mining to construction and R & D.

In addition, to harvest the highest emissions reduction potential it is essential to ensure that all these activities are performed in the most environmentally sound way. While the last stage of the battery production value chain could be rather straightforward to decarbonize due to the possibility of producing the cells with renewable energy sources, there are significantly more challenges related to the value chain of the primary materials used in LIBs, as the impact across the value chains is affected by several parameters [97].

5. Conclusion

As shown in this study, high electrification scenarios, regardless of the socioeconomic pathway, entail substantial effort for the supply of key battery materials, investment needed to build the necessary production and recycling facilities, and the education of a skilled workforce. Our analysis highlights the effort needed for the electrification of the transport sector in a manner both compliant with climate targets and sustainable resource strategies. This combination entails significant investment to build the manufacturing capacity, which consequently requires global coordination to ensure that batteries are properly recycled and mining activities can supply enough materials. At the same time, it is challenging to make such estimates due to the uncertainty related to the future EV uptake, particularly due to the data scarcity regarding the current estimates of mine capacities, and production and recycling facilities in the pipeline. While there is no apparent shortage of resources, the complexity of the supply chains involved in the LIB sector combined with the lack of enough geographical diversification for key resources, both virgin and refined, can pose a future threat to the entire supply chain. A shortage of either LIBs or materials for LIBs due to the disruption of the supply chain at any random point may hinder the ability to fully electrify the fleet of passenger LDVs by 2050.

Author contributions

LU, JJL and AHS designed the study. LU collected the data, wrote the code and performed all the calculations. EE provided the vehicle deployment scenarios. LU, JJL, EE, OSB and AHS analyzed the results. LU wrote the main draft of the manuscript. JJL, EE, OSB and AHS provided feedback and helped in writing the final version of the manuscript.

Conflicts of interest

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

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files) and at the following repository: (https://github.com/lorenzousai/LIBs-demand-).

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