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A Perspective on the Battery Value Chain and the Future of Battery Electric Vehicles

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ABSTRACT

Even the most conservative projections suggest that significantly higher demand for batteries in the transport sector is expected in the coming years. A relevant concern is the supply security of lithium-ion batteries, which has been raised and discussed in existing literature in the context of sustainability and the technological readiness of different parts of the battery value chain. However, an up-to-date analysis of this value chain is beneficial to spotlight the main current bottlenecks. This perspective article aims to make a worthwhile contribution in two respects: first, to encourage further research in the techno-economic aspects of lithium-ion and beyond battery chemistries; second, to aid investors and policymakers in the decision-making process paving the road for the realization of the sustainability goals in the transport sector.

1 | Introduction

Lithium-ion batteries (LIBs) have a successful commercial history of more than 30 years. Although the initial market penetration of LIBs in the nineties was limited to portable electronics, this Nobel Prize–winning invention soon diffused into other sectors, including electric mobility [1]. The demand for LIBs to power electric vehicles (EVs) has continuously grown since 2010, catalyzed by the global consensus over the urgent need to electrify the transport sector to combat climate change. In particular, the number of new EVs registered globally has increased from 0.7 million in 2016 to more than 10 million in 2022 (Figure 1). During the same period, this corresponds to an equivalent rise in the yearly addition of LIB capacity from 43.8 to 550.6 GWh/year [2]. The light-duty vehicle (LDV) is the dominant market for the LIBs followed by the 2–3 wheelers, trucks, and buses (Figure 1). In the LDV category, 60 kWh is the current average size of the battery packs, which reflects the consumer desire for higher range and SUV cars [2, 3]. The exact correlation between the pack size and the driving range depends on many parameters including the weight of the car and its real-time energy consumption. However, it is safe to assume a typical driving range of 350 and 600 km for a medium-size EV with a pack of 50 kWh (e.g., Volkswagen ID3) and an SUV of 100 kWh (e.g., Tesla Y), respectively (Figure 1). These specifications can be compared with those of an EV truck powered by a 620 kWh battery with a range of 500 km (e.g., Mercedes eActros600) [3, 4].

The concerns over the sustainability of LIBs have been expressed in many reports during the last two decades with the major topics being the limited reserves of critical components [5–7] and social and environmental impacts of the production phase of the batteries [8, 9]. In parallel, there is a continuous quest for alternative battery technologies based on more sustainable chemistries, such as lithium–air, lithium–sulfur, and Na ion [10, 11]. Notwithstanding the significant research progress in post-LIBs, industrial maturity remains the prerogative of the LIBs. This is particularly a major advantage for LIBs in view of the pressing challenge of electrifying road transport and its scale. As such, as expressed by the battery experts, the futuristic chemistries are complementary to the LIBs instead of competitors [12]. In this regard, the current status of the battery value chain is discussed in view of the future demands in the EV market to identify the main impediments to the security of the supply chain.

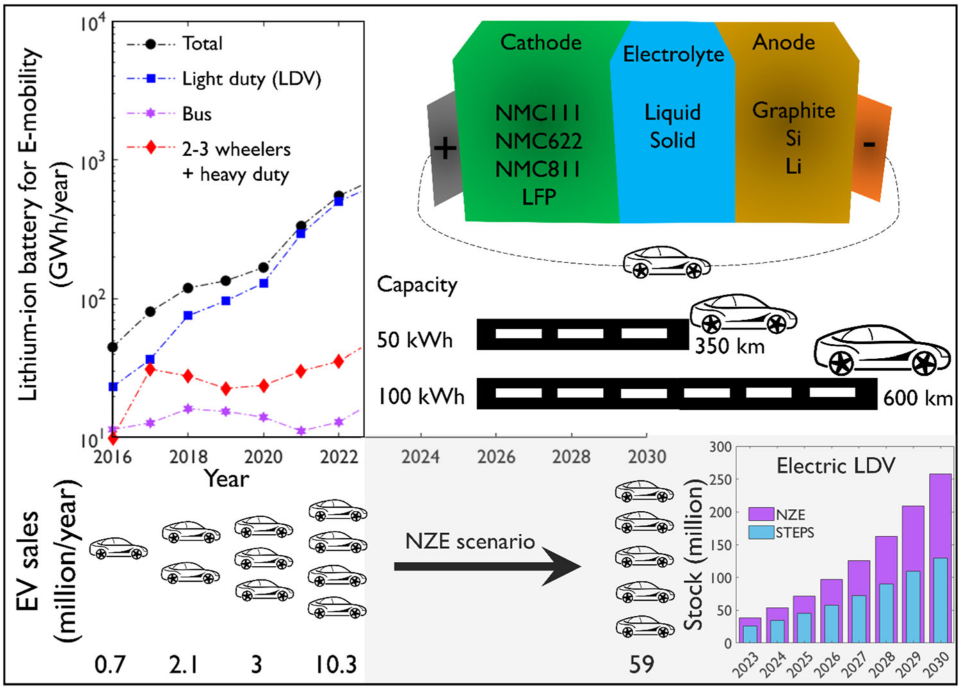


FIGURE 1 | The evolution of the global capacity of lithium-ion batteries and the sales of electric vehicles during the last decade (left) and the projections up to 2030 (right).

2 | Material Supply and Demand for LIBs

The International Energy Agency (IEA) has developed a comprehensive modeling approach to investigate the long-term scenarios for the transition of the energy sector toward a net zero CO_2 emission by 2050 [13]. A couple of main scenarios have been formulated to represent the different prospects and timing of implementation for the government announcements in reaching the emission targets. The Net-Zero-Emission scenario (NZE) assumes that an efficient and fast implementation of clean energy technologies is commensurate with limiting the global temperature rise to 1.5°C by 2050.

A more conservative and slower transition is the Stated Policies scenario (STEPS), which reflects the existing policy landscapes, infrastructure, and financial constraints of countries in the full realization of their commitments. In the NZE scenario, the accelerated uptake of EVs is assumed to enlarge the cumulative stock of electric LDVs to above 250 million vehicles by 2030. This can be compared with more than 125 million vehicles in the STEPS scenario (Figure 1) [2, 6].

Regardless of the pack size, very similar components are found inside the lithium-ion cells. In short, the cathode and anode electrodes contain the so-called Li-insertion particles, which are capable of storing lithium and exchanging lithium ions and electrons with the electrolyte and the external circuit, respectively, during the (dis)charge of the battery. In the current generation of LIBs, the only liquid component is the electrolyte, which is an ionic medium for the transport of lithium between the two electrodes, and once replaced with a solid electrolyte can boost the safety of the LIBs in the next-generation solid-state batteries (Figure 1) [10]. The Li-insertion particles at the cathode, hereafter referred to as cathode active material (AM), are the main components of LIBs exposed to sustainability issues. This originates from the chemical composition of the cathode AMs, which contain lithium (Li) and have been historically rich in critical non-abundant elements, such as cobalt (Co). Particularly, the $LiNi_xMn_yCo_{1-x-y}O_2$ family, known as NMC, are the favorite AMs in EVs [14]. In 2022, this sector was dominated (66%) by the NMC622, which is a subclass of NMC with the Ni to Co ratio of 3 (i.e., $x = 0.6$, $y = 0.2$). This is a higher Ni content NMC compared to an older NMC111 with an Ni to Co ratio of 1 (i.e., $x = 0.333$, $y = 0.333$; Figure 2) [2, 14]. Another common cathode AM is the $LiFePO_4$ (LFP) with no critical metal in its composition. In 2022, the LFP had the second-largest share in the EV market (27%). The use of non-abundant elements such as Co, Ni, and Li has two main side effects. First, the low concentration of these elements in the natural minerals means a more complicated and energy-intense production phase during the mining and chemical processing steps. It is obvious that an energy-intensive process increases the emission footprint of the cathode AMs on account of the present low levels of electrification in the mining and chemical industry [6]. Second, an unsupervised accelerated consumption of the critical elements can perturb the balance between supply and demand and eventually lead to the depletion of the global reserves. In 2022, the EV market accounted for 60%, 30%, and 10% of the total demand for lithium, cobalt, and nickel, respectively (Figure 2) [2, 6]. The recent historical data suggest that supply and demand have simultaneously increased for these elements without any instance of significant imbalance during the last decade (Figure 2). The global reserves for Li, Co, and Ni amounted to 22, 8.3, and 95 million tones to be compared with the global resources of 89, 25, and 300 million tons, respectively [6, 15]. It is important to distinguish between the "reserves" and "resources" of a mineral. A mineral reserve is a fraction of the known resources of which extraction and mining

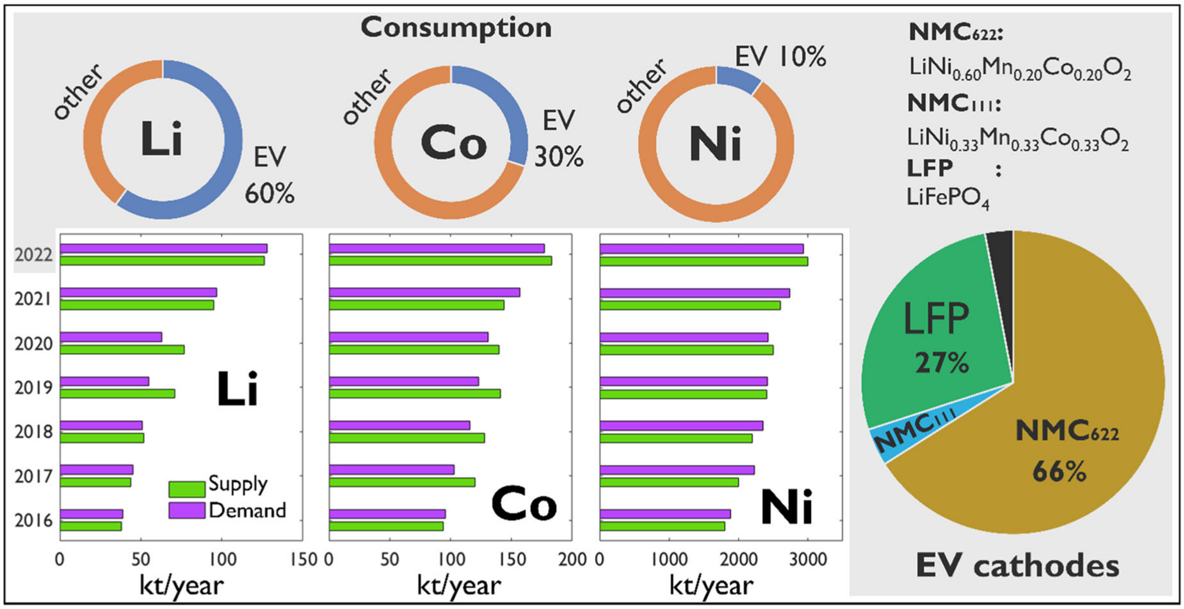


FIGURE 2 | Historical data for the demand and supply of Li, Co, and Ni (white shade) together with their market share for the manufacturing of the major cathode materials in lithium-ion batteries in 2022 (gray shade).

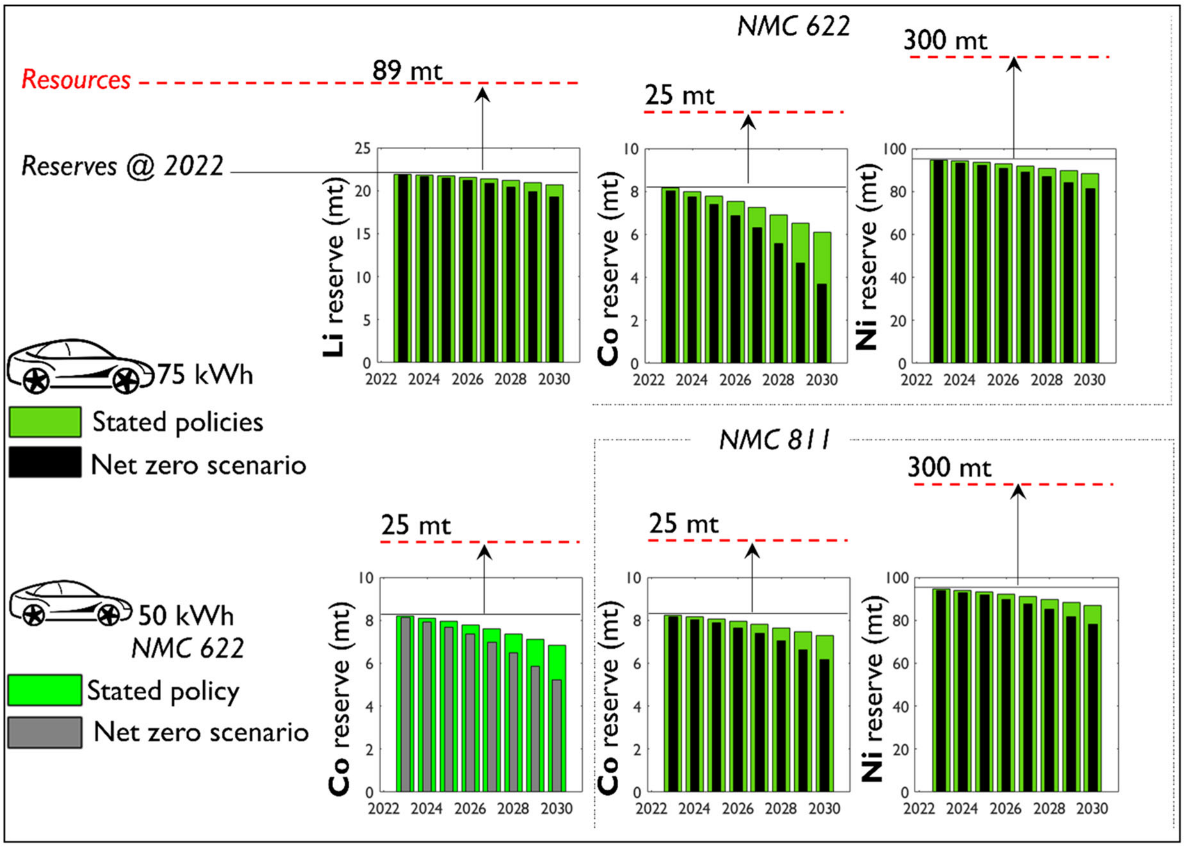


FIGURE 3 | Potential depletion of the Li, Co, and Ni reserves driven by the demand rise in the electric vehicle market evaluated for NZE and Stated Policy scenarios and different cathode chemistries in lithium-ion batteries.

are feasible under the existing social and economic conditions. The global resources indicate the potential maximum stretch in the future production capacity of a mineral. The 2022 identified reserves of the Li, Co, and Ni will be used in the 2022–2030 period by 12%, 55%, and 14%, respectively, for the LDV market under the NZE scenario with NMC622 LIB chemistry and assuming no expansion in the global reserves (Figure 3). The data clearly identify Co as the most critical element of LIBs with an average depletion rate of 6% per year compared to 1.3% and 1.5% per year for Li and Ni, respectively.

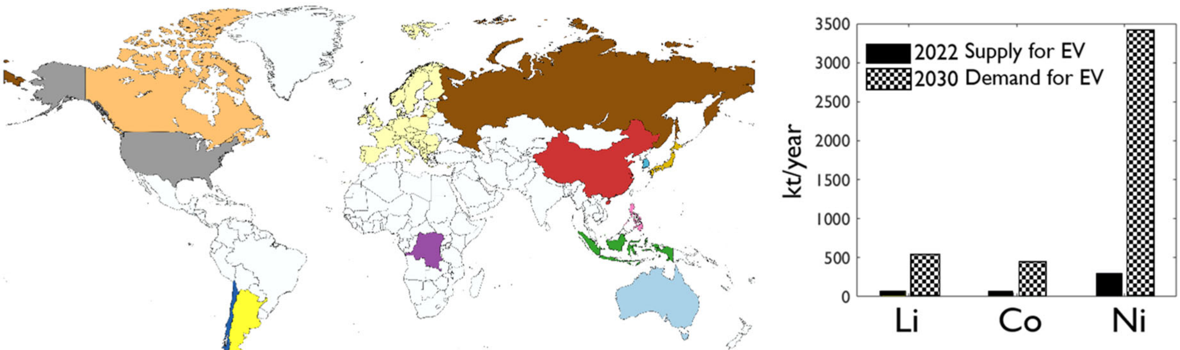
The assumptions of NMC622 chemistry, NZE scenario, and an average pack size of 75 kWh emulate a combination of very extreme conditions. For instance, the substitution of NMC622 with NMC811 enables a lower depletion of 26% for Co under the NZE scenario (Figure 3). Clearly, the consumer acceptability for the smaller pack sizes (e.g., 50 kWh) can remove one-third of the stress from the Co reserves (Figure 3).

3 | Supply Chain of LIBs: Current and Future

There are limited reports on the quantitative assessment of the battery value chain. This literature can be classified into two main groups: "criticality" analyses [16, 17] and life-cycle assessment (LCA) [18, 19]. The main objectives in the former and latter groups of research are to evaluate the sustainability of the value chain in view of the supply security of the materials and the greenhouse gas (GHG) emissions of battery production, respectively. In both groups and from a methodological point of view, the material flow analysis (MFA) [20] and System Dynamics approaches [21] are common ways to conduct retrospective and prospective investigations of a value chain. However, the majority of available reports on the battery value chain rely solely on the material balance (MFA) [22] and neglect the causal links and feedback loops pertaining to a complex system, such as the interactions between the price and demand, among others [21]. In the "criticality" studies, the supply risk and its impact on the battery value chain (vulnerability) is quantified by a series of indicators. For instance, the probability of the supply disruption is calculated to quantify the risk of supply by measuring the market concentration via an index such as the Herfindahl–Hirschman (HHI), which rates the oligopoly level of the market [16]. Moreover, some measures of governance quality, such as the Worldwide Governance Indicator (WGI), are combined with the HHI to account for the sensitivity of the supply chain to the governance quality of the regions and countries contributing to the value chain [23].

Here, a simple material balance at the global level was performed to evaluate the supply capacity in response to the growing demands for the Li, Co, and Ni in the EV sector. There will be a significant jump in the demand for Li, Co, and Ni from the EV market in 2030 compared to 2022. Although there is a low chance of reserve exhaustion, a considerable boost in the production of these elements from the existing mines and exploitation of the new sites is inevitable. For instance, under the NZE scenario and assuming 75 kWh NMC811 battery packs, the Li, Co, and Ni demand will be 7, 8, and 11 multiples, respectively, of the supply figures in 2022 (Figure 4). This requires a considerable acceleration in building up the production capacities compared to the 2016–2022 period during which the supply of Li, Co, and Ni only expanded by 220%, 90%, and 70%, respectively [6, 15]. This is quite challenging in view of the long lead times for such projects. For instance, according to S&P Global, the new Li projects can take as long as 7 years to complete [24].

The non-optimal geographical distribution of the supply chain can be a hindrance to the sustainability of the batteries for the EV market. Except for China, there is a significant imbalance between the local shares of the passenger car demand and the battery supply chain (Figure 4) [25–27]. For instance, in 2022, Europe had a 21% share of the global new sales of passenger cars, which is considerably more significant than its current share in the supply chain of EV batteries. Currently, the Li-ion cell production capacity in Europe approximately accounts for 7% of the global capacity of the giga-factories, compared to China's global share of 76%.



	Li mine	Li process	Co mine	Co process	Ni mine	Ni process	Cathode	Cell	LDV sales
China	17%	65%	-	74%	-	17%	70%	76%	40,99%
Chile	26%	29%	-	-	-	-	-	-	0,55 %
Argentina	-	5%	-	-	-	-	-	-	0,45%
Canada	-	-	-	4%	-	-	-	-	0,45%
Indonesia	-	-	5%	-	49%	43%	-	-	1,36%
Russia	-	-	-	-	6%	5%	-	-	1,10%
Australia	47%	-	3%	-	-	-	-	-	1,35%
Congo	-	-	74%	-	-	-	-	-	-
Philippines	-	-	-	-	10%	-	-	-	0,39%
Japan	-	-	-	-	-	-	14%	4%	6%
South Korea	-	-	-	-	-	-	15%	5%	2,47%
Europe	-	-	-	10%	-	-	-	7%	21,99%
United States	-	-	-	-	-	-	-	8%	4,97%

FIGURE 4 | The geographical distribution of the lithium-ion battery value chain, along with the gap between the supply in 2022 and projected demand in 2030 for the Li, Co, and Ni assuming the NZE scenario (top right corner). The map was created using MapChart.

The Co-mining and processing sectors are dominated by Congo (74%) and China (74%), respectively. Australia dominates the Li supply (47%), whereas China leads the Li refining (65%), and Indonesia is the major player in the supply (49%) and refining (43%) of the Ni. The synthesis of the cathode material powder is currently concentrated in China (70%), South Korea (15%), and Japan (14%) [26]. Recycling is the least developed part of the EV battery value chain, which is noteworthy from two perspectives. First, recycling provides an opportunity to decrease the current geographically non-uniform spread of the value chain by planning new recycling sites closer to the end users. Second, end-of-life management is a crucial element in the sustainability of the battery value chain [28]. This is to be understood not only in view of the residual value of the precious elements residing within the retired batteries but also with respect to the emission loads associated with their production phase [29]. The current literature suggests that the primary energy consumption and GHG emissions from LIB production lie within a range of 200–500 kWh/kWh and 70–175 kg CO_2-eq/kWh, respectively [19]. The recycling can reduce the GHG emissions by 5–29 kg CO_2-eq/kWh. Currently, an insignificant fraction (2%–5%) of LIBs is properly collected and recycled in the EU, the United States, and Australia [30]. Many end-users tend to store these spent batteries at home (> 50%), whereas a smaller group (< 15%) discards them in municipal waste [29]. This situation certainly cannot be tolerated for the EV batteries considering the size and safety limitations and the significant value of the residual critical materials in the spent EV batteries. Although few main players are currently operational for recycling LIBs, more than 150 new recycling projects have been announced with a total capacity reaching more than 2.5 mt/year by 2030 [31].

The current instream of retired EV batteries is rather limited; therefore, the main feedstock to the battery recyclers originates from the production scraps at the giga-factories. At this moment, this might seem not very conducive to the rapid growth of the recycling market. However, this condition will drastically improve in the near future where > 1500 and > 20000 kt of EV batteries are expected to retire by 2030 and 2040, respectively [32]. Therefore, the extraction of ~25 kt Li and 75 kt Co from the retired batteries by 2030 is possible assuming a recovery rate of 95%. This is equivalent to 4%–12% and 7%–19% of the Li and Co demand in 2030, respectively, for the production of new LIBs for the EVs under the NZE and STEPS scenarios (Figure 3). However, material recycling is not the only option to treat retired EV batteries. For instance, restoring the electrodes from the batteries and their direct integration into the new cells with minimal processing can save cost and energy that otherwise would be needed for the traditional material recovery practices [33] Such processes usually involve a series of mechanical and thermal pretreatments of the batteries to obtain a "black mass" that is further refined to its constituent metals using the pyrometallurgical and hydrometallurgical processes or a combination thereof [34]. "Reuse" or "repurpose" is another strategy to refurbish the retired batteries for a second life without opening the cells. Such refurbished batteries can offer more affordable options in emerging applications such as renewable energy integration, peak shaving, EV charging, microgrids, and large-scale energy storage, among others [35]. In this regard, in the near term, the second-life approach is a rewarding option for the players in the recycling market to grow. Moreover, by 2030, the demand for utility-scale storage is projected to reach ~200 GWh/year, which can be matched by the repurposing of the expected ~100–200 GWh of the retired EV batteries by the same year [36].

4 | Newcomers and Sustainability

There are many post-lithium-ion chemistries that are currently under research and development, such as sodium-ion batteries (NIBs). This research is mainly motivated to enhance the sustainability of the battery value chain for the EVs and stationary storage markets. The futuristic technologies such as NIBs are still not mature relative to the LIBs, but in-depth studies are urgently essential to evaluate their sustainability considering the whole battery value chain [37, 38]. This is particularly crucial to aid the decision-making and the optimal and timely allocation of investments. In this respect, the battery price per unit of energy ($/kWh) and the recycling cost at the end of service time are noteworthy parameters. The latter price is inversely proportional to the abundance of the raw material and the energy density (Wh/kg) of the active materials made thereof. A higher energy density cathode or anode implies a lower cost for the processing, production, and recycling of a battery pack with a given capacity. Although the weight and space limitations are not very stringent in stationary storage applications, it is still rewarding to employ higher energy density materials to decrease the battery cost. The absence of precious materials in the battery composition can complicate the business model of the recycling phase of the batteries. In case of employing very cheap materials, the recycling cost needs to be covered somewhere in the value chain. Comprehensive studies are yet required to quantify these aspects for the different futuristic battery chemistries and active materials. The few available comparative techno-economic analyses (TEA) between the LIBs and NIBs are divergent in conclusions, which might stem from the limited available data on NIBs [39–41]. The current announced global manufacturing capacity of NIBs is estimated to be 100 GWh, which is significantly lower than the 1500 GWh of LIBs [2]. The reported data suggest that the state-of-the-art NIBs are inferior to LIBs in terms of energy density, whereas no significant difference in the battery cost per kWh is observed between the two technologies [10, 39–42]. The NIBs are at the early stages of commercialization, and the optimization of the cathode AMs will enable higher energy density NIBs. However, the fundamentally lower molecular weight and higher electropositivity of the Li compared to the Na render the LIBs unsurpassable in terms of energy density. As such, the stationary storage market seems to be a suitable ground for the NIBs to mature and manifest as an affordable and sustainable solution next to the LFP-based cells.

In the stationary storage market, the new installations of LIBs were less than 40 GWh in 2022 compared to 500 GWh in the EV sector. However, the demand in the stationary storage market is rising and forecasted to surpass a global cumulative capacity of 1200 GWh by 2030 [6, 43, 44]. The NIBs with the cathodes and anodes formulated with more abundant materials, such as Prussian blue derivatives (e.g., Na_x Fe [Fe $(CN)_6$]) and hard carbon, respectively, have the potential to facilitate the growth of the stationary storage market by providing cost-effective solutions [42]. The current size of the NIB market is 150 m$ and is expected to grow more than 230 m$ in the next 5 years [45]. The major industrial players for NIBs currently target the applications in stationary storage, low-speed EVs, two-wheelers, hybrid EVs, and power tools. This is in line with the current inferior energy density of NIBs relative to the LIBs. For instance, the recent *Yiwei* EV from the JAC is powered by a 23 kWh NIB pack composed of cylindrical 10 Ah cells with 140 Wh/kg energy density produced by HiNa Battery Technology [46]. Although the targets for more energy-dense cells, approaching 200 Wh/kg, have been announced by the major NIB players, stationary storage is predicted to remain the dominant field of application for NIBs till 2032 [45, 47, 48]. The combination of LIBs and NIBs to power the same device is another promising avenue that deserves further attention. For instance, CATL recently unveiled the Freevory Super Hybrid Battery composed of the LIB and NIB cells for the extended range EVs (EREVs) and plug-in hybrid EVs (PHEVs) [49]. The added value of this combination is an enhanced performance at lower temperatures (−40°C) and fast charge (4 C) capability of the hybrid pack. Moreover, similar to internal-combustion cars, EVs also need a low-voltage (12 V) battery to power the non-propulsion systems (e.g., infotainment and airbag). Although this market is currently dominated by lead-acid batteries, EV manufacturers have started to replace them with LIBs [50]. The low cost and sustainability are the major remaining advantages left for the lead-acid technology compared to the LIBs. In this regard, the low-voltage battery market seems to be a good fit for the NIBs considering their alleged superior sustainability and affordability relative to the LIBs. Currently, NIBs with low capacities are available in the market with an approximate price of 350 $/kWh for a pack of 1.2 kWh with an energy density of 75 Wh/kg and 97 Wh/L and a lifetime of 3000–6000 cycles (8 years) [51]. An equivalent LFP pack costs 254 $/kWh with an energy density of 100 Wh/kg and 90 Wh/L and a lifetime of 4000–15,000 cycles (8–10 years) [52]. Therefore, currently, the LFP is 45% cheaper than NIBs. Future projections suggest the cost of NIBs to be as low as 40 $/kWh and 50 $/kWh at the cell and pack levels, respectively, by 2034 [45]. This is to be compared with the cost projections for LIBs that estimate 80 $/kWh at pack level by 2030 [53]. Although these estimations are uncertain, they herald a very tough competition between the two technologies at the price level. However, these speculations should be assessed in the context of the existing knowledge about the historical dynamics of the retail prices of the LIB packs and the battery-integrated devices in the stationary and mobility sectors. The available data bespeak a very weak correlation among the cost of LIBs and the retail prices of the EVs and home batteries in the western countries. The average cost of LIB cells has dropped from 500 $/kWh in 2013 to 120 $/kWh in 2022. During the same period, a similar trend is observed for the LIB packs with a price decline from 732 to 151 $/kWh [54, 55]. However, the EV price tags have hardly declined in the West during the past decade. According to a JATO report, the volume-weighted average retail price of battery EVs in the United States and Europe has increased by 55% and 42%, respectively, between 2011 and 2019 [56, 57]. This is in contrast to the Chinese market, where EVs became 52% cheaper over the same period. This clearly reflects the pivotal impact of local policy, regulations, and incentives in promoting the EV market for the industry and consumers. Therefore, a cheaper raw material is not a sufficient condition for the timely and massive diffusion of EVs into the mobility markets of the United States and Europe. As long as the EVs are targeted, and priced accordingly, only for the early adopters, even further decline in the battery cost will not be sufficient to make EVs affordable for the late majority of consumers who are budget-conscious [57].

5 | Conclusion

A diverse portfolio of battery chemistries is certainly beneficial to the energy storage market. However, newcomers such as NIBs need to further mature and grow in capacity over the whole value chain before the practical merits and downsides can be identified and assessed in depth. Particularly, the battery lifetime is a critical characteristic to be further improved for the next-generation batteries. Currently, the useful lifetime of the LIBs is less than the lifespan of the passenger cars. In the electric LDVs, the capacity retention of a pristine LIB is guaranteed to stay above ~70% during the first ~8 years of the vehicle's life. This lifetime discrepancy between the vehicle (> 10 years), and the battery is not in favor of the sustainability of the battery value chain. Moreover, the success of the second-life business model for retired EV batteries hinges upon the presumption of their extra +10 years of longevity in the second application. In this respect, any futuristic battery chemistry such as NIBs, with a lower economic feasibility for recycling, should be optimized for a longer lifetime compared to the state-of-the-art LIBs. However, this requirement can be loosened if the EVs are used for the transportation-as-a-service (TaaS) where a lower number of EVs and batteries needs to be produced compared to that for the traditional concept of private cars. As such, in the future of the mobility sector, NIBs might have a considerable role to play within the TaaS concept.

Although the new emerging chemistries such as NIBs have the potential to increase the sustainability of the battery value chain, their possible side effects on the ongoing sustainability initiatives for the LIBs should be carefully assessed and minimized. For instance, the availability of mass-produced and cheap NIBs in the near future will be disadvantageous to the feasibility of the recycling and second-life tracks to be adopted for the retried LIBs. Moreover, the development of more sustainable approaches for cell production in the giga-factories should be accelerated, which can benefit both LIBs and NIBs. For instance, the advanced coating methods for the preparation of the thick porous electrodes can decrease the consumption of inactive materials (e.g., Cu and Al current collectors) in the cells. In this regard, a dry coating technique holds a bright future considering its added value in eliminating the use of toxic solvents (e.g., NMP) that would otherwise be used in the conventional methods during the preparation of the electrode slurry.

The predictive models of the battery value chain are scarce in the literature and the market variables including the battery and EV prices are rarely considered in the projections of the demand. Such models will be extremely helpful in conducting more reliable and comparative TEA and LCA investigations of different battery chemistries. These modeling frameworks when integrated with an optimization algorithm can facilitate the identification of the most appropriate combination of battery chemistries for the different (sub)sectors of the stationary and mobility markets.

A well-timed scale-up of production over the whole battery value chain will be the main challenge for any battery technology if the NZE mobility targets are to be met. However, the resource depletion of Li, Co, and Ni is unlikely to be a limiting factor for LIBs even under the extremely demanding NZE scenario. In a broader sense, a geographically distributed production ramp-up is expected to be a shared bottleneck between Li-ion and post-Li batteries, which calls for more serious support and commitment from governments and policymakers.

Conflicts of Interest

The author declares no conflicts of interest.

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