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Transition to Electric Vehicles in China:  
Implications for Private Motorization Rate and Battery Market

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ABSTRACT

China has recently enacted the dual-credit mandate to replace the existing subsidies as a continued effort to electrify its ground transportation sector. This study quantifies the impacts of such policy transition on private motorization rate and battery market. Throughout the next decade, affordability remains the determinant for vehicle purchases; forcing broader adoption of pricier battery-powered cars without subsidies will inevitably diminish the market growth. Under the mandate, China’s electric vehicle sales will continue to grow through 2030 despite the temporary car market contraction. Cumulative private electric vehicle sales are projected to reach 66 million by 2030 (with 37% sales market share); this will drive the battery demand from China’s private car sector to expand rapidly and accumulate ~420 GWh (2 million tonnes) of spent lithium-ion batteries. This significant increase in battery demand will exacerbate pressure on the global supply for lithium and cobalt. The cobalt demand from China’s private vehicle sector in 2030 alone would be almost half of the total global cobalt production in 2017; up to 16% of this 2030 demand could be satisfied by battery recycling. A recycling-based battery supply chain is needed to alleviate the concerns of supply shortages and to achieve a circular economy.

Keywords:
Private car/ Electric vehicle/ Battery demand/ Spent battery/ Battery recycling
1. INTRODUCTION

Being a major and fast-growing economy, China has led world growth in demand for private car ownership over the past decades, surpassing the United States to become the biggest automotive market in 2008 (OICA, 2017). However, on a per capita basis, China’s car ownership is still relatively low and just passing a level of ~13% (i.e., 13 cars per 100 people) that the U.S. achieved in 1923, in contrast with ~80% in the U.S. today (Davis et al., 2014). In the absence of any constraint or effective countermeasures, private motorized transport will continue to increase as purchasing power further grows.

China’s economic boom has promoted the development of its automotive industry and allowed more than 100 million citizens to experience the convenience of personal mobility. However, growing private vehicle travel—primarily powered by internal combustion engines (ICEs) in the modern transportation systems—has caused more pollutant and greenhouse gas emissions, as well as increased China’s dependency on oil imports. To reduce these negative externalities, the Chinese government has put forth policies to encourage the adoption of alternative fuels vehicles—plug-in electric vehicles (PEVs) in particular; PEVs include pure battery vehicles (BEVs) and plug-in hybrid vehicles (PHEVs). The generous subsidies toward the purchases of PEVs of the past several years have pumped up sales; about half the world’s PEVs were sold in China in 2017 (IEA, 2018). When the subsidy program is removed after 2020, the new dual-credit scheme mandate, enacted recently, is expected to continue the strong growth in the local PEV market (Ou et al., 2018).

From now to 2030, private vehicle sales volume in China is mostly controlled by affordability—per-capita income divided by car price (Hsieh et al., 2018), and thus mandating wider adoption of cleaner but more expensive PEVs will inevitably shrink the car market in the absence of subsidies. Moreover, the new mandate will force increased battery-powered vehicle sales, correspondingly leading to a growing demand for lithium-ion batteries (LIBs) as well. The increased significance of LIBs—largely driven by
China’s strong PEV demand—is believed to pose several challenges throughout the world in the upcoming decade:

(1) Global supply shortages of critical elements, especially cobalt, lithium, and perhaps also nickel (Chagnes and Pospiech, 2013; Lv et al., 2018). Disruptions in the supply chain of raw materials may cause materials cost to surge and thus, diminish the benefits from learning effects in battery price reductions. This already occurred in late 2018 when the price of cobalt surged to more than US$90,000/ton (LME, 2019), more than 4 times the price 15 months earlier due in part to increasing demand and in part to political instability in the largest cobalt producer—Democratic Republic of Congo (DRC). Although the cobalt price has since dropped, the worries of supply shortages and raw materials price volatility still remain.

(2) Potential environmental and health risks caused by the improper disposal of spent LIBs (Heelan, et al. 2016). Most of the LIBs produced in the past decade have been for use in portable electronics, and few of them are recycled—the vast majority of batteries are discarded along with the devices that contain them. The battery-recycling rate in Australia, for example, is just 2% (King, Boxall and Bhatt 2018). Over the next three decades, the automotive sector is expected to be the fastest-growing source of spent LIBs, mainly due to the movement toward vehicle electrification. Since LIBs contain toxic substances, environmental concerns arise if large volumes of spent LIBs go to landfills. In landfills, LIBs may catch fire and lithium can leach into groundwater, creating a new source of hazardous waste. To help alleviate these concerns, recycling spent LIBs is being considered as a promising approach (Natarajan and Aravindan, 2018). However, the battery recycling industry lags behind the continuing LIB development and uses by the automotive industry.

The vehicle market in China is already changing in response to rising incomes, emerging battery technologies, and PEV policies. Significant impacts are anticipated during the transition to electrification,
and this paper aims to quantify some policy implications for the private passenger vehicle (also called private car in this study for brevity) market and the PEV-driven battery market. With a focus on China—the largest market for both PEVs and ICEVs in the foreseeable future—we first explore how the car price and the private motorization rate will change when vehicle emission standards get more stringent and as more expensive PEVs penetrate the auto market. We then project the annual private PEV sales and the corresponding battery raw material demand, examining the concerns of global supply shortages for battery minerals. We also estimate the potential market size of spent batteries when installed PEV batteries reach their retirement age throughout the next decade. We conclude with key findings and implications for policymakers. The time horizon for this study is between 2020 and 2030; during this time period, Nickel-Manganese-Cobalt (NMC) Li-ion batteries are expected to dominate the passenger vehicle market.
2. CHINA PRIVATE CAR OWNERSHIP AND SALES MODEL

We previously built a national-level fleet model projecting China’s private car market based on the evolution of car affordability index ($A$), defined in Equation (1) (Hsieh et al., 2018).

$$A_i = \frac{x_i}{p_i}$$  \hspace{1cm} (1)

where $x_i$ is the per-capita disposable income in year $i$ and $p_i$ is the car price index in year $i$. Car price index was defined to be the average new car price in year $i$ relative to that in year 2003 (i.e., $p_{2003} = 1$). Driven by excess capacity and price competition, the car price in China decreased rapidly since 2003 (approximately 50%), which is similar to the price trend happened in the early motorization stage (from 1913 to 1930) in the U.S. (Davis et al., 2014). The fleet model showed that the number of vehicles in China will continue to be fairly sensitive to affordability from now to about 2030: 10% decrease in the car price index or 10% increase in the disposable income would increase the car ownership level by 5% (Hsieh et al., 2018). However, our previous study did not account for China’s rapidly evolving PEV policies, which will lead to more expensive battery-powered vehicles replacing ICEVs in the sales mix after 2020, and thus, increase the average car price. Hence, the car price index and the projected car sales in China require reevaluation in the light of the new mandate.

To project the future average new car price index, we need to determine 1) the car sales market share by different types of vehicle technologies and 2) the relative price of PEV to ICEV. The governing equation is shown in Equation (2).

$$p_i = p_{ICEV,i} \times \left( MS_{ICEV,i} \times 1 + MS_{PHEV,i} \times \frac{p_{PHEV,i}}{p_{ICEV,i}} + MS_{BEV,i} \times \frac{p_{BEV,i}}{p_{ICEV,i}} \right) / 100\%$$  \hspace{1cm} (2)

$p_i$ is the average new car price index in year $i$ ($i$ starts from year 2020 to 2030); $p_{v,i}$ is the price index of vehicle type $v$ in year $i$ ($v = ICEV, PHEV, and BEV$); $MS_{v,i}$ is the sales market share (%) of vehicle type $v$ in year $i$; $\frac{p_{PEV,i}}{p_{ICEV,i}}$ is the ratio of PEV price to ICEV price in year $i$ ($PEV = PHEV and BEV$). The PEV market
share projection is discussed in Section 2.1 and the methods for estimating the relative price of PEV to ICEV are detailed in Section 2.2; the resulting car price indexes of different vehicle types are presented in Table 1.

2.1 PEV Market Share

The PEV market penetration projection is quite uncertain since it is still an emerging technology and highly affected by evolving government policies. Based on the historical PEV sales market share (IEA, 2019), the government’s new energy vehicle technology roadmap (Li, 2016), and the new energy vehicle industry development plan (DRC, 2019), we simulate China’s private PEV adoption rate using a Gompertz function. We estimate that PEVs could account for 21% and 37%\(^1\) of the total private passenger vehicle market share in 2025 and 2030, respectively. The fitted curve, shown as the black line in Figure 1, is taken as the PEV market penetration in this study. Moreover, since the government policies are more selective to encourage BEVs (Zhang et al., 2017), we further assume that the ratio of PHEVs to BEVs sold in China continues to stay constant at the 2018 level—about 3/10 (IEA, 2019). Figure 1 shows the resulting market shares for the different types of new vehicle sales between 2020 and 2030. Sensitivity analysis is performed to address the uncertainty in these PEV penetration assumptions (Appendix A).

\(^1\) Our projected value of 2030 PEV sales market share (37%) is similar to Liang et al.’s estimation (38%) (Liang et al., 2019).
Figure 1. Sales market share of ICEV, PHEV, and BEV in China assumed in this study; the government targets are indicated in red square and the fitted curve for PEV market penetration is presented in black line.

2.2 Relative Price of PEV to ICEV

2.2.1 Reference Vehicle Models

Car price analysis is based on the average of the best-selling 5-seat compact vehicle models in 2017 in China. Key parameters for the comparable reference ICEV, PHEV, and BEV are described here, while the detailed vehicle specifications of the selected vehicles are listed in Hsieh and Green (submitted); the car models included in reference vehicle derivation are carefully chosen to facilitate apples-to-apples comparisons.

- ICEV: a gasoline-powered car with a curb weight of 1,280 kg, equipped with a 1.5 L and 85 kW engine. Its on-road fuel consumption is 7.6 L/100 km and the driving range is 685 km.

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2 Reference vehicle specifications are the averages over the best-selling compact vehicle models. Compact car segment is the most popular size segment in China in the base year 2017 (chyxx.com, 2018).
• PHEV: a hybrid electric car with a curb weight of 1,623 kg, equipped with a 1.5 L and 78 kW engine and a 11.9 kWh NMC Li-ion battery. It provides 64 km of all-electric range and additional 615 km of gasoline-powered range.

• BEV: a battery-powered car with a curb weight of 1,619 kg, equipped with a 50.5 kWh NMC Li-ion battery. It has an all-electric range of 352 km.

The prices of the comparable reference ICEV, PHEV, and BEV with the model year 2017 are 136,700, 173,800, and 223,500 Yuan, respectively.

2.2.2 Battery Pack Price Projection

Widespread market penetration of PEVs is impeded in part by the high vehicle purchase price, mostly due to high battery price. Battery pack price, a large part of the manufacturer’s suggested retail price (MSRP) in a BEV, is expected to drop significantly in the near future as battery production volume increases. Our previous study proposed that the battery pack price should follow a 2-stage learning curve approaching a price floor dominated by the active materials costs, while the active materials costs themselves approach a price floor determined by the mineral costs. The results indicated a 3.5% learning rate for the materials synthesis stage and a 16.5% learning rate (±4.5%) for the battery production stage (Hsieh et al., 2019). Realizing the practical limits set by materials costs on battery price reductions, the model suggested that the continued maturation of the existing NMC-based lithium-ion batteries (LIBs) is unlikely to get as low as $100/kWh (~ 630 Yuan/kWh assuming the exchange rate of USD/Yuan is 6.32) by 2030. Battery pack price of $100/kWh is widely considered as the level at which BEVs become economically competitive with ICEVs in the absence of incentives (Knupfer et al., 2017). Figure 2 shows the declining trajectories of PEV battery pack prices used in this study based on the 2-stage learning curve model results (in the solid lines). PHEV battery pack costs are assumed to be $65/kWh higher than BEV pack costs in 2015 ($356/kWh) due to their higher power density (National Research Council, 2013), and have the same
learning rate as BEV batteries. We further assume that the battery prices in year \( i \) determine the powertrain costs of PEVs with model year \( i+1 \). Note that the projections from some other studies (Berckmans et al., 2017; Schmuch et al., 2018) are also shown in Figure 2 to point out the uncertainty in future battery pack price trajectory. Sensitivity analysis is performed to address this uncertainty (Appendix A); the sensitivity results suggest that the uncertainty in future battery pack price projections only has a very small impact on the projected private car stock in 2030.

![Figure 2. Projected NMC Li-ion battery prices for BEV and PHEV relative to 2016 BEV battery pack price (i.e., $289/kWh) from various existing models; the projections based on 2-stage learning curve model (Hsieh et al., 2019) are used in this study (in solid lines); the uncertainty in future battery price projections is addressed by conducting the sensitivity analysis (Appendix A).](image)

### 2.2.3 Relative Vehicle Price Projection

Future vehicle prices are hard to project. Government regulations (such as the dual-credit mandates in China) are likely to force the industry to sacrifice ICEV profits to internally subsidize PEV sales. However, business pricing strategies are always nonpublic and uncertain to predict. Therefore, based on what we
observed from the price and cost structures of the reference vehicles with the model year 2017\(^3\), we assume that average profit margin (i.e., retail price divided by manufacturing cost) per car stays constant from 2020 to 2030. Although this assumption is not perfect, we expect its impacts on the average car price projections are mild: If the automakers decide to raise the prices of ICEVs while lowering the price of PEVs to persuade consumers to purchase the required fraction of PEVs, this would also cause the average car price to increase because ICEVs sales are contributing more to the total car sales mix than that of PEVs.

From the available literature on the underlying technology costs (German, 2015; Hummel et al., 2017), we estimate the manufacturing cost structures for the reference vehicles with the model year 2017, as indicated in Figure 3. The base car, defined as the car without a propulsion system, is assumed to be the same across different vehicle technologies; all the cost components are normalized by the base car which is thus 1 (shown in the dark blue segment). According to the teardown cost analysis\(^4\) (Hummel et al., 2017), 1) direct powertrain cost for ICEV, including combustion engine (CE) parts, ICE auxiliary, transmission, exhaust system, and engine control unit/sensors, was shown to sum to 20% of the entire compact car cost; 2) the BEV’s powertrain excluding the battery pack was estimated to be 16% less expensive than the counterpart ICEV’s full powertrain. For a PHEV, the battery pack is smaller but still needs to provide a high level of power, i.e., a higher rated energy-to-rated power ratio, and thus resulting in a higher cost of energy storage (see Figure 2). In addition to an electric motor and high-energy battery, a PHEV is also equipped with a combustion engine (smaller and less costly than that of ICEV), exhaust system, and conventional transmission. After 2020, ICEV cost of production is assumed to stay constant owing to the tighter emissions standards (e.g., standards China 6a and China 6b will be implemented

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\(^3\) The profit margins (as a percentage of sales price) of the reference vehicles with the model year 2017 are found to be nearly uniform across different types of vehicle technologies (Hsieh and Green (submitted)).

\(^4\) UBS did a complete teardown and cost analysis on the Chevrolet Bolt. They also provided vehicle cost breakdown comparison between Bolt (BEV) and the counterpart VW Golf (ICEV).
nationwide in 2020 and 2023, respectively (Cui et al., 2017)) and the increasing maturity of the Chinese automotive industry (Perkowski, 2018), while PEV costs are expected to continue decreasing toward 2030 as the battery pack price drops. The governing equations for the relative PEV prices are shown in Equation (3) and Equation (4) where \( BPP \) denotes battery pack price and \( i \) starts from year 2020 (see Table 1 for the resulting car price index).

\[
p_{PHEV,i}/p_{ICEV,i} = \left(1 + 0.1 + 0.28 + 0.21 \times \frac{BPP_{PHEV,i-1}}{BPP_{PHEV,2016}}\right)/(1 + 0.17 + 0.08) \quad (3)
\]

\[
p_{BEV,i}/p_{ICEV,i} = \left(1 + 0.21 + 0.81 \times \frac{BPP_{BEV,i-1}}{BPP_{BEV,2016}}\right)/(1 + 0.17 + 0.08) \quad (4)
\]

Table 1. Projected price indexes of ICEV, PHEV, and BEV in China \((p_{2003} = 1)\)
### 2.3 Car Price Index Projection

Combining the PEV market share (Section 2.1) and the relative vehicle price (Section 2.2), we project the average car price index from 2020 to 2030 using Equation (2). Figure 4 presents both the previous (Hsieh et al., 2018) and updated car price index projections; as discussed in Section 2.2.3, this study updates the car price assumption to reflect the impacts of vehicle electrification and tighter emission standards. Before 2020, we expect that the average new car price would keep dropping but at a slower rate compared to the previous projection, shown in dash line, in which no PEV adoption is assumed. After 2020, the car price index is anticipated to start increasing owing to the constant ICEV production costs and the growing market share of more expensive PEVs.

<table>
<thead>
<tr>
<th>Year</th>
<th>ICEV</th>
<th>PHEV</th>
<th>BEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i)</td>
<td>( p_{ICEV,i} )</td>
<td>( p_{PHEV,i} )</td>
<td>( p_{BEV,i} )</td>
</tr>
<tr>
<td>2020</td>
<td>0.505(^a)</td>
<td>0.621</td>
<td>0.724</td>
</tr>
<tr>
<td>2025</td>
<td>0.505</td>
<td>0.604</td>
<td>0.659</td>
</tr>
<tr>
<td>2030</td>
<td>0.505</td>
<td>0.598</td>
<td>0.632</td>
</tr>
</tbody>
</table>

\(^a\) Based on the assumption that the ICEV price in China up until 2020 would follow a similar price trend as seen in the U.S. between 1910 and 1930 (Hsieh et al., 2018).
Figure 4. Past and projected car price index in China considering the impacts of more PEV market penetration; the updated projection is shown in red circles and the previous projection (Hsieh et al., 2018) is shown in dashed line. The timeline of interest of this study is from 2020 to 2030.

2.4 Vehicle Sales Market

Car sales were decomposed into new-growth purchases (associated with increases in car ownership due to rising income) and replacement (for scrapped cars); the split between these two segments determines the maturity level of the auto market: in a mature car market, most car purchases are replacing retired vehicles.

New-growth purchase in year $i$ is determined by the growth of car stock between year $i$ and year $i-1$ as car affordability index ($A$) increases. The update in car price index is described in Section 2.3; for the other key model input—per-capita disposable income, we assume that it would increase at the same rates as GDP from 2015 to 2030. The assumed compound annual growth rates are 7.00% for 2016-2020,
5.36% for 2021-2025, and 4.60% for 2026-2030 (Zhang et al., 2013). Both the previous (Hsieh et al., 2018) and updated car affordability index projections are presented in Figure 5.

![Figure 5](image)

**Figure 5. Past and projected car affordability index in China; the updated projection is shown in red circles and the previous projection (Hsieh et al., 2018) is shown in dashed line. The timeline of interest of this study is from 2020 to 2030.**

Replacement purchase, on the other hand, is determined by the private vehicle scrappage pattern. We update the passenger vehicle survival function by fitting a two-parameter logistic model (shown in Equation (5)) to the data points between survival ratio of vehicles ($SR_V$) and the vehicle age ($y$) that were recently published (CATRC, 2017).

$$SR(y) = 1/[1 + \exp(b \cdot \left(\frac{y}{L_{50}} - 1\right))] \quad (5)$$

where $L_{50}$ is the vehicle age when 50% of the vehicles are retired (=11.5 years) and $b$ is the shape factor related to the scrappage intensity (=6.62), i.e. how spread out the scrapping distribution is. Figure 6 presents the fitted vehicle survival pattern in China. Due to the limited data, we assume the scrappage patterns of PEVs are the same as that of ICEVs; however, care should be taken when drawing parallels.
between these two different vehicle technologies. The scrappage patterns of the PEVs and battery are inherently uncertain—depending on charging behaviors and driving conditions.
3. ELECTRIC VEHICLE BATTERY MARKET ANALYSIS

3.1 Electric vehicle battery demand

China’s private PEV market is expected to be one of the fastest-growing sources of lithium-ion battery (LIB) demand over the next decade, mainly due to the strong government support toward vehicle electrification. Battery demand (or installed battery capacity) within the automobile industry comes from two main sources: one is the new PEV sales that are driven by the ongoing purchase subsidies and the new PEV mandates, and the other one is the battery replacements for existing PEVs due to the lifespan mismatch between PEVs and PEV batteries.

For the evolution of a PEV’s battery capacity (expressed in terms of kilowatt-hours; kWh), we make several assumptions, as discussed below, in accordance with the new dual-credit rules (Cui, 2018). It was reported that the average battery installations per PHEV and per BEV in China in 2016 were about 14 kWh and 32 kWh per car, respectively (JMedia, 2017). Since the credits for PHEVs with the electric range greater than or equal to 50 km are unchanged (i.e., the basic credit of PHEV is fixed at 2; the electric range of 50 km can typically be achieved by a PHEV with 10 kWh battery capacity), we expect automakers would have few incentives to increase the battery size, and thus, assume that the average installed capacity per PHEV will stay at a similar level as that in 2016—15 kWh between 2017 and 2030. On the other hand, many BEVs sold in China in the past had a much smaller range compared to the rest of the world, where the average battery capacity per BEV was about 45 kWh in 2016. However, China’s recent subsidy programs and the new dual-credit scheme rewards long-range BEV models (Ou et al., 2018). Thus, we expect the average installed capacity per BEV to keep increasing toward the future. Based on the rules, the maximum basic credit of BEV is 5, corresponding to the electric range of greater than or equal to 350 km. Moreover, from the fuel economy performance data of various BEV models (Lima, 2017), we determine that the driving range of 350 km can be achieved by a 45 kWh battery. So we assume that the
battery capacity in BEVs in China would linearly increase from 32 kWh in 2016 to 45 kWh in 2020. After 2020, we assume the battery capacity per BEV will further linearly increase to 75 kWh by 2030 to satisfy the demands for larger vehicles and longer driving ranges (Cazzola et al., 2018). It is noted that our calculation considers the ongoing shift from less expensive LiFePO₄ (LFP) to higher specific energy NMC in China. NMC-based LIB contributed to 45%, 58%, and 74% of total China’s new private PEV battery installation in 2015, 2016, and 2017, respectively (JMedia, 2017; RealLi Research, 2016). Further, we assume that Li-ion NMC battery would account for 80% in 2018, 90% in 2019, and then eventually capture the whole battery market of new private PEV sales after 2020, until 2030.

In addition to the battery demand from annual new PEV sales, there is an additional demand for LIBs from battery replacement owing to the lifespan mismatch between PEV and PEV battery. We simulate the scrappage patterns of PEV battery \( SR_B \) using Equation (5), assuming that the median lifetime of PEV battery is 8 years (i.e., \( L_{50} = 8 \)), which is a standard battery lifetime warranty offered by electric car manufacturers, and the scrappage intensity is same as the vehicle (i.e., \( b = 6.62 \)). Figure 6(a) shows the corresponding survival ratio functions of both vehicle and PEV battery in China’s private car sector applied in this study. From the two different scrappage patterns, we derive the probability that battery replacement occurs before the vehicle is retired\(^5\), as presented in Equation (6)\(^6\). Figure 6(b) depicts the obtained probability for battery replacement demand; note that the probability distribution does not sum to 1, which is due to the fact that not everyone needs to replace the battery before scrapping the car.

\[
P_i(BR, VS) = P_{BR|VS,i}(BR|VS)SR_V(i) = [(1 - SR_B(i)) - (1 - SR_B(i - 1))] \times SR_V(i)
\]  

\(^5\) Here we are only interested in the case where battery replacement occurs before vehicle is scrapped; we ignore the probability that battery is replaced twice before the vehicle is retired.  
\(^6\) Assuming battery replacement (that occurs first) and the vehicle survival are independent, we can derive \( P_{BR|VS,i}(BR|VS)SR_V(i) = P_{BR,i}(BR)SR_V(i) \).
where

\[ P_{BR|VS,i} = \text{Probability that battery replacement (BR) occurs at year } i \text{ given that the vehicle survives (VS) until year } i \]

\[ SR_V(i) = \text{Probability that the vehicle survives until year } i \]

\[ P_i(BR, VS) = \text{Probability that battery replacement occurs at year } i \text{ and the vehicle survives (VS) until year } i \]

![Figure 6](image-url)

**Figure 6.** (a) Survival ratio functions of plug-in electric vehicle (PEV) and PEV battery in China; (b) the derived probability of battery replacement occurring due to the lifespan mismatch between PEV and PEV battery.

### 3.2 Spent electric vehicle battery

If China meets its government’s vehicle electrification targets, the resulting PEV boom will lead to a considerable increase in the volume of spent batteries when PEVs and PEV batteries reach their retirement
age. We calculate the volume of spent battery \(\text{SpentB}_i\) in year \(i\) coming from vehicle retirement \((\text{VR})\) using Equation (7) and coming from battery replacement \((\text{BR})\) using Equation (8); the sum of these two segments is the total retired PEV batteries in year \(i\) (Equation (9)). \(r_{NMC}\) is the market share of Li-ion NMC battery in the private PEV battery market; as discussed previously, \(r_{NMC}\) is assumed to be 1 for vehicles sold after 2020.

\[
\text{SpentB}_{i,\text{VR}} = \sum_{j=1}^{i} (r_{NMC, i-j} \times S_{PEV, i-j} \times Bcap_{PEV, i-j} (SR_V (j - 1) - SR_V (j))) \tag{7}
\]

\[
\text{SpentB}_{i,\text{BR}} = \sum_{j=1}^{i} (r_{NMC, i-j} \times S_{PEV, i-j} \times Bcap_{PEV, i-j} P_j (BR, VS)) \tag{8}
\]

\[
\text{SpentB}_i = \text{SpentB}_{i,\text{VR}} + \text{SpentB}_{i,\text{BR}} \tag{9}
\]

where \(i\) starts from year 2016 \((i = 1 \text{ is 2016})\); \(S_{PEV, i-j}\) is the total PEV sales in year \(i - j\) (starting from year 2015); \(Bcap_{PEV, i-j}\) is the average battery capacity per PEV sold in year \(i - j\); \(SR_V\) is the survival rate of vehicles (Equation (3) and Figure 6(a)); \(P_j (BR, VS)\) is the probability that battery replacement occurs at year \(j\) before the vehicle is retired (Equation (6) and Figure 6(b)).
4. RESULTS AND DISCUSSION

4.1 Changes in China’s Private Car Market

Impacts of promoting clean battery-powered vehicles on China’s national private car market are quantified and shown in Figure 7 (see Figure 4 and Figure 5 for the corresponding car price index and car affordability projections). Since car ownership level in China is far behind well-motorized countries, a key uncertainty in the projections is to estimate the eventual probability of owning a car when people have high purchasing power, which was investigated in our previous study (Hsieh et al., 2018). In Figure 7, we only show the mean values of the projection for illustrative purposes; the systematic uncertainty will mostly cancel out when estimating the difference between the scenario with the new mandates and the scenario without significant PEV adoption.

We find that rising car price resulting from the deployment of more sustainable (but more expensive) mobility would significantly diminish the domestic demand growth for private motorization. Private car sales are expected to be reduced by an average of 30% (~5.9 million cars) per year from 2021-2030, resulting in a difference in China’s private car stock of 18% (~69.3 million cars) by 2030 compared to the counterfactual “no PEV adoption” case. This observation is in line with the fleet model’s sensitivity results (Hsieh et al., 2018), showing that car ownership is quite sensitive to car price in near and mid-term future when the car market is still developing. As depicted in Figure 7, the private vehicle market will temporarily shrink in 2021 due to the removal of PEV subsides. However, the growing economy and purchasing power will continue to drive up the demand for private car ownership; from the end of 2021 to 2030, the private car sales are still expected to grow with a compound annual rate of 5%, and the number of car sales would exceed that of 2020 as early as 2025. Table 2 summarizes the expected private car ownership (i.e., cars per 100 people), car stock, car sales, and replacement purchases share (as a percentage of total car sales), together with the modeled standard deviations, by our updated model. It is noted that
while the current car sales in China are mainly driven by new-growth purchases, replacement purchases will dominate the sales market starting about 2021 (i.e., the share of replacement purchases becomes greater than 50%), as the Chinese car market matures; this feature of car market maturity is found to occur four years earlier than what we expected in our previous study that did not consider the evolving PEV policies. However, first-time car buyers will still make up about 25% of car purchases in China in 2030, so the market size will still have some sensitivity to affordability.

Figure 7. Comparisons of projected national (a) private car sales and (b) private car stock in China between no PEVs adoption and with new PEV mandate scenarios

Table 2: Private vehicle stock and sales projections in China (in the form of expected value ± standard deviation) from the updated model considering the new PEV mandate

<table>
<thead>
<tr>
<th>Year</th>
<th>Car ownership (%)</th>
<th>Car stock (million)</th>
<th>Car sales (million)</th>
<th>Replacement purchase share (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
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<td>2030</td>
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</tbody>
</table>
4.2 Private Plug-in Electric Vehicle Market

Given the projected annual private car sales (Figure 7(a)) and PEV market penetration (Figure 1), we derive the yearly private PEV sales ($S_{PEV,j}$) in China. As shown in Figure 8, the new mandate is expected to keep the growth momentum in local PEV market, compensating for the removal of subsidies. PEV sales will continue to grow throughout 2030 even though the whole private car market would shrink temporarily for a few years in 2021. These government supports are expected to boost the annual PEV sales to reach 5 million in 2025 and 11 million in 2030, bringing the total cumulative private PEVs sold to nearly 66 million units in China by 2030.

<table>
<thead>
<tr>
<th>Year</th>
<th>PHEV Sales (Million)</th>
<th>BEV Sales (Million)</th>
<th>Total PEV Sales (Million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>16.5 ± 3.4</td>
<td>230.7 ± 48.2</td>
<td>24.5 ± 4.5</td>
</tr>
<tr>
<td>2025</td>
<td>19.5 ± 4.3</td>
<td>276.1 ± 61.2</td>
<td>25.8 ± 3.0</td>
</tr>
<tr>
<td>2030</td>
<td>22.3 ± 5.2</td>
<td>315.7 ± 73.4</td>
<td>29.9 ± 4.7</td>
</tr>
</tbody>
</table>

Figure 8. Projected annual (left ordinate) and cumulative (right ordinate) private PEV sales between 2020 and 2030
4.3 Battery Market in Private Vehicle Sector

The shift from ICEVs to PEVs will result in large demand growth for lithium-ion batteries (LIBs), raising pressure on the availability of relevant resources. In this section, we quantify the battery demand driven by private vehicle electrification and the expected spent battery market when these batteries hit retirement age.

4.3.1 Battery Demand

From now out to 2030, NMC-based LIBs are expected to dominate the private PEV battery market, and consequently, our evaluation of battery (demand/recycling) market size focuses on the NMC platform. The bars in Figure 9 indicate the projected annual installed capacity, assuming BEVs would hold increasing kWh of energy (thus achieving longer ranges per charge) toward 2030 (see Section 3.1 for more detailed assumptions). The lifespan mismatch between PEV and PEV battery, as shown in Figure 6, leads to the additional demands for LIBs, i.e., battery replacement, on top of the volume from annual new PEV sales. The annual battery installations in China’s private car sector is expected to expand at a rapid compound annual growth rate of 30.2% in the ten-year period, from 62 GWh in 2020 to 873 GWh in 2030. This high growth rate comes from three mutually reinforcing factors: growth in PEV sale (Figure 8), increase in the average installed capacity per BEV, and the expansion in battery replacement demand as PEV stock increases. Growing LIBs demand has driven the essential mineral prices (including lithium, nickel, and cobalt) up over the past three years, fueling fears of a shortage – most notably of lithium and cobalt (Sun et al., 2017). Despite a clear trend toward higher nickel loadings to boost the energy densities for more extended range, the PEV LIB community will still have to continue using cobalt (though with less cobalt content) for materials stability in the foreseeable future (Harvey, 2018). Based on Figure 9, we further compute the corresponding demand (in the unit of tonnes per year) for key battery elements—
lithium, nickel, and cobalt, investigating the potential challenges associated with the secure raw materials supply.

We recognize mining capacity will expand in response to the expected growing LIB demand. However, to examine the potential bottlenecks in the supplies of raw materials, we select the 2017 global production volume as a proxy, comparing the projected battery demands for essential metals to their global mining productions in 2017 (US Geological Survey, 2018). These analysis results are illustrated in the black areas in Figure 10, which informs stakeholders the magnitude of the required expansion in production. The upper bound of the nickel and lower bounds of lithium and cobalt weights are obtained by assuming all the batteries are NMC811 (high nickel and low cobalt content; the numbers denote the molar ratio of nickel, manganese, and cobalt within the cathode), while the lower bound of nickel and upper bounds of lithium and cobalt weights are derived from the opposite case that all batteries are NMC111. Among the three materials, nickel is used much more widely in other industries; about 75% of all primary nickel consumption in 2017 went to the stainless steel industry, while the battery industry only accounted for 3.7% (INSG, 2019). On the other hand, more than 50% of global lithium and cobalt consumption were used in batteries (Global Energy Metals Corp., 2016; Statista, 2018; Milewski, 2019). These statistics suggest that even with China’s strong shift to PEVs, pressure on global nickel supply will be modest, but lithium and cobalt supplies would be largely impacted.

Our analysis (Figure 9) offers some consensus, showing that 1) global nickel supply is unlikely to be a limiting factor for wider battery production; 2) both lithium and cobalt production volumes have to be largely expanded. For lithium supply, more resource explorations and mining activities have occurred recently in response to the growing demand for battery applications (Brown et al., 2019). The supply concerns of lithium are focusing more on whether the lithium production can be speeded up in the

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7 Global demand for cobalt in 2017 was about 104,000 tonnes, and 38% of which was for consumer batteries and 15% of which was for PEV battery.
immediate future, rather than the material quantity itself thanks to the supply diversity in terms of geographical distribution and extraction technology (Kushnir and Sandén, 2012; Olivetti et al., 2017). Compared to lithium, cobalt is more likely to disrupt large-scale battery production. More than 60% of world cobalt mine production occurs in the politically unstable Democratic Republic of Congo (DRC), meaning that the political situation in that region will have a significant influence on the price and the supply security of cobalt. Figure 10 suggests that if new PEV purchases in the rest of the world match China, and cobalt mine production does not increase\(^8\), cobalt demand for PEVs alone (even if all LIBs are NMC811) could approach and even exceed global cobalt production. Besides expanding the production capacity and lessening the amount of cobalt used in batteries, the potential supply risks arising due to geopolitical barriers could be ameliorated with battery recycling.

4.3.2 Spent Battery

Along with the strong movement toward vehicle electrification, a massive volume of spent LIBs will be returned to the Chinese market for recycling. As shown in the red line with right ordinate in Figure 8, the expected spent NMC-based LIBs volume, merely from the private PEV market, will start from around 0.6 GWh in 2020, increase to 18 GWh in 2025, reach 138 GWh in 2030, and grow by another factor of 3 by 2040. Assuming the specific energy of 200Wh/kg for LIBs (Andrews and Jelley, 2017), about 2 million tonnes of spent LIBs will be retired from China’s private car sector through 2030.

Spent battery metals as a weight percentage of global mining production in 2017 are shown in the red areas in Figure 10. It is clear that recycled supply will not be a sufficient source of battery materials in the time horizon considered in the study because the current battery installations are much smaller than the expected great demand due to the rapid growth of the electric vehicle market. However, LIB recycling

\(^8\) Inspired by the high (but highly fluctuating) cobalt price, global cobalt production has increased by about 20% since 2017 (US Geological Survey, 2019).
might be an inevitable need for automotive-battery manufacturers to satisfy electric vehicle demand. In the near term, cobalt supply from mining should meet the demand for LIBs in PEV industry; however, in the long term, besides further reducing the required amount of expensive cobalt, supply from battery recycling will help meet the accelerating cobalt demand driven by widespread PEV adoption. Cobalt demand from China’s private PEV batteries alone would reach at least 46% of the world’s 2017 cobalt mine production by 2030; about 16% of that demand could be met from recycling rather than mining. Though lithium is mostly recyclable, the recycled lithium cannot reach battery-grade quality with the available recycling technology on an industrial scale at the moment (Ziemann et al., 2018). Instead of acting as a battery resource, the recycled lithium is currently used for non-automotive purposes like lubricating greases or sold to the construction industry (Battery University, 2019; Natarajan and Aravindan, 2018); such downgraded purity constrains the contribution of LIB recycling to near-term future lithium availability. Currently, the most widely used commercial battery recycling technology is pyrometallurgical process. With this technology, the transition metals can be recovered effectively—such as cobalt, nickel, iron, and copper, but not lithium and aluminum (Zheng et al., 2018). However, the recovery of battery-grade lithium carbonate is expected to become commercially achievable in the future. Researchers have recently started developing recycling methods to not only recover valuable elements from spent batteries, but regenerate the spent materials—including lithium—into pristine-state cathodes (Li et al., 2017; Zou et al., 2013).

The large number of spent batteries becoming available suggests that a substantial business opportunity exists for LIBs recycling. Because cathode materials are the most expensive battery component, we investigate the potential market for LIB recycling based on key cathode elements. Assuming that all the spent battery capacity shown in Figure 9 is either NMC111 or NMC811, we project

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9 The recovering efficiency is assumed to be 92% for cobalt (Zhuang et al., 2019).
that a China industry for recycling batteries from privately owned electric vehicles could process almost 20 billion Yuan worth of metals per year by 2030 (Figure 11(a)); the uncertainty is from various NMC compositions, ranging from NMC111 (upper bound with a dash line) to NMC811 (lower bound with a solid line). Assumptions about commodity market prices for this analysis are summarized in the inset of Figure 11(a) (lithium and manganese data taken from the USGS mineral commodity summaries report 2018 (US Geological Survey, 2018); nickel and cobalt prices retrieved from the London metal exchange, January 2019 (LME, 2019)). Figure 11(b) and (c) break down the potential market values, derived from two NMC composition trajectories, by essential cathode metals. It is noted that cobalt is currently getting more supply press, but with a shift toward nickel-rich compounds (NMC811), most (>80%) of the mineral values come from nickel and lithium (Figure 11(c)). Furthermore, even though lithium only contributes a small fraction of battery weight compared to nickel and cobalt, the recent increase (by more than 60% from 2016 to 2017) in the lithium carbonate price makes lithium one of the most important contributors to the intrinsic value of LIB recycling business. We note that these numbers likely understate the actual business opportunity for battery recycling since our analysis considers only the most expensive cathode materials in their mineral values. But if the spent NMC can be recycled to produce pristine-state cathode materials, as mentioned earlier, the value of the recycling products would far exceed their mineral values. Moreover, other metals used in battery manufacture, such as copper foils used as the current collector for anode and aluminum foil for the cathode, are also valuable for recycling (King and Boxall, 2019). In addition, it is likely that some of the manufactured assemblies in a battery could be reused, so they have a higher value than the raw materials used to make them. This suggests that landfilling the majority of spent LIBs instead of recycling would not only create environmental problems but also miss a significant economic opportunity.
Figure 9. Projected annual Li-ion NMC batteries installed capacity (left ordinate) and spent batteries volume (right ordinate) (in terms of GWh) in China’s private car sector, 2020-2030

Figure 10. Projected annual installed weight (black, left ordinate) and spent batteries weight (red, right ordinate) of lithium, nickel and cobalt in China’s private car sector as a percentage of global
mine production in 2017; the uncertainty is from the various NMC compositions, ranging from NMC111 (shown in the dashed lines) to NMC811 (shown in the solid lines).

**Figure 11.** (a) The potential market value of battery recycling in China’s private car sector considering only the value of the 4 cathode essential elements; the upper bound (dashed line) assumes all spent batteries are NMC111, and the other assumes all spent batteries are NMC811; the assumed metal prices applied in the analysis are tabulated in the inset; (b) and (c) Pie charts break down the values by cathode metals; Co in orange, Mn in green, Ni in blue, and Li in gray.

### 5. CONCLUSION AND POLICY IMPLICATIONS

China is leading the world in local plug-in electric vehicle (PEV) deployment, mostly credited to the strong government supports. The recent enactment of the dual-credit system mandate is expected to increase PEV adoption in China and correspondingly increase battery production dramatically. Greater production volume will drive the battery costs down owing to improved manufacturing efficiency;
however, the ultimate production cost reduction will be constrained by the essential battery materials (lithium, nickel, and cobalt), making it unlikely that the price target of $100/kWh for widespread PEV adoption will be achieved by 2030. Due to this practical limit on battery prices, PEVs are expected to remain more costly than the counterpart internal combustion engine vehicles (ICEVs) through 2030.

Over the next decade when car ownership in China is still sensitive to affordability (income divided by car price), forcing broader vehicle electrification while phasing out subsidies will noticeably decrease the growth rate of the Chinese private car market. The average new car price is expected to keep dropping—but at a much slower rate compared to the historical trend—until 2021, and then it would start evolving in the reverse direction as more expensive PEVs penetrate the market and emission standards tighten. The rising car price will diminish the consumers’ car affordability, resulting in a decline in the stock by 18% (~ 69 million cars) in 2030 compared to the counterfactual “no PEV adoption” projections. The results suggest that the private car stock of China would reach nearly 280 million and over 315 million in 2025 and 2030, respectively. Driven by the mandate, the annual private PEV sales in China are projected to keep growing and reach over 11 million (cumulatively 66 million units) by 2030 despite the anticipated temporary contraction in the private car market when the new dual-credit rules come into effect. With the analysis of the relative car price of PEVs to ICEV as well as the considerations of the evolving PEV policies, this study provides up-to-date insights on China’s private vehicle market size.

This PEV expansion will accumulate around 420 GWh (~ 2 million tonnes) of spent NMC-based LIBs in need of recycling throughout the next decade. The core ingredients in cathode materials are finite and thus valuable, most notably cobalt. The cobalt demand merely from China’s private PEV sector in 2030 will make up at least 46% of the 2017 annual global cobalt mine production, suggesting that battery recycling may be needed to reduce the risk of supply shortages and mineral price spikes. While cobalt supply is currently more stressed, with newer battery formulations most of the mineral cost is for nickel
and lithium. Nickel supply is not likely to be significantly impacted because LIBs only account for a small portion of nickel use. Lithium, on the other hand, should receive greater attention, especially on its recycling technology where high-quality lithium recovery is not yet commercially achievable. If the recycling rate is low, China would not only create a number of environmental problems but also miss a significant economic opportunity. Thus, the policymakers should help integrate the entire industry chain among automakers, battery producers, used-car dealers, and scrap companies in battery recycling systems to achieve a more sustainable and circular society. With a recycling-based LIBs supply chain established, not only millions of tonnes of batteries will be saved from entering the waste stream and characterized as hazardous, but also the supply pressures on critical materials will be mitigated.
ACKNOWLEDGEMENTS

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Appendix A. Sensitivity Analysis

The private passenger vehicle market presented in Section 4.1 relies on several parameters (Table A1). We use a tornado diagram (Figure A1) to illustrate how the private car market is conditioned by the PEV-related assumptions. The major PEV-related parameters here are PEV adoption rate, battery pack price, and the ratio of PHEVs to BEVs sold. The sensitivity range for each variable is based on the low and high values provided in Table A1. The governing parametric values described in Section 2 are used to calculate the base case of the tornado diagram (ratio of 1 in Figure A1). We found that PEV penetration rate is the most important parameter; however, all of them have a mild impact of less than 5% on the private passenger vehicle stock in 2030.

Table A1. Parametric values for sensitivity analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Low value</th>
<th>Base value</th>
<th>High value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV sales market share in 2030 (%) a</td>
<td>19</td>
<td>37</td>
<td>75</td>
</tr>
<tr>
<td>Battery pack price ($/kWh) b</td>
<td>93</td>
<td>124</td>
<td>140</td>
</tr>
<tr>
<td>Ratio of PHEVs to BEVs sold (-) c</td>
<td>0.14</td>
<td>0.3</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Note: a To examine what if PEV penetration rate doubles or reduces by half scenario; b ranges for BEV battery prices are taken from our previous study that considered the impacts of materials cost (Hsieh et al., 2019); c the lower value of 0.14 is the ratio of PHEVs to BEVs sold in Korean in 2018, while the higher value of 0.91 is the average ratio of the European market in 2018 (IEA, 2019).
Figure A1. Sensitivity of the projected private car stock in 2030 to the major PEV-related assumptions.