China’s vehicle electrification impacts on sales, fuel use, and battery material demand through 2050: Optimizing consumer and industry decisions

Highlights

- The dual-credit policy is critical to China’s vehicle electrification before 2035
- Market share of battery electric vehicles could reach 30.4%–64.6% by 2050
- Industry weighted average fuel consumption could reach 1.81–3.11 L/100 km by 2050
- Battery recycling alone could satisfy 60% of the vehicle market battery demand by 2050

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China’s vehicle electrification impacts on sales, fuel use, and battery material demand through 2050: Optimizing consumer and industry decisions

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SUMMARY
The promotion of plug-in electric vehicles (PEVs) is pivotal to China’s carbon neutrality strategy. Therefore, it is important to understand the vehicle market evolution and its impacts in terms of costs, sales, industry fuel economy, and PEV’s battery material demand. By examining vehicle technologies, cost, policy incentives, infrastructure, and driver behavior, this study quantitatively projects the dynamics of China’s passenger vehicle market from 2020 to 2050 under multiple technology evolution scenarios. By 2050, battery electric vehicles could gain significant market share—as much as 30.4%–64.6%; and the industry’s sales-weighted average fuel consumption could reach 1.81–3.11 L/100 km. Cumulative battery demand from PEVs could soar to over 700 GWh by 2050, whereas battery recycling alone could satisfy about 60% of the demand by 2050. The key metal supplies—lithium, cobalt, and nickel—for China’s PEV market are projected, and nickel should be concerned more over the coming decades.

INTRODUCTION
China, one of the world’s largest vehicle markets, is developing on-road transportation toward electrification with respect to challenges such as energy security and technology upgrading (He et al., 2020). Although the vehicle market in China faced economic downward pressure on sales in 2018–2020 and uncertainties brought by the COVID-19 pandemic, annual sales of passenger plug-in electric vehicles (PEVs) in China continued their rapid growth, reaching 1.246 million. The PEVs exceeded 6.18% of all new light-duty vehicle sales in 2020 (China Association of Automobile Manufacturers, 2021). Total public chargers reached over 800,000 by 2020, see in Table S1. Monetary and nonmonetary policies have played a critical role in these (Ou et al., 2018b). However, in the long run, it is believed that consumer acceptance along with vehicle technology progress will be the ultimate determinant after financial support from the government ends (He et al., 2020). This study investigates the consumer acceptance (sales and stocks) of various vehicle powertrain types, as well as policy constraints and infrastructure development in China’s passenger vehicle market from 2016 to 2019. In addition, the study projects the impacts of vehicle technology evolution from fuel-saving and battery on market dynamics (sales and stocks), auto industry’s fuel consumption rates, and battery raw material demands of the passenger vehicle market through 2050. This is accomplished by conducting scenario analysis using the New Energy and Oil Consumption Credit (NEOCC) model. The results provide useful insights for industry Research and Development (R&D) planning and policymaking.

The increase in fuel economy requirements and the trend toward electrification prompt automakers to develop more hybridized ICEVs and/or battery electric vehicles (BEVs) powered by electricity only (Eisenstein, 2019; Moss and Mou, 2020). One impetus is that, as the fuel economy of internal combustion engine vehicles (ICEVs) improves, the marginal cost of an additional one mile per gallon gasoline equivalent (MPGGE or MPG in the following context for simplification) improvement increases (National Academies of Sciences Engineering and Medicines, 2021). Hundreds of Chinese companies, including those that dominate the ICEV market, are now competing in the PEV market (Whalen, 2020).

Further development of the PEV market could be restricted by limited room of cost and performance improvement on the lithium-ion battery (LIB) technology (Turcheniuk et al., 2018). Currently, the cost of the battery pack could account for over 40% of the total manufacturing cost of a BEV (Hsieh et al., 2020;
Li et al., 2020). Meanwhile, the cost of the internal combustion engine and its auxiliary accounts for only 14% of the manufacturing cost of an ICEV (Hsieh et al., 2020). Ideally, the US Department of Energy (DOE) expects the cost of electric vehicle batteries to be less than $100/kWh and estimates that it will ultimately reach about $80/kWh (U.S. Department of Energy, 2020a). The battery cost has significantly decreased in recent years. According to estimates by Bloomberg New Energy Finance, battery pack cost quickly fell 80% in real terms from nearly $1,100/kWh in 2010 (Henze, 2019) to $209/kWh by 2017 (Stevenson, 2017), and the number has changed to $137/kWh in 2020 (Henze, 2020). Nevertheless, the current cost is still far away from the DOE’s ultimate target. To increase battery performance with limited cost increase, other materials are being developed, such as lithium-O2 batteries (Qiao et al., 2019), sodium-ion batteries (Eftekhar and Kim, 2018), magnesium-ion batteries (Walter et al., 2020) and aluminum-ion batteries (Walter et al., 2020). However, in the foreseeable future, nickel-rich lithium nickel manganese cobalt oxide (NMC) (Campagnol et al., 2018; National Academies of Sciences Engineering and Medicines, 2021) or solid-state batteries (Zheng et al., 2018) are expected to capture most of the market share. Therefore, the cost and performance of batteries will deeply shape the vehicle market dynamics.

In addition, the geographic disequilibrium between the battery raw material supply such as lithium (Li), nickel (Ni), and cobalt (Co) and the battery manufacturing is becoming a critical issue impacting the growth potential of PEVs (Jaffe, 2017). Olivetti et al. pointed out that the linkages between the raw materials mines and factories are fragile (Olivetti et al., 2017). The major raw materials are concentrated in a few countries. For example, Australia, Chile, and Argentina cite over 80% of Li exports in the global trading by 2019 (Olivetti et al., 2017). On the other hand, 73% of the global battery manufacturing capacity is dominated by China, followed by the United States with 12% (Rapier, 2019). Sun et al. estimated that the LIB supply chain competitions among Korea, Japan, and the United States would be most notable, due to their relatively high similarity on the LIB products and mining sources (Sun et al., 2021).

Quantitative modeling to understand the impacts of technology advancement in vehicle market dynamics could help policymakers evaluate the effectiveness of industry policies. Yeh et al. utilized the bottom-up decision-making model—MARKET model, which characterizes current and future energy technologies in detail—to project technological pathways and greenhouse gas emissions in the US light-duty vehicle sector (Yeh et al., 2008). Hache et al. developed a bottom-up technology optimization model on world transport and projected 75% of the worldwide fleet would be PEVs by 2050 in 2°C scenario (Hache et al., 2019). Tattini et al. combined the discrete choice theory with the energy-economy-environment-engineering (E4) system for transport and energy policy analyses (Tattini et al., 2018). Similarly, the NEOCC model, integrating the discrete choice method with the optimization, is used to project sales and stocks of multiple powertrain technologies and to evaluate the auto industry’s fuel economy and battery raw material demands in the context of China’s growing electric vehicle market (He et al., 2020; Ou et al., 2018b, 2020b).

Focusing on the Chinese market, this study collects vehicle market and technical data, and reviews the most recent literature sources, including peer-reviewed journal articles, government policies, working papers, and reports such as the vehicle cost and performance analysis by the National Research Council (National Academies of Sciences Engineering and Medicines, 2015). These data sources are used to create reasonable assumptions and scenarios for future fuel economy, vehicle manufacturing cost, battery cost, and battery demands. Different scenarios and assumptions are then entered into the NEOCC model for creating quantitative scenarios, which can help industry stakeholders prepare for upcoming business activities and mitigate investment risks in the market. Unless otherwise stated, the exchange rate of $1.00 USD to 6.91 CNY (a yearly currency exchange rate in 2019) is used in this study (U.S. Internal Revenue Service, 2020).

RESULTS

Design of the technology evolution scenarios

This study quantifies the potential impacts of vehicle market dynamics using the NEOCC model under different technology evolution scenarios. The vehicle types discussed in this study are presented in Table S2. The scenarios are described below:

- Scenario (a): Reference scenario. To improve the market penetration of PEVs, in 2017 the Chinese government adopted monetary and nonmonetary incentives with respect to consumer purchases, convenience of parking or driving in urban areas, and charging infrastructure (Ou et al., 2019). More importantly, China released the first version of “Passenger Cars Corporate Average Fuel
Consumption and New Energy Vehicle Credit Regulation” (also known as the dual-credit policy) in 2017 (Ou et al., 2020b) and updated the regulation in 2020 for 2021–2023 to improve the adoption of PEVs. The rules in the dual-credit policy and other long-term government policies and roadmaps are applied in this scenario. Policy assumption details can be referred to He et al. (He et al., 2020). Other assumption details are given in STAR Methods.

- **Scenario (b): No dual-credit policy rules (no rules).** This is the same as Scenario (a), but there are no constraints, such as industry fuel economy standards and PEV quota requirements, from the dual-credit policy to push the market toward electrification. However, PEV incentives, such as government subsidies and vehicle license purchase privileges, and their implementation periods are as they are in the market.

- **Scenario (c): Optimistic fuel-saving technology scenario (opt-FE).** The development of fuel-saving technology for ICEVs is optimistic, and the incremental manufacturing cost per extra MPG in highly fuel-efficient ICEVs, such as hybrid electric vehicles (HEVs), is cheaper than it is in the reference scenario. All costs, but the vehicle manufacturing costs, in this scenario are the same as in Scenario (a).

- **Scenario (d): Pessimistic fuel-saving technology scenario (pes-FE).** The development of fuel-saving technology for ICEVs is pessimistic, and the incremental manufacturing cost per extra MPG in high fuel-efficient ICEVs is more expensive than it is in the reference scenario. All costs, but the vehicle manufacturing costs, in this scenario are the same as in Scenario (a).

- **Scenario (e): Optimistic battery technology scenario (opt-bat).** The development of PEV battery technology is optimistic. Thus, the battery pack cost for a specific energy density is cheaper than it is in the reference scenario. Battery pack cost is expected to be around $83/kWh in 2030 and around $67/kWh in 2050. The battery costs in this scenario are presented in Figure S1. All costs, but the battery costs, in this scenario are the same as in Scenario (a).

- **Scenario (f): Pessimistic battery technology scenario (pes-bat).** The development of PEV battery technology is pessimistic. Thus, the battery pack cost for a specific energy density is more expensive than it is in the reference scenario. Battery pack cost is expected to be around $124/kWh in 2030 and around $110/kWh in 2050. All others are the same as in Scenario (a).

**Impacts of vehicle markup factor on market dynamics and industry profit**

The markup factor is the ratio of the vehicle retail price to the manufacturing cost, which determines the profitability of the vehicle model. It is a critical factor impacting the potential profits obtained by the automakers and their sales strategies for various vehicle types under different policy constraints and vehicle manufacturing cost scenarios. Therefore, the sensitivity analysis and the quantification of the impact of the markup factor on the vehicle market would be necessary when discussing the future market dynamics under the government’s policy constraints and consumer preferences. Here, a sensitivity analysis is conducted on the markup factors for all vehicle powertrain types in China in 2030. Scenario (a), the reference case, is used as the baseline. Four market dynamics indicators—(1) market share of PEVs, (2) market share of LowFC-ICEVs, (3) industry CAFC, and (4) changes in industry profit per vehicle—are simulated by increasing or decreasing markup factors by 20% from each value in the base case. Figure 1 presents the relative changes of the four market dynamics indicators compared with their values in the baseline discussed.
Comparing the results shown in Figure 1, vehicle market indicators such as the share of PEVs, the share of LowFC-ICEVs, and the industry CAFC do not generally vary much due to changes in markup factors for all powertrain types. This is because the relative profit margins among different vehicle powertrain types do not change much when all markup factors simultaneously increase or decrease by 20%. The automakers have no incentive to significantly alter the internal subsidies on their vehicle products to cater to consumers while obeying the policy constraints for better industry profits. However, as shown by the changes in industry profit per vehicle in Figure 1, the profit per vehicle is greatly affected by changes in markup factors. This implies that if the markup factors for some powertrain types (such as PEVs) change much more/less than the markup factors for some other powertrain types (such as ICEVs), the market structure would vary, because the automakers would change their vehicle products for higher profits.

Sales of battery electric vehicles could reach 30%–60% by 2050

As shown in Figure 2, BEVs are estimated to gain significant market share and will be the major driver of market growth in China’s passenger vehicle market regardless of the scenario. The detailed projected annual sales and stocks in 2020–2050 by powertrain type and by scenario are given in Figure S2 and Tables S3–S14, respectively. Due to the evolution of multiple technologies, by 2050 the annual vehicle sales could be 26.0–30.2 million; the vehicle stocks could reach 359.3–397.1 million; and the market penetration of BEVs is expected to be 30.4%–64.6% in the passenger vehicle market. In addition, the vehicle market can be more prosperous under the optimistic technology evolution scenario than under the less optimistic technology scenario, regardless of whether the development is from fuel-saving technology or battery technology. This might be because, under the policy constraints that push the industry forward for a clean and sustainable transportation solution, the improvement of vehicle technology reduces the cost of producing more efficient vehicles. The expense of these vehicles, relative to the increased household incomes, becomes more affordable.

Considering the policy-market relationship, the dual-credit policy constraints in China will not be the driving force pushing the industry toward electrification beyond 2035, because more than one-third of consumers will be likely to buy BEVs even in the absence of purchase incentives after 2035. PHEVs seem to be a transient technology in the path towards vehicle electrification. The market share of PHEVs will increase and reach its peak during the next ten years (2020–2030). After 2030, the share of PHEVs will decrease due to the increase in BEVs or LowFC-ICEVs market share. This means that, prior to 2030, PHEVs are cost-effective.
enough to help automakers meet fuel economy standards. However, they are not sufficiently cost-effective to help automakers in the long term because their manufacturing cost seems to be higher than that of other vehicle technologies.

In addition, Figure 2 shows that the market penetrations of vehicle powertrain types under Scenario (a) and Scenario (b) are not very different after 2035: both achieve around 50% BEV penetration by 2050. This is because, as the PEV market develops (resulting in more convenient charging infrastructure and cheaper PEV prices), the current incentives will be gradually less effective in forcing PEV market expansion. The model projects that, by 2038, the market alone would be the only driving force, unless the government wants an even higher market penetration of PEVs.

China’s vehicle market is big enough for the development of both PEVs and ICEVs through 2050. It appears that the projected market share of LowFC-ICEVs (referring to hybrid electric vehicles) varies, especially in the near term (2020–2030). When fuel-saving technology is cheaper, the LowFC-ICEVs will be the first choice, and the market strength of LowFC-ICEVs can be maximized. However, as battery cost continuously decreases, the market share of LowFC-ICEVs will stabilize or slightly decrease in all scenarios. Therefore, the share of LowFC-ICEVs is suppressed by the growth of BEVs to some extent. On the other hand, although PEV sales are expected to grow under all scenarios, ICEVs will remain an important portion of the passenger vehicle market in China through 2050. In the reference scenario, the sales market share of ICEVs is 42%, and the share of ICEV stocks could be 55% by 2050. Even in Scenario (d) where fuel-saving technology is less developed or Scenario (e) where the battery technology is well developed, ICEV stocks could still be over 40% by 2050.

**The dual-credit policy is vital to reducing the industry average fuel consumption rate before 2035**

Reducing the incremental manufacturing cost ($/MPG) of improving ICEV efficiency allows the auto industry to more easily reach the fuel economy targets set by policymakers. This study compares the industry average fuel consumption (CAFC) rates under different conditions, as shown in Figure 3. The CAFC has been adjusted to the fuel consumption rate under the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) driving cycle in the NEOCC model. The upper and lower bounds of the green area indicate the pes-FE and opt-FE scenarios, respectively. The upper and lower bounds of the gray area indicate the pes-bat and opt-bat scenarios, respectively. First, due to the major vehicle policy constraints (the dual-credit policy), the industry’s CAFC is significantly lower than the CAFC under the scenario without any policy constraints before 2035. Even in scenarios with high manufacturing cost for ICEVs or in scenarios with high battery cost, the industry’s CAFC is still lower than the CAFC under the scenario without any policy constraints. In addition, due to policy constraints, the possible values of the industry’s CAFC vary in a very small range. Therefore, the dual-credit policy or similar vehicle fuel economy policies in China are vital to reducing the industry’s CAFC before 2035. However, after around 2035, the impacts of policy constraints could decrease gradually, and the industry’s CAFC could become more susceptible to changes in the manufacturing cost of ICEVs or changes in battery cost. This is because market selection becomes the dominant factor.
affecting sales of different powertrain types, making vehicle performance and cost important. By 2050, the industry’s CAFC is expected to be 1.81–3.11 L/100 km.

Demand for battery raw materials depends on recycling and second use

With the strong policy-driven shift from conventional petroleum-based fuels to electrification, the demand for LIBs is expected to grow rapidly. In the reference scenario, the annual LIB demand from China’s passenger vehicle sector could expand at a compound annual growth rate of 10.1%, increasing to 374 GWh in 2035 and reaching 765 GWh in 2050. This fast-expanding PEV market will, on one hand, lead to a great increase in the volume of spent batteries over the next decades when PEVs reach their retirement age. The expected spent LIBs under the reference scenario will increase to 200 GWh in 2035 and grow another factor of 3 throughout 2050. This rapid growth in battery demand, on the other hand, would create significant pressure on the availability of key battery materials. Recycling LIBs is a pressing need due to limited resources, and closed-loop recycling has been shown to be feasible with high recovery efficiencies (Chen et al., 2019; Gratz et al., 2014). When PEV batteries degrade below PEV requirements (e.g., energy storage capacity decreases by 20%–30%), they could be reused for second-life applications such as grid-level energy storage (Podias et al., 2018). Second-use applications of PEV batteries would increase battery useful life. The lifespan of second-life batteries depends on their applications, ranging from 6 years in area regulation grid services to 30 years in fast electric vehicle charge support applications (Casals et al., 2019). This study explores the potential impact of recycling (or recycled supply) on the mining demand for battery raw materials and how that would be affected by the second-use battery deployment in China’s passenger vehicle market. Because cathode materials consist of scarce or valuable metals, we focus our investigation on key cathode elements.

Figure 4 and Table S20 shows the temporal evolution of the cumulative demands for Li, Ni, and Co from PEV batteries in China’s passenger vehicle market under the reference scenario, based on the average from the two NMC composition scenarios. The stacked bars (i.e., the sum of the dark-shaded and light-shaded bars) represent the cumulative battery material demand without recycling and second use. The light-shaded parts indicate the maximum reductions in raw materials demand due to 100% battery recycling, and the black solid lines denote the cumulative material demand considering recycling and second-life applications. The analysis indicates that recycled supply will be negligible until 2040 because the current battery installations are much smaller than the fast-growing demand from new PEV sales in the coming decades. Recycling could potentially satisfy more than 60% of the cumulative battery demand by 2050, increasing from about 10% in 2030. Second-use applications of used PEV batteries will postpone the time of recycling and thus reduce the availability of recycled supply (i.e., increase the demand for

Figure 4. Cumulative battery raw materials demand from China’s passenger vehicle market under the reference scenario

The analysis considers the potential impacts of recycling (in the light shaded bars) and second-life use (2020–2050). Second-life battery deployment would delay the time of recycling and extend the useful lifetime for another 6 to 30 years depending on the applications, which therefore reduce the availability of recycled supply and increase the demand for mining production. The projection results are presented in Table S20.
primary raw materials) in the following years. The results show that even though it has the world’s second-largest lithium reserves, China will still need to import the minerals to meet its soaring LIB demand.

Based on China’s projected passenger vehicle sales, we further evaluate its battery demand from a global perspective (BloombergNEF, 2020). With comparisons to the global battery material demand, Figures S3–S5, and Tables S21–S23 present the annual battery material demand from China’s passenger vehicle market under different scenarios (in different color shades). The uncertainty comes from two NMC composition trajectories: one is NMC622 and the other is NMC9.5.5. The global demand for raw materials (fixed at the 2019 level) due to increases in the demand from passenger electric vehicle batteries and other uses is depicted by red dashed lines, whereas the global annual mining production in 2019 is indicated by black solid lines. Lithium supply is expected to triple by 2025, as resource exploration and mining activities have recently increased in response to the growing demand for LIBs (Latham and Kilbey, 2019). Consequently, the lithium supply is unlikely to be a limiting factor for widespread PEV adoption until the later part of the next decade. On the other hand, cobalt and nickel are getting more supply pressure. Cobalt supply is currently more stressed because it suffers from strong geographical concentration: about 60% of the global cobalt production occurs in the politically unstable Democratic Republic of Congo. Compared with lithium and cobalt, the supply concern about nickel has been underscored. While the nickel market is currently focused on stainless steel, the demand from LIBs will increase dramatically in the coming years. A shift toward nickel-rich compounds could cause a nickel supply deficit, disrupting large-scale battery production. The results here reveal the pressing need to expand the production capacity to eliminate the potential bottlenecks in the supplies of raw materials. Although lithium and cobalt have attracted more attention than the other battery metals, nickel—as an increasingly important component of battery cathode chemistry in the coming decades—should receive prompt consideration regarding the supply chain concerns to achieve the green energy transition.

DISCUSSIONS

Based on the NEOCC model—an optimized bottom-up vehicle technology decision-making model—this study integrates the vehicle cost analysis model for market dynamics and battery demand projection. The contribution of this study is a framework for systematically investigating future trends in advanced vehicle technologies based on their technology evolutions, as well as evaluating the impacts of these trends on...
vehicle sales and stocks, industry average fuel consumption rate, and battery materials demand in 2020–2050. The NEOCC model and the corresponding analyses and insights can be useful to stakeholders in the Chinese vehicle market.

Advanced technologies in PEVs promotion brings prosperity to China’s passenger vehicle market. From the perspective of energy transition, this study specifically considers the progress of fuel-saving technology in ICEVs and battery technology in PEVs. Regardless which technology advances, technology progress can increase vehicle sales. In addition, under all technology evolution scenarios, BEVs will gradually be the dominant vehicle type in China’s vehicle market. The market penetration of BEVs is expected to be around 30.4%–64.6% by 2050. However, the primary force driving BEV growth varies over time. Before 2035, the dual-credit policy in China will be very effective at pushing the industry towards electrification. After 2035, as BEVs become more affordable, consumer choices based on vehicle ownership costs will be vital. In addition, the vehicle markup factor—an indicator of the profit margin of a single vehicle—has less impact on the market shares among different vehicle types and the overall industry average fuel consumption rate before 2035, unless the markup factors among different vehicle types are relatively large. This is because the dual-credit policy can heavily determine the market dynamic trends in China’s auto industry, at least before 2035. Therefore, automakers should pay significant attention to the government policies when formulating corresponding company strategies.

This study also indicates that China’s vehicle market is large enough for the coexistence of both PEVs and ICEVs through 2050. With the implementation of the dual-credit policy for 2021–2023, LowFC-ICEVs (hybrid electric vehicles) will have more market share. The sales of LowFC-ICEVs will also quickly increase when the fuel-saving technology in ICEVs becomes cheaper. Unsurprisingly, as battery cost continuously decreases, BEVs will become more competitive, and the sales growth of LowFC-ICEV will be suppressed. On the other hand, stocks of ICEVs will still be at least over 40% by 2050, even in the scenarios where the battery technology is well developed or fuel-saving technology is underdeveloped.

Due to changes in China’s vehicle market structure, the Chinese auto industry’s average fuel consumption rate is expected to be 1.81–3.11 L/100 km by 2050. This study shows that the dual-credit policy is the primary factor markedly reducing in the industry’s average fuel consumption rate prior to 2035. However, after 2035, the industry’s average fuel consumption rate becomes more susceptible to technology evolution, which determines the vehicle manufacturing cost.

This study projects the potential battery raw material demand resulting from the vehicle technology evolution in China. Vehicle electrification offers the Chinese government a good way to reduce its reliance on oil imports. However, it puts growing pressure on the critical raw material supply chain. By 2050, recycled supply could satisfy about 60% of the cumulative battery demand for China’s passenger vehicle market. More importantly, we find that increasing nickel content to increase driving range could create a deficit in the global supply of nickel from 2022 onwards if there is no significant expansion in nickel mining capacity. On the other hand, there is little risk of a lithium supply shortage in the next decade, as lithium production is expected to triple by 2025. In sum, enhancing self-sufficiency in battery raw materials supply is a pressing need for China to improve its national energy security.

Limitations of study

Some caveats should be noticed. This study presumes the LIB, or more specifically, the NMC LIB, would dominate the light-duty vehicle market by 2050. It ignores the analysis on other major battery raw materials such as graphite and the demands on the rare earth elements. In addition, this study does not consider the impacts of the dynamic relationship between the raw materials’ supply and demand. Furthermore, this analysis focuses on the light-duty vehicle segment only; the electrification of medium- and heavy-duty vehicle segments would be our research goals in the future.

In addition, some assumptions are made (such as fuel economy projections), and some calculations are simplified for data analysis purposes. For example, when discussing the raw materials demand for batteries, the study ignores the reverse impacts of the supply of battery raw materials. The impact of a PEV battery’s residual value on its second uses and recycling is not considered either. The historical sales data used for model calibration are based on annual new vehicle registrations, which could be smaller than the annual
sales reported by automakers or industry associations. Therefore, the vehicle sales or stocks projected by this model could also be lower than those from automakers or industry associations.

**STAR METHODS**

Detailed methods are provided in the online version of this paper and include the following:

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  - Cost model for plug-in electric vehicles
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**SUPPLEMENTAL INFORMATION**

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2021.103375.

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**AUTHOR CONTRIBUTIONS**

The authors confirm contribution to the paper as follows: study conception and design: S. Ou; data collection: S. Ou, Y. Hsieh, and R. Yu; analysis and interpretation of results: S. Ou, Y. Hsieh, Z. Lin, and X. He; draft manuscript preparation: S. Ou, Y. Hsieh, Z. Lin, X. He, S. J. Bouchard, and Y. Zhou. All authors reviewed the results and approved the final version of the manuscript.

**DECLARATION OF INTERESTS**

Co-authors Xin He and Jessey Bouchard are from Aramco Americas, which has financial interests in the subject of the study but did not influence any research stage of this study. Co-author Zhenhong Lin (Z. L.) is currently an editorial board member of the journal. This article appears in a special collection of which Z.L. served as a guest editor. Z.L. had no part in manuscript handling, which was handled exclusively by the in-house editorial team. All co-authors declare scientific independence with no competing interests.

**INCLUSION AND DIVERSITY**

We worked to ensure sex balance in the selection of non-human subjects.

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**STAR METHODS**

**KEY RESOURCES TABLE**

| REAGENT or RESOURCE | SOURCE | IDENTIFIER |
|---------------------|--------|------------|
| Deposited data      |        |            |
| China vehicle market and technology information | China Automotive Technology and Research Center | www.catarc.ac.cn |
| China macroeconomics statistics | National Statistics Yearbook | http://data.stats.gov.cn/english |
| Energy prices in China | EastMoney.com | https://data.eastmoney.com/ckjs/yjtz/default.html |
| Software and algorithms | Excel® Visual Basic for Applications (VBA) | Microsoft www.microsoft.com |

**RESOURCE AVAILABILITY**

**Lead contact**

Further information and requests for resources and method details should be directed to and will be fulfilled by the lead contact, Zhenhong Lin (linz@ornl.gov).

**Materials availability**

This study did not generate new unique reagents.

**Data and code availability**

Original data used for model construction and calibration have been summarized and uploaded in the supplementary information file and the supplementary excel files: Data S1 and S2.

This paper does not report original code, which is available for academic purposes from the lead contact upon reasonable request. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

**METHOD DETAILS**

The NEOCC model is adopted to perform the impact analysis of vehicle technologies, policies, costs of consumer ownership, and vehicle manufacturing in China. The NEOCC model is a market simulation tool that can quantify and project the market shares of different vehicle technologies by considering relevant attributes of industry dynamics, vehicle technologies, and consumer behavior under multiple vehicle policy constraints (Ou et al., 2020b). Integrating a discrete choice model, the model calculates the market sales and share for each vehicle technology, following the logic that consumers choose the vehicle with the least total cost of ownership. The model assumes that the industry allocates internal subsidies to each vehicle technology so that the total industry benefit is maximized under the constraints of government policies such as fuel economy standards or electric vehicle incentives (Ou et al., 2020b). This version of the NEOCC model includes vehicle technologies ranging from ICEVs to PHEVs and BEVs. ICEVs are categorized into three types: high-fuel-consumption vehicles (HigFC-ICEV), medium-fuel-consumption vehicles (AvgFC-ICEV), and low-fuel-consumption vehicles (LowFC-ICEV). PHEVs and BEVs are categorized by their electric driving range. For sedans, there are two types of PHEVs (50 km and 80 km) and five types of BEVs (150 km, 200 km, 250 km, 300 km, and 400 km). For SUVs/crossovers, there is one type of PHEV (no breakdown) and two types of BEVs (250 km and 350 km). In total, 16 different vehicle types are analyzed and projected in this NEOCC version. More detailed descriptions of vehicle classification by powertrain type in this model version can be found in Table S2, and descriptions of model algorithms can be found in Figure S6 and Ou et al. (Ou et al., 2020b).

Figure S7 presents the analysis flow chart. Consumer characteristics and government policies are based on literature review. In addition to the monetary and non-monetary incentives for PEVs, the dual-credit policy...
used by the Chinese government to improve the industry average fuel economy and to stimulate the market penetration of PEVs is adopted as the major vehicle policy in the NEOCC model. Furthermore, the development of charging infrastructure is also considered by the NEOCC model, and its assumptions are presented in Table S15. The aggregated vehicle information for 2016–2019, the basic economics information, and the assumed charging infrastructure information in China is collected through the China Automotive Technology and Research Center (CATARC) and summarized in the Data S2. The manufacturing cost model and related estimates for ICEVs and PEVs are discussed in Sections 4.1 and 4.2. Battery demand, recycling, and second use are discussed in Section 4.3.

Cost model for internal combustion engine vehicles

The incremental manufacturing cost of ICEVs grows as fuel economy (MPG) increases (National Academies of Sciences Engineering and Medicines, 2015). This study assumes that the manufacturing cost of a vehicle, for both ICEVs and PEVs, comes from two parts: (1) the base car; and (2) the propulsion system and its ancillary systems (Hsieh et al., 2020; Xie and Lin, 2017). For an ICEV, the base car is defined as a car without the propulsion system; and the propulsion system includes the engine and its ancillary systems (Hsieh et al., 2020). The manufacturing cost is calculated by Equation (1).

\[ C_{ICEV} = C_{B,\text{ICEV}} + C_i \cdot F \]  

(Equation 1)

where \( C_{ICEV} \) is the total manufacturing cost ($) of an ICEV; \( C_{B,\text{ICEV}} \) is the manufacturing cost ($) of a base car for ICEV; \( C_i \) is the incremental cost ($/MPG) which varies with the fuel economy; and \( F \) is the vehicle fuel economy (MPG).

Through calibration with the historical market data in the NEOCC model, this study obtains the base car costs and incremental manufacturing costs presented in Table S17. It shows that the cost of the engine and its ancillary system account for a larger share of total vehicle cost as vehicle fuel economy increases. Generally, the cost of the engine and its ancillary system accounts for 20%–27% of the total manufacturing cost for ICEVs with fuel economy ranging between 30 and 45 MPG, which seems reasonable and is in accordance with the ICEV cost investigated by Hsieh et al. (Hsieh et al., 2020).

Manufacturing cost for internal combustion engine vehicles in 2016–2019

The vehicle manufacturing cost is first estimated based on it in the U.S. vehicle market through the U.S. National Research Council (NRC) report (National Academies of Sciences Engineering and Medicines, 2015), regulation compliance cost publications (Ou et al., 2020a; Wang et al., 2019; Xie et al., 2017), and the results of Autonomie, a vehicle systems simulation tool (Islam et al., 2018). The NRC report reveals the cost curve between the fuel economy (MPGGE) and vehicle manufacturing cost ($) for cars, car-sized SUVs (CSUVs), pickups, and truck-sized SUVs (TSUVs) in 2017, 2020, and 2025 (National Academies of Sciences Engineering and Medicines, 2015). The cost curves can be fitted with several piecewise functions, using the form shown in Equation (1) in the Experimental Procedures section. Summarized based on literature review (National Academies of Sciences Engineering and Medicines, 2015; Xie et al., 2017) and Autonomie simulation results, Table S16 presents the slopes of these piecewise functions and their adoption ranges, respectively. For example, in 2017, the incremental manufacturing cost is about $40 to $43 per MPG for a car with fuel economy ranging between 0 and 35 MPG, and the incremental manufacturing cost is about $72 to $97 per MPG for a car with fuel economy ranging between 35 and 60 MPG. It also shows that the incremental manufacturing cost for each fuel economy range decreases gradually from 2017 to 2025. This might be due to an increase in economy of scale and improvements in production efficiency. Since the U.S. has been a mature vehicle market for a while, and its automakers have globalized the supply chain for cheaper costs, we believe the results for the U.S. market summarized in Table S16 can be used as a reasonable reference for the current and future Chinese vehicle market.

The study also finds that the vehicle manufacturing cost in China follows the same rules as the cost for the U.S. market: the total vehicle manufacturing cost consists of a base car cost and the propulsion system and its ancillary systems cost (Ou et al., 2020a), as shown in in Equation (1) in Experimental Procedures. Ou et al. collected the historical conventional vehicle market data through collaboration with the China Automotive Technology and Research Center (CATARC) and quantified the relationships between ICEV vehicle prices and vehicle features such as fuel economy (Ou et al., 2020a). To translate vehicle price to vehicle manufacturing cost, this study assumes a markup factor of 1.50 as a reference. Deng and Ma estimated that the markups in China’s automotive industry ranged from 1.10 to 1.60 in the 2000s (Deng and Ma,
A U.S. Department of Energy (DOE) study by Argonne National Laboratory examined the literature and suggested that a markup factor of 1.50 is an appropriate value for manufacturers with vehicle parts that are outsourced (Wang and Kelly, 2020).

Manufacturing cost for internal combustion engine vehicles in 2020–2050

The manufacturing cost for ICEVs has two components: (1) base car cost and (2) incremental manufacturing cost per MPG. Considering the maturity of the ICEV manufacturing process in China, the base car cost of future ICEVs is assumed to be unchanged and will remain the same as shown in Table S18. Because the current hybrid electric vehicle (HEV) market in China is still underdeveloped, the incremental manufacturing cost of fuel economy for highly fuel-efficient vehicles uses Japanese vehicle models—the Nissan Note (a compact car) and the Nissan Serena (a minivan)—as a reference (Nissan, 2019a, 2019b). Japanese cars have a reputation for fuel-saving technology. In fact, the Nissan Note and the Nissan Serena are two of the most popular fuel-saving vehicle models currently sold in Japan, and both are available in a conventional ICEV version and an E-Power serial hybrid version. The price difference between the ICEV version and hybrid version is $4,475 for the Note (Nissan, 2019a) and $3,852 for the Serena (Nissan, 2019b). A markup factor of 1.5 is used here to convert the price difference to the cost difference. The fuel economy difference between the conventional ICEV and the hybrid is 13.8 km/L for the Note and 9.0 km/L for the Serena under the JP08 driving cycle adopted in Japan (Nissan, 2019a, 2019b). Translating the fuel economy difference from the JP08 driving cycle to the Worldwide Harmonized Light-duty Vehicles Test Procedure (WLTP) adopted in China, the incremental cost of fuel economy is adjusted to about $110–$160/MPG (Kühlwein et al., 2014). Furthermore, we also reference the fuel economy regulation compliance cost of ICEVs found by Wang et al. for the Chinese vehicle market (Wang et al., 2019). In the end, we assume that the incremental regulation compliance cost would be $135/MPG in 2025 and $65/MPG in 2030.

This study assumes the major automakers in China could achieve a similar level of fuel-saving technology as their Japanese counterparts by 2030. For sedans with fuel economy over 45 MPG, in the reference scenario, the incremental manufacturing cost is assumed to reach $110/MPG by 2030 and decrease to $70/MPG by 2050. In the pessimistic fuel-saving technology (pes-FE) scenario, the incremental manufacturing cost will not be close to the Japanese car level until 2050, and it will decrease to around $190/MPG by 2030. In the optimistic fuel-saving technology (opt-FE) scenario, the incremental manufacturing cost will reach the Japanese car level by 2025 and will then decrease to $80/MPG by 2030 and to $50/MPG by 2050. For SUVs/crossovers with fuel economy over 42 MPG, in the reference scenario, the incremental manufacturing cost is assumed to reach $140/MPG by 2030 and decrease to $96/MPG by 2050. In the pes-FE scenario, the incremental manufacturing cost will not be close to the Japanese car level until 2050, and it will decrease to around $220/MPG by 2030. In the opt-FE scenario, the incremental manufacturing cost will reach the Japanese car level by 2025 and will then decrease to around $100/MPG by 2030 and to around $80/MPG by 2050. However, for sedans with fuel economy less than 45 MPG and SUVs/crossovers with fuel economy less than 42 MPG, the incremental cost changes much less due to the maturity of the technology. Thus, the yearly changes in incremental cost are based on the changes in the U.S., as shown in Table S16. The incremental costs of fuel economy in other years are all interpolated between the key years, and the costs are adjusted for smoothness. Table S18 shows the assumptions for the incremental cost of fuel economy in China in key years.

Based on the literature review and relevant assumptions stated above, we can draw the vehicle manufacturing cost curves for fuel economy from 20 to 80 MPG, as shown in Figure S8. The cost curve consists of three piecewise functions for sedans (0 ≤ MPG<30, 30 ≤ MPG<45, and MPG ≥ 45) and three functions for SUVs/crossovers (0 ≤ MPG<30, 30 ≤ MPG<42, and MPG ≥ 42). The difference in manufacturing cost between cost curves generally narrows by year, and this change is more prominent when the fuel economy is higher. This is because the better fuel-saving technology is becoming more popular, and, with economies of scale and improved manufacturing efficiency, their incremental direct manufacturing costs would be lower. In addition, compared with the changes in the manufacturing cost of sedans, the manufacturing cost of SUVs/crossovers changes even faster.

Cost model for plug-in electric vehicles

The manufacturing cost for electric vehicles is assumed to consist of two parts, the cost of the base car and the cost of the battery pack and its auxiliary systems, which is consistent with Equation (1). Most current electric vehicles use a LIB as the electric power source, but the future evolution of battery materials is still...
uncertain. Therefore, the improvement in battery technology in this study focuses on battery cost, specific energy density, and raw materials demand but ignores the reversal effects due to supply constraints. The estimate of battery pack cost is presented in Figure S1, and the estimate of the electricity consumption rate of electric vehicles is presented in Table S19.

The analysis of manufacturing cost for BEVs is slightly different from the analysis for PHEVs. Similar to the ICEV, the BEV is divided into two parts: (1) the base car, a car without the propulsion system; and (2) the battery system and its ancillary electric propulsion systems. The total vehicle manufacturing cost can be described in relation to battery size (energy capacity in kWh), as shown by Equation (2).

\[
C_{BEV} = C_{B, BEV} + \beta \cdot C_{bat} \cdot E
\]

(Equation 2)

where \(C_{BEV}\) is the total manufacturing cost ($) of a BEV; \(C_{B}\) is the manufacturing cost ($) of a base car for BEV, the same as Equation (1); \(C_{bat}\) is the battery pack cost ($) per kWh; \(E\) is the battery size (energy capacity in kWh); and \(\beta\) is a coefficient added into Equation (2) so as to consider the costs for both the auxiliary electric propulsion systems in addition to the battery system. Correspondingly, \(\beta\) should be no less than 1.0. The value of \(\beta\) is obtained through calibration with the vehicle price of BEVs in the 2016–2019 market. The markup factor for PEVs in the 2016–2019 market is assumed to be 1.2–1.3, which is the supplier markup factor in a low-profit-margin scenario discussed by the National Research Council (National Research Council, 2011). This is because, as an emerging successor, it is less likely that the profit margin of PEVs can be as high as that of ICEVs in the short term. Figure S9 presents the relationship between battery pack cost and the total PEV manufacturing cost in 2016–2019.

The method used to estimate PHEV manufacturing cost is different from the one used for BEVs because a PHEV integrates both a conventional engine-powered system and an electric propulsion system. Therefore, the manufacturing cost of PHEVs (\(C_{PHEV}\)) consists of three components: (1) the cost of the base car, (2) the cost of the conventional engine-powered system, and (3) the cost of the electric propulsion system, as shown in Equation (3). The value of \(\beta\) used for PHEVs is the same as the value used for BEVs.

\[
C_{PHEV} = C_{B, PHEV} + C_{F} + \beta \cdot C_{bat} \cdot E
\]

(Equation 3)

Table S17 summarizes the base car cost for BEVs and PHEVs in 2016–2019. It can be calculated that, by 2019, the ratio of battery pack cost to the total vehicle manufacturing cost is about 20%–40% for BEVs and about 10%–13% for PHEVs. The estimated manufacturing costs of the vehicles by powertrain type (including both PEVs and ICEVs) in 2020–2050 under all scenarios are presented in Data S1.

**Outlook for battery pack costs in 2020–2050**

The battery pack costs for electric vehicles used in this study are primarily from the most recent reviews, investigations, and forecasts from several third parties until 2020. Since China is one of the world’s largest battery manufacturers and manufacturing has become so globalized, we assume the cost of batteries in the American and Japanese cars reviewed in the literature would be the same for those in China. In our previous study, we estimated the battery pack costs prior to 2020 to be $180/kWh in 2017 and $156/kWh in 2019 (Ou et al., 2020b), which are consistent with the estimates from Bloomberg New Energy Finance (Henze, 2019). For battery pack costs after 2020, Kittner et al. and Schmidt et al. anticipated that they will decrease to $124–$175/kWh by 2020 (Kittner et al., 2017; Schmidt et al., 2017). Thus, $147/kWh (the mid-point of this range) is assumed as the battery pack cost in 2020 in the reference scenario. The Chinese Automotive Industry Strategic Advisory Committee and Society of Automotive Engineers (SAE)-China projected that the battery pack cost will reach around $130/kWh in 2025 and $116/kWh in 2030 in the report Technology Roadmap for Energy Saving and New Energy Vehicles (The Strategic Advisory Committee and SAE-China, 2016). Furthermore, the International Council on Clean Transportation summarized the recent projection of the battery pack costs from technical reports and automaker statements in its 2019 report (Lutsey and Nicholas, 2019). The battery pack cost is projected to decrease to $85–$133/kWh by 2025 (Berckmans et al., 2017; Hummel et al., 2017; Lutsey and Nicholas, 2019). The maximum difference among these projections is nearly $50/kWh. In fact, there is considerable variation in battery pack cost projections from different sources. For example, Bloomberg New Energy Finance optimistically believes battery pack cost will fall to $100/kWh by 2025 (Stevenson, 2017) and will drop to $74/kWh by 2030 (Curry, 2017), but MIT researchers predict that battery cost will not reach $124/kWh until 2030 (Green et al., 2019).
After reviewing the literature and filtering out some outliers or extreme values, we arrived at the battery pack cost projections for 2020–2050 shown in Figure S1. Because the projected battery pack costs vary among sources, sometimes quite significantly, this study classifies them into three scenarios: a reference scenario, an optimistic battery cost (opt-bat) scenario, and a pessimistic battery cost (pes-bat) scenario. The reference scenario assumes that the long-term goal of the battery pack cost set by the U.S. DOE ($80/kWh) will be reached by 2040 (U.S. Department of Energy, 2020a) and that the cost will stabilize at around $75/kWh by 2050. Under this scenario, the battery pack cost will be about $120/kWh in 2025, $104/kWh in 2030, and $75/kWh in 2050. Under the opt-bat scenario, the battery pack cost will be around $83/kWh in 2030 and around $67/kWh in 2050. Under the pes-bat, the battery pack cost will be around $124/kWh in 2030 and around $110/kWh in 2050. The battery pack costs for other years are interpolated based on the values for key years.

Outlook for electricity consumption rates in plug-in electric vehicles in 2020–2050
Improvement in the vehicle electricity consumption rate is an important factor to consider when estimating the manufacturing cost of electric vehicle technology because higher electricity utilization efficiency means a smaller, less expensive battery can be used. Historical information on the electricity consumption of Chinese electric vehicles comes from vehicle specifications collected by CATARC: the sales-weighted average electricity consumption for BEVs in 2019 is 13.8 kWh/100 km. In addition, the future evolution of the electricity consumption of Chinese vehicles is estimated using the simulation results from the Autonomie model. Autonomie provides the energy consumption rate (MPGGE) for PEV technologies in the U.S. for years 2015, 2020, 2025, 2030, and 2045 (lab year) (Islam et al., 2018). It provides estimates for fuel economy under the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Test (HWFET) cycles. The comprehensive energy consumption is calculated by assuming that the ratio of UDDS to HWFET driving is 43%–57%, according to the method used by the U.S. Environmental Protection Agency (U.S. EPA, 2019). A conversion factor of 0.031 gallon/kWh is used to convert units between the electricity consumption (kWh/100 km) and the energy consumption (MPGGE) (U.S. Department of Energy, 2020b).

Although the energy-saving technology used in China and the U.S. could be very close, the fleetwide average electricity consumption rate for vehicles in these two countries could still vary due to size and weight differences in vehicles sold in each market. Thus, literature review is necessary to adjust the projection. According to the New Energy Vehicle Industry Development Plan (2021–2035) by the Chinese government in 2020, the average electricity consumption rate for electric vehicles should decrease to 12.0 kWh/100 km in 2025 (Ibold et al., 2020). Considering the evolution of energy-saving technology alone, this study assumes that the annual change in the average electricity consumption rate in 2025–2030 is consistent with the rate in 2020–2025, and the average electricity consumption rate of BEVs will decrease to 11.0 kWh/100 km by 2030. In addition, to reach a reasonable assumption for the electricity consumption rate of electric vehicles in 2050, we assume the energy efficiency of electric vehicles by 2050 can be equivalent to that of “super fuel-saving ICEVs” in China, which have a fuel economy of more than 73.5 MPG (3.2 L/100 km) (Ministry of Industry and Information Technology, 2019). By assuming the tank-to-wheel energy efficiency is ~30% for ICEVs (hybrid version) and ~75% for BEVs (Curran et al., 2014; Gupta et al., 2016; Wang, 2001), we can estimate the average electricity consumption rate of electric vehicles by 2050 to be 10.6 kWh/100 km. Table S19 presents the electricity consumption rate for some BEVs in key years.

Evaluate vehicle manufacturing costs in 2020–2050
In general, the larger the battery size, the greater its share of the overall vehicle cost. In addition, comparing the base car costs between BEVs/PHEVs and ICEVs with fuel economies ranging from 30 to 45 MPG, we can find that the base car cost for BEVs is less than it is for ICEVs, while the base car cost for PHEVs is much higher than it is for ICEVs. This is because, in the Chinese vehicle market in a few years prior to 2019, many BEVs were sold by Chinese automakers that used a low-price strategy (Ou et al., 2019). Therefore, some of these vehicles are of low quality. Conversely, most PHEVs were high-end cars sold by high-end international automakers (Ou et al., 2019). With the development of the PEV industry, the manufacturing cost and quality of the base car in PEVs should gradually approach that of the base car used in common ICEVs. China expects the annual sales share of PEVs to reach 25% after 2025 (Ministry of Industry and Information Technology of P.R.C, 2020). This means PEVs would gradually become a mainstream product, like ICEVs, after 2025. Therefore, the study assumes the base car cost of PEVs will reach that of ICEVs with a fuel economy of 30–45 MPG by 2030.
As shown in Data S1, in general, the manufacturing cost of PEVs would decline through 2050, with the most rapid decrease occurring through 2030. In addition, as the market matures, some low-end vehicle models will be phased out, and more reliable and high-quality vehicle models will enter the PEV segment, especially those with an electric range less than 250 km. It is expected that the manufacturing cost of these BEVs would increase and then decline.

**Battery materials demand in China’s vehicle market in 2020-2050**

To examine the potential supply bottlenecks associated with critical battery materials affected by China’s passenger vehicle market, we first derive the global demand for Li, Co, and Ni for non-passenger vehicle batteries at present by subtracting passenger vehicle battery demand from the global mining production in 2019, assuming their global consumption (or demand) are equal to production. Then, by summing up the derived 2019 demand for non-passenger vehicle battery uses and the projected PEV batteries uses, we could get a conservative estimate of the total demand. Note that, for the projected uses of PEV batteries, we consider both the battery installations due to new PEV sales as well as the battery demand due to batteries replaced in existing PEVs due to the lifespan mismatch between PEVs and batteries.

The scrappage patterns of PEVs and batteries are uncertain and depend on charging behaviors and driving conditions. This study simulates the scrappage patterns of batteries following the approaches described by Hsieh et al. (Hsieh et al., 2020). Since battery degradation rates are improving (Harlow et al., 2019), it is assumed that lifetimes of batteries will match those of PEVs by 2030 (i.e., the median lifetime of a PEV battery increased from 8 years in 2020 to 12 years in 2030), and there will be no need for owners to replace the batteries before their PEVs reach retirement age.

The Nickel-Manganese-Cobalt (NMC) LIB is expected to dominate the PEV battery market from now to 2030, with a shift toward nickel-rich compounds with higher specific capacity and less use of expensive cobalt (Co) in the future (Hsieh et al., 2019). Predicting which battery chemistry will become prevalent beyond 2030 cannot be done with certainty. One of the most promising battery chemistries that may emerge as the mainstream choice for PEVs is solid-state lithium-metal (Li-metal) battery technology. Compared to state-of-the-art LIBs, solid-state battery technology—replacing a liquid electrolyte with a solid electrolyte—has further advantages, including lower cost, higher energy density, enhanced safety, and better fast-charging capability (Bindra, 2020). However, even with the advanced development and commercialization of solid-state batteries, the demand for critical elements, such as cobalt, lithium, and perhaps nickel, will likely still exist for the cathode needs. To better understand concerns about global supply shortages for battery minerals, we quantify the future demand for battery raw materials under different passenger vehicle electrification levels.

In this study, the ongoing deployment of battery chemistries up to 2030 is taken from Mckinsey Basic Material Institute’s battery raw material demand model (Campagnol et al., 2018). After 2030, we expect and assume nickel-rich NMC will be the dominant cathode chemistry in the PEV battery market. A key uncertainty is the evolving rate of advanced battery technologies. For representation purposes, we consider two NMC composition scenarios to capture the uncertainty: one is NMC622 and the other is NMC9.5.5 (where the numbers denote the molar ratio of nickel, manganese, and cobalt within the cathode).

The assumptions for the battery market in 2019 are as follows: The global markets for lithium products were estimated to be batteries (59%), ceramics and glass (19%), lubricating greases (6%), polymer production (5%), and other uses (11%). The global markets for nickel products were estimated to be stainless steel (70%), alloy steels and castings (8%), non-ferrous alloys (8%), plating (8%), batteries (5%), and other uses (2%) (Roskill Information Services Ltd., 2018). The global markets for cobalt were estimated to be batteries (41%), superalloys (16%), carbides and diamond drills (10%), catalysts (7%), steel (7%), colors (6%), and other uses (13%) (Erkan, 2019).

At last, we recognize that the materials demand for non-passenger vehicle battery uses will change. However, the derived demand trajectories serve as a proxy for examining the bottlenecks in the supply of raw materials.