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Transition to Electric Vehicles in China:
Implications for Total Cost of Ownership and Cost to Society

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ABSTRACT

China is driving the transition away from internal combustion engine vehicles (ICEVs) to plug-in electric vehicles (PEVs, including plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs)) to address its pressing energy security and environmental pollution problems. The recent enactment of the dual-credit scheme mandate will compensate for the phase-out of the subsidy program, while ostensibly shifting the burden of filling in the cost gap between PEVs and ICEVs from the government to the automakers (though in practice to car buyers). We estimate that creating an inflection point for PEV demand via the mandate will put substantial transition costs on the society—on average on the order of 100 billion Yuan per year from 2021 to 2030, consuming about 0.1% of China's growing GDP each year; these transition costs should be compared to societal benefits of PEVs (e.g., enhanced energy security, climate change mitigation, and improved public health) to evaluate the net social value of vehicle electrification. The consumer-centric total cost of ownership (TCO) is investigated using the local data: thanks to the generous subsidies, China's subsidized PEVs are in TCO parity with counterpart ICEVs from 2016 to 2020. Nevertheless, after subsidies are eliminated at the end of 2020, this TCO parity is unlikely to be achieved for BEVs, if the automakers keep the same price structure as today. The range of TCO ratio of BEV to ICEV for 2030 is: a lower quartile of 1.03; median of 1.07; and upper quartile of 1.10. It is uncertain how the cost gap will be covered when the subsidies are removed. However, automakers are expected to use internal subsidies to lower PEV prices and raise ICEV prices as needed to achieve the mandated percentage of sales.

Keywords:
Private car; Electric vehicle; Total cost of ownership; Transition cost to society

1. INTRODUCTION

Over the past decades, China's massive economic growth has driven demand for private car ownership, improving mobility but causing more pollutant and greenhouse gas emissions associated with combustion and increasing the country's dependence on imported petroleum. To mitigate these problems, the Chinese government is promoting new energy vehicles via aggressive policies, giving priority to plug-in electric vehicles (PEVs); PEVs include pure battery vehicles (BEVs) and plug-in hybrid vehicles (PHEVs).
China's central and local governments are currently providing generous subsidies toward the purchases of PEVs, boosting national sales to account for nearly half the world's PEV market in 2017 [1]. However, paying subsidies is expensive for the government, and thus the authorities have decided to phase out PEV subsidies at the end of 2020. Instead, the government will be relying on the dual-credit scheme mandate to achieve its goal of high electrification of transportation by forcing increased battery-powered vehicle production volumes. The dual-credit policy, enacted recently, was shown to be able to pump up the annual PEV sales in China to over 2 million units by 2020 if the policy is strictly complied with [2]. The incremental cost of PEVs over counterpart internal combustion engine vehicles (ICEVs), which is recognized as one of the major barriers to electromobility, will be imposing significant transition costs on society during the shift from ICEVs to PEVs. With a specific focus on China – the largest market for both PEVs and ICEVs – this paper is offered as a contribution towards assessing the costs to society during the transition towards electric transportation. In this study, societal costs are defined as the "direct" cost incurred to society due to the car's purchase and uses themselves; the external costs caused by the ownership of the car—such as greenhouse gas emissions and air pollutants—are not within the study's scope (but were addressed in De Clerck et al. (2018) [3]).

Since consumer decisions are mainly driven by the private cost (excluding vehicle externality costs), this paper also evaluates the lifetime private cost to individuals by employing the total cost of ownership (TCO) method. A comprehensive review of the TCO method can be found in Letmathe and Suares (2017) [4]. Existing literature has developed a mature TCO analysis framework with a range of region-specific studies, but few research has been done regarding TCO of PEVs versus ICEVs in China's context. Hao et al. (2014) [5] estimated the impacts of China's PEV subsidy scheme on consumer's TCO, focusing on the subsidy duration from 2010 to 2015. Zhang et al. (2017) [6] applied TCO approach to determine the effectiveness of China's PEV financial policy in 2014. Yet, none of the existing studies systematically related the emerging battery technologies and the evolving PEV policies to the temporal variation in TCO. To the best of our knowledge, this paper is the first to study the mixed impacts—including decreasing battery pack price, phase-out of PEV subsidies, vehicle ownership restriction policy, and the introduction of PEV mandates—on consumer's vehicle ownership costs, providing the latest insights on TCO competitiveness of PEVs relative to ICEVs in China.

Great impacts are anticipated during the transition to electrification, and this paper aims to quantify such policy implications for societal and consumer costs. Profit margins have a big impact on the future TCO of PEVs (van Velzen et al., 2019 [7]) and thus should be taken into careful consideration. We select the vehicle models that are popular in China and are comparable to each other in terms of vehicle specifications. Some low-volume vehicle models sell at very different prices than the popular models, probably because the automaker is taking a very different profit margin on those models. We cautiously avoid those models having unusual retail prices to reduce the distortion in vehicle price estimates. We compute the transition cost to society due to the price gap between PEVs and ICEVs and demonstrate that this is non-negligible and should be considered when researchers quantify the total cost to society associated with vehicle electrification. We also investigate the consumer ownership cost competitiveness of PEVs, exploring how it would change in conjunction with the policy evolution. We test the robustness of our projections for the years 2020, 2025 and 2030 using Monte Carlo simulations. The time horizon for this study is between now and 2030; during this time period, lithium-ion nickel-manganese-cobalt (Li-ion NMC) batteries are expected to dominate the PEV market [8]. The detailed abbreviations and definitions used in the paper are listed in Table 1.

Table 1. List of abbreviation and acronyms used in the paper.

Abbreviation	Definition	Abbreviation	Definition
BEV	Battery Electric Vehicle	**O&M**	Operation & Maintenance Cost
BPP	Battery Pack Price	**PC**	Purchase Cost
BR	Battery Replacement Cost	**PEV**	Plug-in Electric Vehicle
CRF	Capital Recovery Factor	**PHEV**	Plug-in Hybrid Electric Vehicle
CS	Cost to Society	**PVF**	Present Value Factor
FE	Fuel Economy	**TCO**	Total Cost of Ownership
FP	Fuel Price	**TrCS**	Transition Cost to Society
IC	Insurance Cost	**VAT**	Value-Added Tax
ICEV	Internal Combustion Engine Vehicle	**VKT**	Vehicle Kilometer Traveled
LFP	Lithium Iron Phosphate	**VP**	Vehicle Price
LIB	Lithium-Ion Battery	**VPT**	Vehicle Purchase Tax
MC	Maintenance Cost	**VRF**	Vehicle Registration Fee
NMC	Lithium Nickel Manganese Cobalt	**VUT**	Vehicle Use Tax

2. METHODOLOGY AND DATA

2.1 Selected Passenger Vehicle Models

The leading auto market players in China are different from the rest of the world: in 2018, local Chinese brands accounted for 92% of PEVs sold [9][1], and the Chevy Bolt, the world's first true mass-market BEV with a range well above 200 miles (322 km) on a single charge, is not currently sold in China. In the past, many PEVs sold in China had a much smaller range, but China's recent subsidy programs and the new dual-credit scheme system favor pure battery electric sedans with a more extended range (greater than 250 km) [2]. These government policies have driven the ongoing shift from less expensive $LiFePO_4$ (LFP) to higher specific energy NMC in China's private car sector. Therefore, we choose those NMC battery-powered compact cars with a driving range greater than 300 km as our representative BEVs—BJEV EU400, Geely NEV EV450, and Changan Eado EV 300, and the counterpart PHEVs (Trumpchi GA3S PHEV, Geely NEV PHEV, and Changan Eado PHEV) are also equipped with a NMC Li-ion battery as one of their power sources. It is noted that other popular BEV models like BJEV EC series, Zhidou D2, and Chery EQ are not considered here because they are categorized as micro/small vehicles rather than compact cars. BYD Qin PEVs are not included in our analysis because they are powered by an LFP battery. For the representative ICEVs, we choose seven of the top 10 best-selling compact gasoline cars that have comparable vehicle characteristics to the selected PEVs. We estimate the reference vehicle specifications based on the average of these selected cars with the model year 2017, as presented in Table 2.

The reasons why we exclude the comparable ICEVs made by Chinese car brands—BAIC Senova D50, Geely Emgrand, and Changan Eado—from our model selections are because 1) these local car companies are not the best sellers in the ICEV sector; 2) their current price structures are probably distorted: the retail price ratios of the local automakers' PEVs to ICEVs are found to be much higher than the manufacturing cost ratios of PEVs to ICEVs. The manufacturing cost of a compact BEV with a driving range of 322 km was estimated to be 75% higher than the counterpart ICEV[2]. However, the retail price of BJEV EU400 (BEV) is about 130% more expensive than the counterpart BAIC Senova D50 (ICEV) and the Geely NEV EV450 (BEV) is about 140% more expensive than the counterpart Geely Emgrand (ICEV). These very high retail price ratios of PEVs to ICEVs are caused by unusually low ICEV prices. We speculate the Chinese automakers might be offering lower prices for their ICEVs than the market leaders to grab market share. Therefore, to avoid giving any biased estimations, we do not select these local brand ICEVs in the analysis.

[1] Even joint venture brands are growing their sales market share, under "Made in China 2025" industrial plan, the government wants local Chinese brands to have an 80% market share of PEVs sold in China [10].

[2] Chevy Bolt (BEV)—the world's first true mass-market BEV with a range well above 200 miles (322 km; 60 kWh Li-ion NMC battery) on a single charge—was estimated to be about 75% more costly than the counterpart VW Golf (ICEV) [11].

Table 2. Specifications of the reference compact passenger vehicles with the model year 2017; all the numbers are from the average of the selected vehicles.

Vehicle Technology	ICEV	PHEV	BEV
Selected Models	FAW-VW: Golf, Sagitar, Bora; SAIC-VW Lavida; SAIC-GM Buick: Hideo, Verano; GAC-Toyota Camry	Trumpchi GA3S Geely NEV Changan Eado	BJEV EU400 Geely NEV EV450 Changan Eado EV300
MSRP (Yuan)	136,700	173,800	223,500
Fuel Consumption	7.6 L/100 km	Gasoline = 6.0 L/100km Battery = 18.6 kWh/100km	14.4 kWh/100 km
Vehicle Platform	4573*1787*1463 (mm) Curb Weight=1,280 kg	4600*1790*1530 (mm) Curb Weight=1,623 kg	4618*1801*1517 (mm) Curb Weight=1,619 kg
Engine Power	1.5 L, 84 kW Engine	1.5 L, 78 kW Engine + 108 kW Electric Motor	103 kW Electric Motor
Energy Storage	52 L Fuel Tank	37 L Fuel Tank + 11.9 kWh NMC Battery	50.5 kWh NMC Battery
Performance	Range = 685 km Max Speed = 185 km/h	Range = 64 km electric + 615 km gasoline Max Speed=180 km/h	Range = 352 km Max Speed=140 km/h

2.2 Total Cost of Ownership (TCO)

The total cost of ownership (***TCO***) refers to the costs incurred during the car ownership period, which entails several different cost categories: vehicle purchase cost, fuel cost, and non-fuel operation and maintenance cost. The TCO per kilometer calculation approach applied in this study is shown in the following formulas; noted that all the upfront costs are amortized across all of the kilometers to get the levelized costs of driving.

$$\boldsymbol{TCO\ per\ km} = \frac{\boldsymbol{PC \times CRF + FC + O\&MC}}{\boldsymbol{VKT}} \tag{1}$$

where

$$\boldsymbol{PC = VP + VPT + VRF - FinInc} \tag{2a}$$

$$\boldsymbol{FC = \frac{1}{FE} \times FP \times VKT} \tag{3}$$

$$\boldsymbol{O\&MC = IC + MC + VUT + BR \times PVF \times CRF - TaxInc} \tag{4}$$

$$\boldsymbol{PVF} = \frac{\mathbf{1}}{(\mathbf{1}+\boldsymbol{r})^{\boldsymbol{n}}} \tag{5}$$

$$\boldsymbol{CRF} = \frac{\boldsymbol{r}(\mathbf{1}+\boldsymbol{r})^{\boldsymbol{N}}}{[(\mathbf{1}+\boldsymbol{r})^{\boldsymbol{N}}-\mathbf{1}]} \tag{6}$$

r is the discount rate, ***N*** is the vehicle lifespan, and ***n*** is the battery lifespan; ***PC*** is the vehicle purchase cost incurred at time zero, which is made up of vehicle price (***VP***), vehicle purchase tax (***VPT***), vehicle registration fee (***VRF***), and financial incentives such as purchase subsidies (***FinInc***); ***FC*** is the fuel cost incurred every year, determined by the fuel economy (***FE***; unit of km/L), fuel price (***FP***) and annual vehicle kilometers traveled (***VKT***); ***O&M*** is the annual non-fuel operation & maintenance costs, including insurance cost (***IC***), maintenance cost (***MC***), annual vehicle use tax (***VUT***), battery replacement cost (***BR***) (which is only incurred in year ***n***), and tax incentives (***TaxInc***); ***PVF*** is the present value factor to discount the future battery replacement cost (***BR***) incurred in year ***n*** to time zero; ***CRF*** is the capital recovery factor that is used to distribute the upfront costs (including ***PC*** and the present value of ***BR***) to all the kilometers driven. Vehicle residual value is not considered here for simplicity, and also because the recent studies showed that expected resale value did not feature prominently among the critical factors for purchasing a new passenger car [12].

We build up a China-specific consumer-centric TCO model and analyze the ownership cost competitiveness of PEVs by taking the tax/ subsidy scheme in Beijing as representative of China average. We project temporal variations in TCO out to 2030 to examine the economic viability of an unsubsidized PEV after 2020 when all the subsidies are scheduled to be phased out. The potential impact of the city-level vehicle ownership restriction policy on TCO is also explored in addition to the financial incentives.

2.2.1 Vehicle Price without VAT

When we estimate the future vehicle price trajectory, we exclude the value-added tax (***VAT***) from the retail price (i.e., MSRP shown in Table 2 includes the VAT rate of 17%) so that we can separate price changes caused by production cost reductions from that caused by VAT cuts.

We identify the pre-VAT price structure of the selected vehicle models by applying a "Top-Down" approach, as shown in Figure 1(a), given that the battery pack prices are $324/kWh and $289/kWh for PHEVs and BEVs with the model year 2017 (as discussed below; Table 3), respectively. The top-down (i.e., based on manufacturing suggested retail prices, MSRP) approach gives a price ratio of 1.27 and 1.63 for a PHEV and a BEV relative to an ICEV. The price difference between PEVs and ICEVs is mainly due to the expensive battery pack costs and possibly because of the higher R&D and investment in new factories for PEV than ICEV. Compared to the vehicle cost ratio obtained from a "Bottom-Up" approach (i.e., based on vehicle component manufacturing cost; Figure 1(b) from Hsieh, Pan and Green (accepted)), we find that the profit margins (as a percentage of sales price) of the reference cars are nearly uniform across different types of vehicle technologies.

Assuming that the ICEV pre-VAT price in China before 2020 would follow a similar vehicle price trend as seen in the U.S. between 1910 and 1930 [14], the reference ICEV price would decrease by 11%

from 2017 to 2020[3]. Automakers' pricing strategies are hard to project, and here we assume that profit per car would stay constant throughout 2030. For simplicity's sake, all the price segments except for battery pack are assumed to remain the same from 2020 to 2030. The price of the battery pack, which is a large cost item in a PEV, is expected to drop more significantly during the time horizon of this study, so this price variation is taken into account when projecting the future vehicle prices. The governing equations for estimating the future reference vehicle prices are shown in Equation (7) - (9) where *BPP* denotes battery pack price (see Table 3), $preVAT\ VP_{v,i}$ is the price of reference vehicle type v excluding VAT in year i (v = *ICEV*, *PHEV*, and *BEV*), and i starts from year 2020.

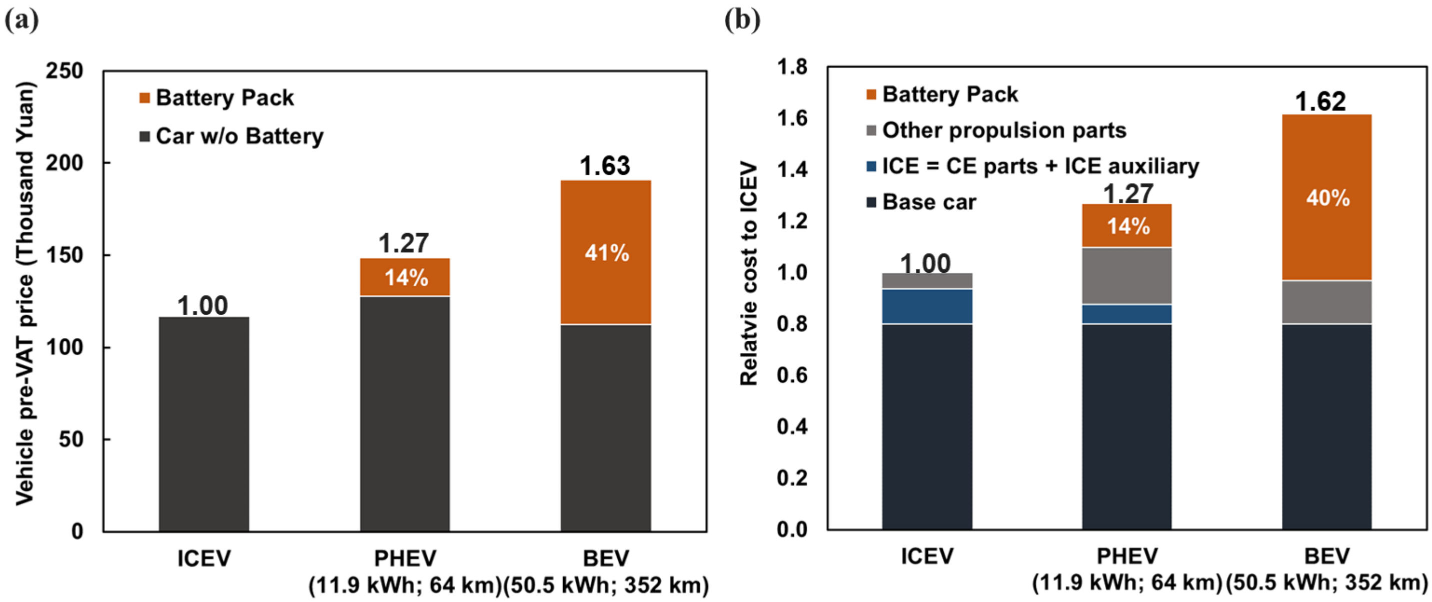

Figure 1. (a) Pre-VAT prices of the reference ICEV and PEV with the model year 2017; (b) manufacturing costs of the reference PEVs relative to ICEV cost with the model year 2017 (from Hsieh, Pan and Green (accepted)). For the reference cars in 2017, the PEV/ICEV price ratio was almost the same as the manufacturing cost ratio.

$$preVAT\ VP_{ICEV,i} = \frac{136{,}700}{(1+17\%)} \times (1-11\%) = 104{,}000 \tag{7}$$

$$preVAT\ VP_{PHEV,i} = preVAT\ VP_{ICEV,i} \times 1.27 \times \left(14\% \times \frac{BPP_{PHEV,i-1}}{BPP_{PHEV,2016}} + 86\% \times 1\right) \tag{8}$$

$$preVAT\ VP_{BEV,i} = preVAT\ VP_{ICEV,i} \times 1.63 \times \left(40\% \times \frac{BPP_{BEV,i-1}}{BPP_{BEV,2016}} + 60\% \times 1\right) \tag{9}$$

Battery Price Projection

Our previous study [8] suggested that the continued maturation of the existing NMC-based lithium-ion batteries (LIBs) is unlikely to reach the price target of $100/kWh (where BEV could be economically competitive with ICEV in the absence of incentives [15]) over the next decade. Table 3 shows the battery pack price trajectories of PEVs used in this study, which are derived from the projections

[3] Based on the historical data, the ICEV price in China had dropped by ~45% from 2003 to 2017 [14]

of Hsieh et al., (2019). The exchange rate for USD/Yuan is set to be 6.32 (occurred in February 2018 [16]). PHEV batteries have a higher Yuan/kWh cost than BEV batteries due to their higher power density [17]. We assume that the battery prices in year *i-1* determine the powertrain costs of PEVs with model year *i*.

Table 3. Projected price (Yuan/kWh) trajectories of NMC Li-ion battery pack for BEV and PHEV from 2-stage learning curve model [8]

Model Year (*i*)	**PHEV ($BPP_{PHEV,i-1}$)**	**BEV ($BPP_{BEV,i-1}$)**
2017	1,825	2,043
2020	1,310	1,474
2025	944	1,046
2030	797	871

2.2.2 Purchase Cost (*PC*)

The primary purchase cost is from vehicle price (***VP***); in 2017, the price of BEVs in China equipped with Li-ion NMC batteries price was about 1.6 as much as the counterpart ICEVs (see Figure 1). The vehicle purchase tax (***VPT***) rate in China is 10% of pre-VAT (value-added tax) vehicle price (i.e., ***VPT*** = 10% × ***preVAT VP*** = 10% × ***VP***/(1+***VAT***)), and PEVs are exempted from ***VPT*** until 2020. China's ***VAT*** rates for the manufacturing sectors were cut from 17% to 16% in 2018 and then further lowered to 13% in 2019 [18]; we assume that the ***VAT*** rates will remain 13% from 2019 to 2030. Vehicle price without VAT projection is discussed in Section 2.2.1.

The registration fee (***VRF***) in Beijing is about 500 Yuan. To lower the upfront vehicle purchase costs of PEVs, the Chinese government is currently providing generous financial incentives (***FinInc***). The consumer subsidy program has been renewed and modified every two to three years, favoring long-range BEVs. Figure 2 indicates the subsidies that the reference BEV (range of 352 km) and PHEV (electric range of 64 km) receive during 2015-2020, showing that the subsidy program is more selective to promote BEVs. According to the current government policy, all financial incentives for PEVs in China will be phased out at the end of 2020.

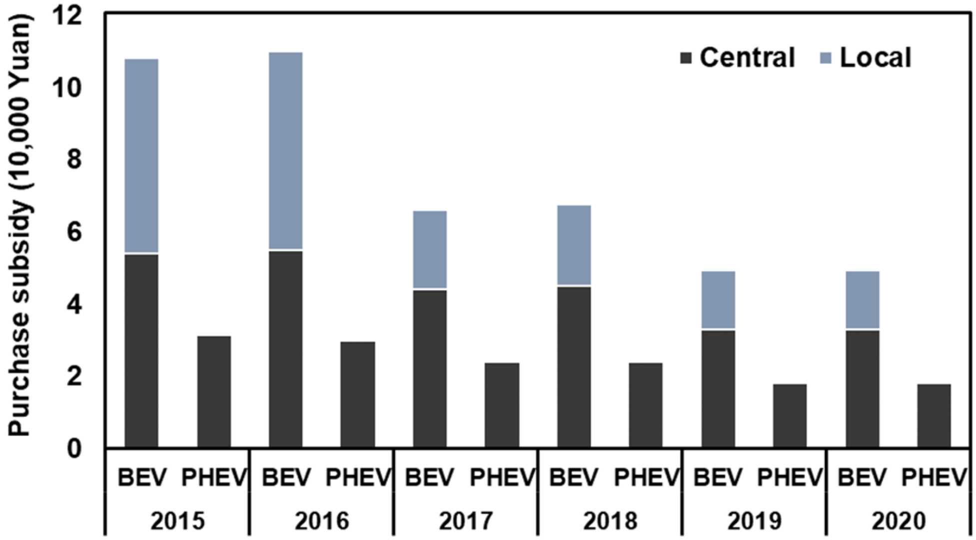

Figure 2. Purchase subsidy available for a BEV (R=352 km) and a PHEV (R=64 km) from 2015 to 2020 from the Chinese central government and Beijing local government; after 2020 all subsidies are to be ended.

2.2.3 Operating Cost

Operating costs, including fuel cost (***FC***) and non-fuel O&M cost (***O&MC***), vary significantly depending on driving patterns, travel habits, charging frequency, and vehicle lifespan. For example, the cost of electricity is highly variable: while the residential electricity rate is about 0.47 Yuan/kWh for home charging (when VAT is 13%), the rate for public charging stations is more than double due to the service fee (about 0.5 Yuan/kWh) imposed by public charging operators. Another example is that if the PEV ownership period is less than 8 years and the car is not heavily used, then the owners do not need to worry about battery replacement costs because a standard battery warranty coverage is for 150,000 km or 8 years, whichever comes first. Here all the battery replacement costs incurred after 2030 are assumed to be the same as 2030; this is because the replacements are very likely to (or might have to) retain the same battery specifications and pack design as the retired ones, meaning that even if disruptive battery chemistries are commercialized after 2030, the battery replacement costs will remain around the same as in 2030 for several years.

The vehicle kilometer traveled per year (***VKT***) in China was shown to decrease over a period when the car ownership increases rapidly [19]. While the annual VKT had decreased by about 30% from 2005 to 2015 [20], we expect that the VKT level will gradually stabilize after 2020 as the auto market is maturing in China. For the base case in this study, we assume that the national average passenger VKT in China is 12,500 km throughout 2030, which is the average value of the high and low projections given by Huo et al. (2012). The discount rate (***r***) is assumed to be 5%, which is about the same as the current Chinese central bank's interest rate for long-term (i.e., more than five years) loans [21]. The average passenger vehicle lifespan in China is about 12 years [22] while the PEV battery is assumed to last for 8 years (i.e., ***n*** = 8, which is a standard battery lifetime warranty offered by electric car manufacturers). Based on the empirical studies on Shanghai [23], we assume 76% of kilometers traveled by PHEV are powered by a battery. About future fuel price (***FP***), we assume that PEVs owners would do 85% of their charging at home and 15% charging at public stations—resulting in an average electricity rate of 0.66 Yuan/kWh with VAT of 13%. The retail gasoline price (including all types of taxes[4]) is assumed to stay constant at 7.48 Yuan/L.

The key non-fuel O&M costs for representative vehicles are summarized in Table 4. Annual insurance cost is based on Beijing insurance quote (including compulsory accident liability insurance, vehicle damage insurance, third-party liability insurance, deductible-exempt insurance with deductible amount of 10,000 Yuan) with vehicle model year 2017 [24]; the incremental insurance costs of PEVs over ICEVs are found to be proportional to the differences of the vehicle MSRP (i.e., $\Delta \boldsymbol{IC} = 0.0131 \times \Delta \boldsymbol{MSRP}$), suggesting that the insurance costs for future PEVs purchases will be less due to the decreasing battery prices and thus the decreasing MSRP. Maintenance cost is derived from multiple sources [23,25,26], showing that BEV holds a significant cost advantage in maintenance thanks to its much simpler propulsion system compared to the counterpart ICEV regarding mechanical complexity. In addition to the purchase grants, tax incentives (***TaxInc***) are also provided to promote more green consumption in China: energy-saving vehicles (including ICEVs with the engine not greater than 1.6L and PHEVs) are eligible for a reduction in vehicle use tax (***VUT***) by half, and BEVs are entirely exempted from the use tax (see the last row in Table 4 for the tax incentives provided to the selected vehicles in 2018). We assume that these tax incentives will also be removed at the end of 2020, along with the phase-out of the PEV purchase subsidies.

Table 4. Non-fuel operating and maintenance costs for the selected passenger vehicles in 2018; tax incentives are assumed to be removed at the end of 2020.

Vehicle Technology	ICEV	PHEV	BEV
Annual Insurance Cost (Yuan/year)	4,180	4,665	5,314
Maintenance Cost (Yuan/10,000 km)	900	720	220
Vehicle Use Tax (VUT) (Yuan/year)	420	420	300
Tax incentives for VUT (Yuan/year)	210	210	300

2.2.4 Impact of vehicle ownership restriction policy on TCO

To curb the fast-growing vehicle population, some China's megacities (including Beijing, Shanghai, Guangzhou, Shenzhen, Tianjin, and Hangzhou) are adopting car ownership restrictions, and PEVs are often exempted from these city's vehicle license plate control systems [27]. Shanghai was an early adopter

[4] The retail gasoline price in China includes multiple taxes—VAT, sales tax, urban maintenance and construction tax, education surcharges, local education surcharges, corporate income tax (and imported oil tax). These gasoline taxes would account for about 38% of the retail gas price (7.48 Yuan/L) when VAT is 13%.

of license auctioning and the bid-weighted average price for an ICEV plate was about 92,850 Yuan in the end of 2017 [28]. Beijing was the second city adopting a car ownership restriction policy, opting for a lottery system; the odds of winning an ICEV plate was about 0.04% [29]. Compared to ICEVs, the license plates for PEVs in Beijing are distributed on a first-come, first-serve basis. Based on the price difference between a car with a license plate and a counterpart car without a license plate in the used car market, the license plate value in Beijing was estimated to be 130,000 Yuan [30]. Guangzhou, Shenzhen, Tianjin, and Hangzhou adopted hybrid policies, allowing residents to opt in to either an auction or a lottery for ICEV plates.

For the cities having vehicle ownership restriction policy, the TCO per kilometer is also computed from Equation (1), but the purchase cost for ICEV is slightly different from Equation (2a)—containing one more cost contributor "ICEV license plate ($\boldsymbol{LP_{ICEV}}$)" (Equation (2b)). We take the license plate value in Beijing as representative for those megacities with car ownership restrictions.

$$\boldsymbol{PC = VP + VPT + VRF + LP_{ICEV} - FinInc} \tag{2b}$$

2.3 Transition Cost to Society (TrCS)

Transition cost to society (***TrCS***) is identified as part of the societal costs on the way to electromobility owing to the incremental costs of PEVs over ICEVs. In this analysis, the system boundary of cost to society (***CS***) is limited to the car's purchase and uses themselves, including fuel/electricity consumption, insurance, maintenance, and battery replacement; all the other less direct societal impacts imposed by the vehicle ownership and uses (e.g., environmental, health, balance of trade, national security, employment) are outside this study's scope. ***TrCS*** is obtained from multiplying PEV sales ($\boldsymbol{S_{PEV}}$) in year *j* by the incremental cost to society of PEV over ICEV (see Equation (10)). When we assess the incremental ***CS*** due to the switch from an ICEV to a PEV, all the taxes- and incentives-related terms in Equation (2) - (4) are excluded since they are just a redistribution within China instead of a cost to society as a whole. Taxes excluded from the ***TrCS*** calculation are ***gas tax*** (about 41% in 2017, 40% in 2018 and 38% between 2019 and 2030 of the retail gasoline price) and all the ***VAT*** embedded in the vehicle price, electricity price, insurance and maintenance costs (17% in 2017, 16% in 2018 and 13% from 2019 to 2030).

Unlike the ***TCO*** model that amortizes the upfront costs across all the kilometers to obtain the consumer levelized cost of driving, the ***TrCS*** model discounts all the future costs to their present values to compute the lump sum societal cost difference (i.e., $\boldsymbol{CS_{PEV}}$- $\boldsymbol{CS_{ICEV}}$) for a PEV sold in a specific year *j*, as shown in Equation (10) – (11). Note that battery replacement cost (***BR***) is only incurred in the 8th year (i = 8) (Equation (14)).

$$\boldsymbol{TrCS_j = S_{PEV,j}(CS_{PEV,j} - CS_{ICEV,j})} \tag{10}$$

where

$$\boldsymbol{CS = VP' + \sum_{i=1}^{N} \frac{(FE \times FP' \times VKT)_i + (IC' + MC' + BR')_i}{(1+r)^i}}$$

$$\boldsymbol{= \frac{VP}{(1+VAT)} + \sum_{i=1}^{N} \frac{(FE \times FP' \times VKT)_i + \left(\frac{IC+MC+BR}{1+VAT}\right)_i}{(1+r)^i}} \tag{11}$$

$$\boldsymbol{FP'_{gas} = FP_{gas} \times (1 - gas\ tax)} \tag{12}$$

$$FP'_{electricity} = FP_{electricity}/(1 + VAT) \quad (13)$$

$$BR = 0 \;\; when\; i \neq 8 \quad (14)$$

2.4 Uncertainty Analysis

Table 5 indicates the key governing parameters in our ***TCO*** and ***CS*** analyses, with the possible ranges identified for the future projections. We examine the uncertainties to these assumptions. Ranges for PEV battery prices are taken from our previous study that considered the impacts of materials cost [8]. The uncertainty of electricity price is large: while the lower bound represents the residential electricity rate (i.e., 100% home charging), the upper bound of electricity price is the rate for PEV owners doing all the charging during the peak hour at the public charging stations in Beijing [31]. We conduct a Monte Carlo analysis with 1,000 simulations to test the robustness of the results (2020, 2025, and 2030), assuming that all the uncertainties in the parameters are uniformly distributed and the vehicle lifespan is fixed at 12 years.

Table 5. Governing parameters and the associated uncertainties in the TCO and CS analyses

Parameters		Base Value	Range	Unit
Gasoline Price		7.48	6 ~ 8	**Yuan/L**
Electricity Price (including VAT of 13%)		0.66	0.47 ~ 1.74	**Yuan/kWh**
Discount Rate		5	4 ~ 6	**%**
Vehicle Distance Driven		12.5	10 ~ 15	**Thousand km/year**
PHEV Battery-Driven Percentage		76	60 ~ 90	**%**
BEV Battery Price in MY	**2020**	1,310	1,249 ~ 1,354	**Yuan/kWh**
	2025	944	811 ~ 999	
	2030	797	610 ~ 886	
PHEV Battery Price in MY	**2020**	1,474	1,414 ~ 1,512	**Yuan/kWh**
	2025	1,046	911 ~ 1,094	
	2030	871	682 ~ 953	

3. RESULTS AND DISCUSSION

3.1 Transition Cost to Society

High battery pack prices make electrified transportation with PEVs more expensive than travel by ICEVs. Here we calculate the total cost to society of the transition from ICEVs to PEVs implied by the dual-credit scheme mandate. We first compute the cost to society difference between PEV and ICEV (i.e., $\boldsymbol{CS_{PEV}}$ - $\boldsymbol{CS_{ICEV}}$) from 2021 to 2030, and then estimate the yearly transition cost to the society ($\boldsymbol{TrCS_j}$) based on the PEV sales in that year ($\boldsymbol{S_{PEV,j}}$) using Equation (10); the results are shown in Figure 3.

As the battery pack prices drop, the delta cost to society (ΔCS) for a switch from one ICEV to a PEV will be shrinking. We find that a PHEV is likely to achieve CS parity with an ICEV faster than a BEV; a BEV using a large battery pack will stay more than 20,000 Yuan more costly to society than an ICEV even out to 2030 (Figure 3(a)). The new mandate, on the one hand, is expected to drive the local PEV sales from 1.7 million per year in 2021 to 11.2 million per year by 2030 (with 37% sales market share) (Hsieh, Pan and Green (accepted)); but on the other hand, this would impose substantial transition costs upon the whole society. Since the annual number of PEVs sold will increase more rapidly than the decreasing rates of ΔCS, the yearly transition cost to society is expected to keep growing toward 2030—from 59 billion Yuan per year in 2021 to 228 billion Yuan per year in 2030 (bars shown in Figure 3(b)). This transition cost to society associated with the mandate would be – on average – on the order of 100 billion Yuan per year from 2021 to 2030, consuming about 0.1% of the projected annual GDP in China[5] each year (Figure 3(c)), equivalent to about 2% of the total size of the transport sector of China's GDP[6].

This transition cost should be taken into account when researchers are attempting to quantify the total cost to society associated with vehicle electrification. It is noted that cities having ICEV license restrictions (e.g., Beijing, Shanghai, Shenzhen, Tianjin, Hangzhou, and Guangzhou) will have higher PEVs adoption rates than the others [34]; depending on how PEVs and ICEVs are priced across China and how gasoline tax revenues are shared, those cities might contribute either more or less to the total transition cost than other parts of China. Regardless, it is expected that people in all regions of China will feel the transition cost by having less access to cars, so decreased mobility and fewer trips.

It should be noted that all the societal benefits of PEVs are not quantified in this study. However, there are large non-monetary benefits needed to be considered and compared with the monetary transition costs to evaluate the net social value of vehicle electrification. First, the large battery production volumes will help drive down battery prices, thus closing the cost gaps between PEVs and ICEVs; second, electrifying private mobility would lead to substantial societal benefits in the long run due to reduced emissions leading to lower health costs and increased quality of life and life expectancy in urban areas; third, this transition has additional potential long-term societal benefits to China in terms of the balance of trade and national security due to reduced reliance on imported petroleum. Both the costs and the benefits associated with this mandate are substantial, and so deserve careful consideration.

[5] China's GDP is assumed to grow with the compound annual growth rates of 7.00% in 2016-2020, 5.36% in 2021-2025, and 4.60% in 2026-2030 [32].

[6] From 2012 to 2018, the sector of "transport, storage and post" had contributed 4.5% of China's GDP per year [33].

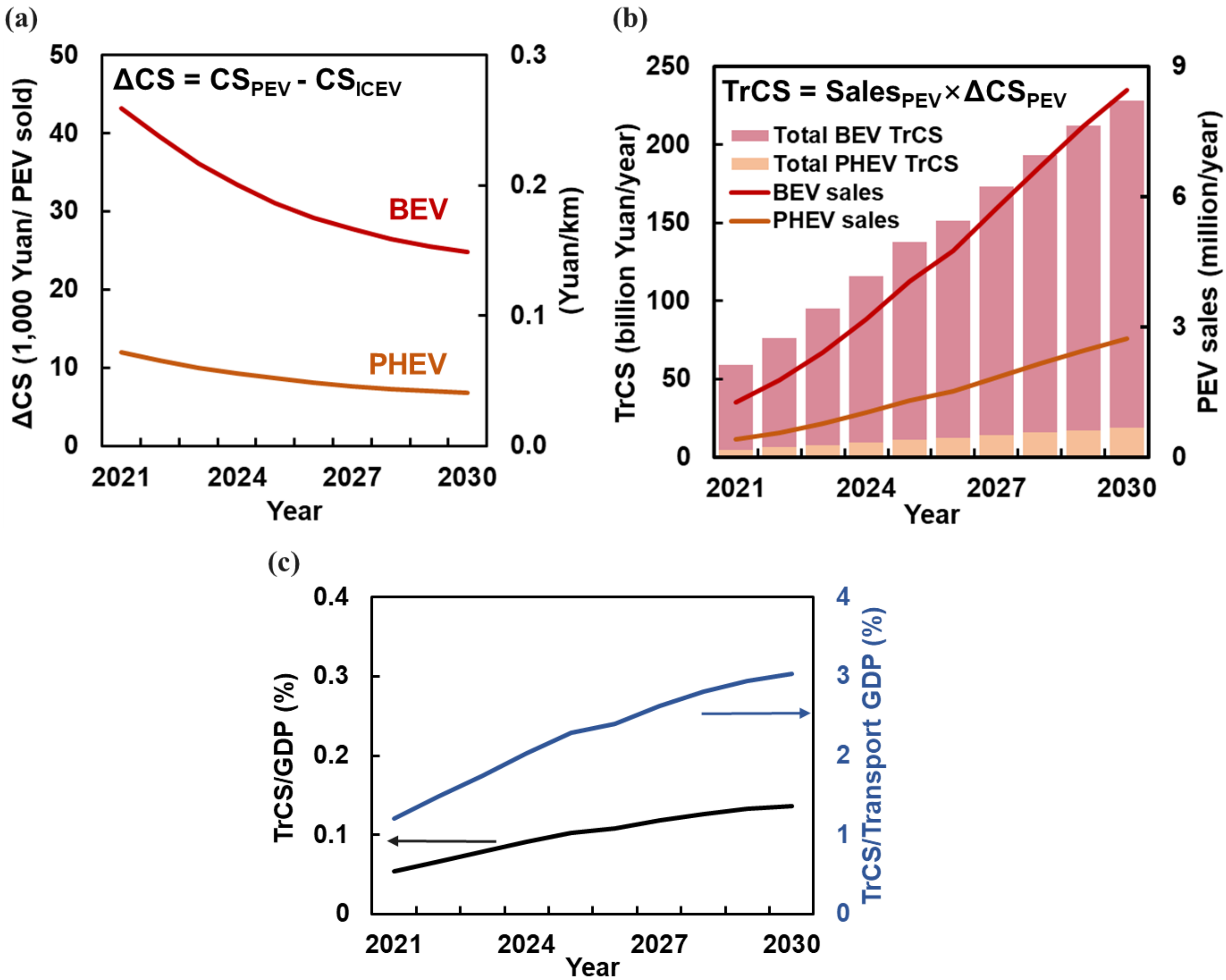

Figure 3. (a) The delta cost to society (ΔCS) for a switch from ICEV to PEV; both the 12-year (with 12,500 km driven/year) lump sum CS differences (left ordinate) and the corresponding per km CS differences (right ordinate) are presented; (b) the yearly transition cost to the society (left ordinate) for forcing the targeted PEV market penetration (right ordinate) by 2030; PEV sales are from Hsieh, Pan and Green (accepted); (c) the transition cost's contribution to the Chinese growing economy (left ordinate) or to its transport sector composition (right ordinate). Note that large societal benefits of PEVs (e.g., enhanced energy security, climate change mitigation, and improved public health) are not considered here but should be compared with these transition costs to evaluate the net social value of vehicle electrification.

3.2 Ownership Cost to Consumer

Consumer decisions are determined by personal cost rather than societal cost; taxes, subsidies, mandates, and regulations could significantly alter the actual ownership costs. Thus, we evaluate total ownership costs borne by the consumers for per-kilometer driving, exploring how the local tax/ subsidy scheme and car ownership restriction policy would affect the relative ownership cost competitiveness across different vehicle technologies from now out to 2030. It is noted that the results shown in Section 3.1 and 3.2 assume a home-dominant charging behavior where PEV owners have access to home charging and prefer to do most charging at home. The uncertainty in drivers' charging patterns—home charging versus public charging—is addressed in Section 3.3.

3.2.1 Current Status in China (2018)

First, we investigate the differences in levelized TCO considering the government financial incentives (including purchase subsidies and tax breaks/ exemptions) and ICEV license plate quota policy across ICEV, PHEV, and BEV in China, using the reference vehicles' parameters. While the solid bars in Figure 4 represent the results of 12-year levelized TCO, the error bars are from the uncertainty in the vehicle lifespan ranging from 8 to 15 years.

The current financial incentives for a PHEV/ BEV purchased (with subsidy) in Beijing amount to 54,435/ 118,785 Yuan reductions in lifetime 12-year (i.e., 150,000 km) TCO, equivalent to 0.36/ 0.79 Yuan reductions per kilometer traveled respectively, making PHEVs and BEVs more economically attractive than conventional gasoline cars. The ICEV license plate quota policy, on the other hand, would impose an additional cost of 1.17 Yuan per kilometer traveled on ICEV purchase, causing ICEVs to be much more costly than subsidized PEVs in China's megacities. However, in the absence of financial incentives and quota policy, the current 12-year TCO of PHEVs/ BEVs is 3%/ 24% higher than that of ICEVs; this reemphasizes that government subsidies or mandates are essential for PEV take-off at today's economics.

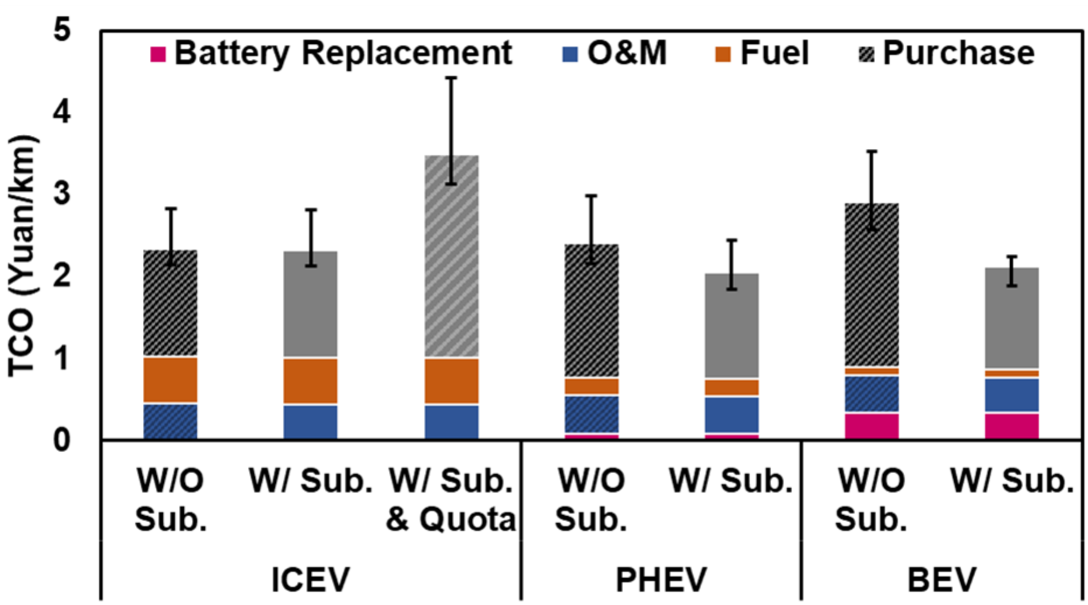

Figure 4. TCO component breakdown with and without the government subsidies and ICEV license plate quota policy in 2018 across three different vehicle technologies in China (Beijing); the upper error bound is assuming the vehicle lifespan is 8 years, while the lower error bound assumes 15 years. Note that different hatchings reflect different policy environments' effects on purchase cost (gray) and O&M costs (blue).

Figure 5 compares the subsidized per-km TCO results (i.e., W/ Sub. in Figure 4) across various vehicle lifespans: 8, 12, and 15 years. Current subsidies are shown to be sufficient to make the TCO of PEVs lower than that of ICEVs with all 3 vehicle lifespans in China. However, most consumers still prefer ICEVs nowadays, suggesting that other barriers beyond cost (of ownership) have to be overcome as well to achieve mass PEV adoption; barriers include limited access to charging infrastructure, range anxiety, and consumer familiarity. Figure 5 also points out that no matter which propulsion system a vehicle is equipped with, the longer period a car is owned and used, the cheaper per-km TCO would be, even considering the battery replacement cost. For vehicle lifespans greater than 8 years, consumers should be aware that battery replacement costs would be very likely to incur since the battery age is beyond the warranty coverage (i.e., 8 years). However, compared to the per-km TCO with the vehicle lifespan more than 8 years, the expensive battery replacement costs would be offset by the increased total vehicle distance driven. While the battery pack prices are about 1,590 Yuan/kWh for BEVs (MY 2018) and 1,814 Yuan/kWh for PHEVs (MY 2018), they are expected to drop to around 900 Yuan/kWh and 994 Yuan/kWh, respectively, in the next 8 years when they achieve their retirement age [8].

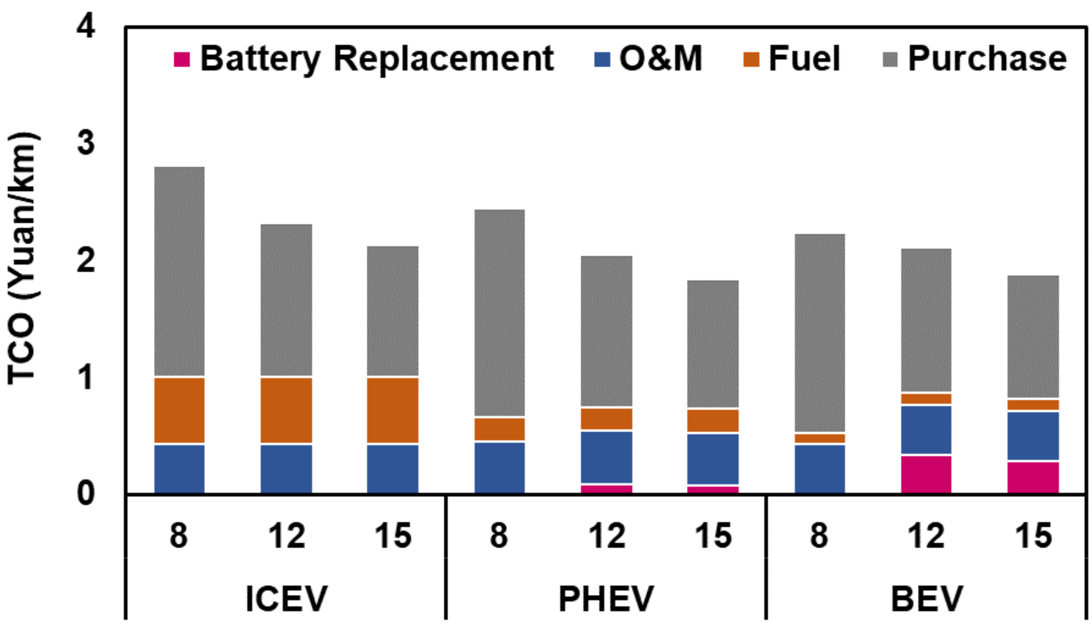

Figure 5. TCO component breakdown including 2018 government subsidies for vehicle lifespans of 8, 12, and 15 years across three different vehicle technologies in China (Beijing); battery replacement is not expected to incur when the vehicle lifespan is 8 years. "Fuel" includes electricity.

3.2.2 TCO Trajectory toward 2030

Based on the battery price (Table 3) and the subsidy (Figure 2)/ ICEV license plate quota policy scheme in Beijing, the temporal 12-year TCO variations during 2015 to 2030 in China are computed. The TCO ratios between PEVs and ICEVs are shown in Figure 6, and several observations and findings are worth highlighting:

2015-2020

- The battery pack of a BEV is larger than a PHEV (i.e., 50.5 kWh for a BEV and 11.9 kWh for a PHEV in this analysis), and thus the purchase cost reduction owing to the large decrease in battery prices in 2016 is more notable in a BEV.
- The substantial cuts in BEV subsidy in 2017 and 2019 result in the two rises in TCO ratio of BEV to ICEV.
- Since the government is closing the cost gaps through subsidies and differences in taxes collected, China's TCO ratio of PEV to ICEV is about 10% less than 1 (i.e., TCO parity is achieved) in the period of 2016 to 2020. The government has been heavily subsidized the PEV industry, making PEV more profitable in China than in some other countries.
- For China's megacities with car ownership restrictions, the special treatments on licensing (i.e., with PEV exemption) and financial subsidies make PEVs much more cost-attractive than the counterpart ICEVs; these have catalyzed the sales of PEVs in these megacities. The six megacities in China that currently have car ownership restriction policies (Beijing, Shanghai, Guangzhou, Shenzhen, Tianjin, and Hangzhou) have contributed about 50% of national annual PEV sales in 2017 and 2018 [35].

2021-2030

- The plan to entirely phase out all the subsidies by the end of 2020 will lead to a big jump in TCO ratios in 2021. If the automakers keep the same price structure as today, the TCO of a BEV in the absence of incentives and quota policy will no longer achieve parity with an ICEV even out to 2030. On the other hand, TCO parity is expected to remain achieved for PHEV even with no subsidies and no quota policy.
- It is reasonable to expect that consumer-centric TCO (including subsidies, taxes, different automakers profits on different types of vehicles) for BEV and ICEV will have to be comparable (i.e., TCO ratio close to 1 or even less than 1) for broader vehicle electrification by 2030 in accord with the government targets.
- It is uncertain how the cost differentials will be covered when some of the current PEV subsidies in China are replaced by mandates. Based on the experience in the USA with CAFE (Corporate Average Fuel Economy) standards[7], car manufacturers are likely to raise the price of ICEVs while lowering the price of PEVs to persuade consumers to purchase the required fraction of PEVs. This change in the vehicle pricing strategy will address the consumer cost differential, and shift much

[7] CAFE standards would impose a constraint on automakers' profit maximization problem that creates an implicit subsidy for fuel-efficient vehicles and an implicit tax for fuel-inefficient vehicles [36].

of the societal cost of vehicle electrification onto Chinese purchasers of ICEVs. Nevertheless, we expect that a big fraction of the transition cost will continue to be borne by the government due to the reductions in gasoline tax revenues, and the automakers may bear part of the cost differentials in the form of reduced profit margins during the transition period.

- Under car ownership restriction policy with PEV exemption, PEVs will remain their cost competitiveness advantages even after the phase-out of the subsidies. However, there remains uncertainty surrounding the long-term implications of the quota policy. Fearing the impact of additional city-level ownership restrictions on China's domestic car manufacturing industry—particularly with vehicle sales falling in 2018 for the first time since the 1990s—China's national government announced a new policy to temporarily stop local government from implementing new restrictions on car purchases [37]; however, Beijing city government has yet to take any action to respond to this national mandate.

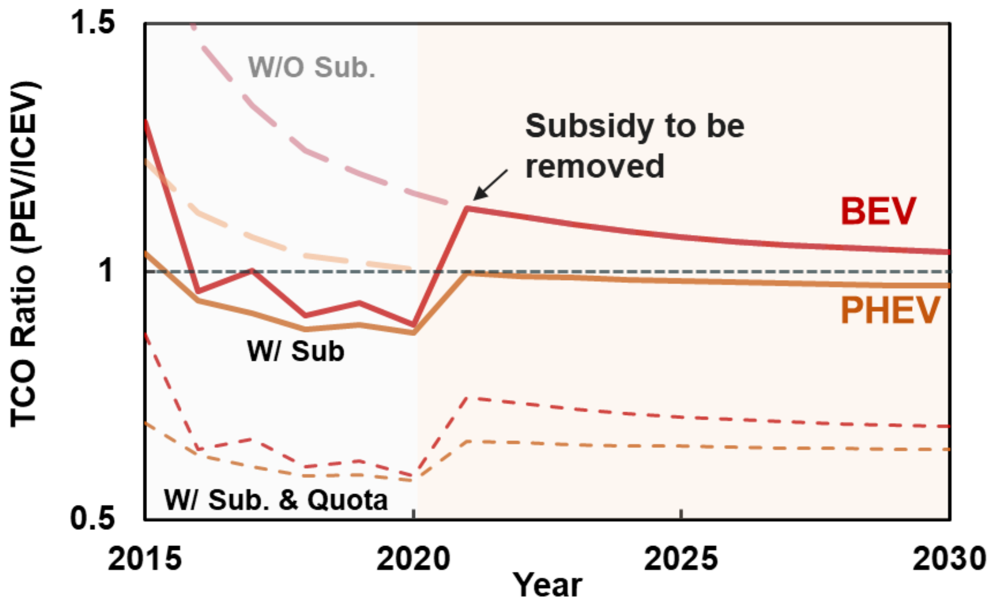

Figure 6. TCO trajectories of PEVs relative to ICEVs in China by 2030. Data up to 2018 are historical; 2019-2030 are the results of assuming the automakers keep the same price structure as today. After 2020 when the subsidies are removed, TCO parity will remain achieved for PHEV but not for BEV even out to 2030 (in most of China's regions where ICEV license plate quota policy does not exist). However, the mandate targets will not be achieved if the TCO of BEVs is higher than TCO of ICEVs. Instead, we expect automakers will raise ICEV price and lower BEV price to keep the TCO ratio less than 1. On the other hand, in some China's megacities with car ownership restrictions, PEVs will remain much more cost-attractive even after the removal of subsidies.

3.3 Uncertainty Analysis

To examine the ***TrCS*** and ***TCO*** result robustness, we perform a Monte Carlo simulation varying the key model inputs, assuming that these parameters are uniformly distributed within the ranges identified in Table 5. Figure 7 and Figure 8 show the uncertainties about the projected ratios of cost to society (i.e., CS_{PEV}/CS_{ICEV}) and of cost to consumers[8] (i.e., TCO_{PEV}/TCO_{ICEV}) in 2020, 2025, and 2030. Each box describes lower quartile, median and upper quartile values; most extreme values (whiskers) are within 1.5 times the inter-quartile ranges from the ends of the box; outliers are displayed in red + sign; the base case results (presented in Section 3.1 and Section 3.2) are marked in circles. The uncertainty range of BEV is always larger than for PHEV, which is due to the fact that larger battery capacity in BEV magnifies all the uncertainties in future fuel (electricity) costs and battery prices. Besides, the base case results (i.e., circles in the figures) are all in the lower half of variance; this is mainly because in the base case PEV owners are assumed to do 85% of their charging at home, therefore having much lower electricity costs (about 0.66 Yuan/kWh) than for public charging stations (mostly between 1.6 Yuan/kWh and 1.8 Yuan/kWh).

Cost to society (Figure 7):

- Almost all the simulation outcomes of CS ratio of PEV to ICEV are greater than 1, highlighting the fact that a shift away from fossil fuels to battery-powered vehicles will impose costs throughout the entire society, and which should be taken into account when assessing the true transition cost. All the associated transition benefits (e.g., national energy security, climate change, air pollution, and so on) are not considered here. The societal benefits of PEVs should be compared with these transition costs to assess the net social value of vehicle electrification.
- For box-to-box comparison, BEVs are always higher than that for PHEVs, suggesting that a switch to a BEV will impose heavier transition cost than a shift to PHEV; this is mainly because of the larger (thus more costly) battery packs in BEVs.
- BEV direct costs to the Chinese society are always more than ICEV even in 2030. On the other hand, PHEVs have fewer direct costs to society than BEVs and are more likely to be on a par with ICEVs by 2030, making PHEV a promising form of transportation to achieve a less-costly transition from liquid fuels to electrification.

Cost to consumer (Figure 8):

- In 2020 when the subsidies still exist, TCO parity will keep being achieved between PEVs and ICEVs. Moreover, with the help of China's subsidies that favor BEV more than PHEV, the TCO for BEV (even having higher consumer purchase prices) is comparable to that for PHEV, meaning that there are no differences between these two types of PEVs from the perspective of consumer's cost of driving in 2020.
- Most of the outcomes of TCO ratio of BEV to ICEV are larger than 1, pointing out that when the subsidies are removed, BEVs are not likely to achieve TCO parity with ICEVs by 2030 (unless

[8] For brevity, we focus only on uncertainty of TCO with no quota policy to the model assumptions.

carmakers discount the price of BEVs relative to ICEVs). This implies that for BEV take-off over the next decade, either the government has to extend BEVs subsidies or the automakers need to adjust their pricing structures by internal subsidies. On the other hand, PHEVs are very likely to remain less costly than ICEVs to consumers in terms of TCO.

- It should be noted that even without vehicle pricing strategies changed, there is still a possibility that BEVs reach TCO parity with ICEVs; this might happen when gasoline price and annual distance driven are in higher ends of their uncertainty ranges, while electricity price, discount rate, and battery prices are in lower ends.

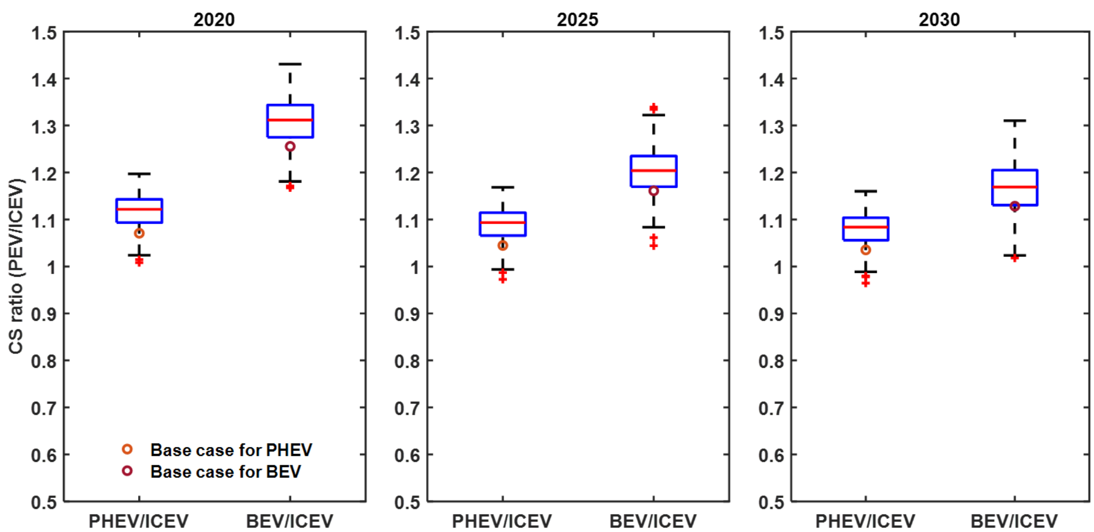

Figure 7. Variations in the projected ratios of cost to society (CS) of PEVs to ICEVs in China in 2020, 2025, and 2030. Since many more PEVs will be sold in 2030 than 2020, the total transition cost to society (TrCS) will be higher then (see Figure 3(b)). Note that the societal benefits (such as improved national energy security and better air quality) of PEVs are not considered here.

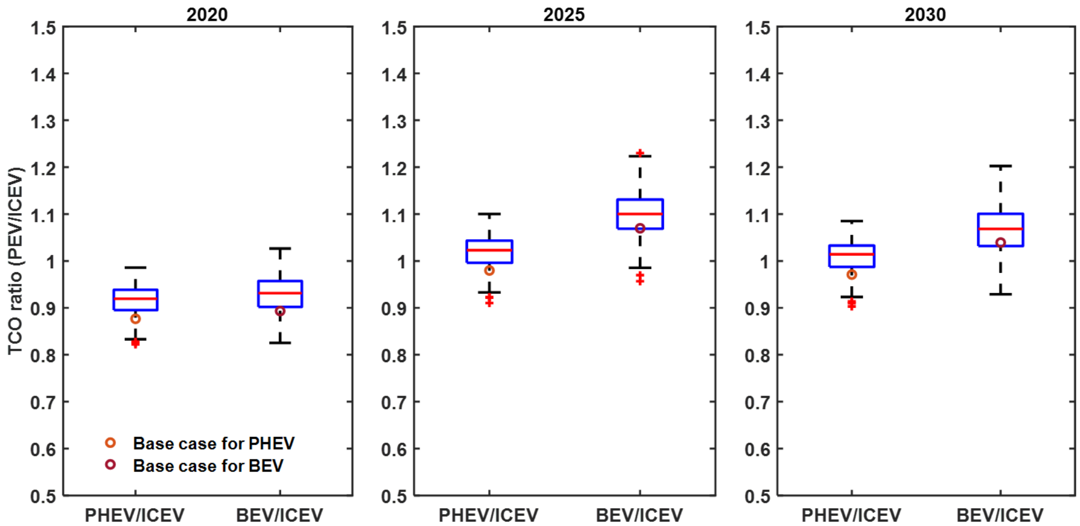

Figure 8. Variations in the projected ratios of the 12-year total cost of ownership (TCO) to consumers between PEVs and ICEVs in China (Beijing) in 2020, 2025, and 2030; subsidies are included in 2020 numbers. We expect automakers to adjust prices to eliminate the TCO differential in order to achieve the mandated sales mix.

4. CONCLUSION

While battery prices have been dropping rapidly over the past decade, the essential battery materials (lithium, nickel, and cobalt) will eventually constrain the declining trajectory of battery production cost and set lower bounds on battery prices. This practical limit would undoubtedly delay the occurrence of the transition to electromobility at an attractive cost, especially if the elemental price spiked resulted from a raw material shortage. We select China as a market of particular interest owing to its leadership position in plug-in electric vehicle (PEV) deployment, mostly credited to the aggressive government policies. The recent enactment of dual-credit system mandate is expected to compensate for the phase-out of the subsidy program, increasing PEV adoption in China dramatically, ostensibly by transferring the burden of subsidizing the PEV industry from the government to the automakers (but most likely to the car buyers).

We compute the transition cost to China of switching from internal combustion engine vehicles (ICEVs) to PEVs and find that PHEVs could provide a less costly transition from liquid fuels to electrification, while BEV direct costs to the Chinese society will always be more than ICEV even in 2030. Moreover, we show that creating an inflection point for PEV demand via the mandate will put substantial transition costs on the entire society: from ~60 billion Yuan for 2 million PEVs sold per year in 2021 to ~230 billion Yuan for 11 million PEVs sold per year in 2030, which is about 0.1% of the growing China's GDP annually—equivalent to 2% of the nationwide expenditure on transport sector every year in China. To evaluate the net social value of vehicle electrification, this sizable societal investment should be compared to the associated social benefits that are not quantified in this study – e.g., electrified mobility may reduce local air pollution and CO_2 emissions with health and climate benefits, and it may also enhance national security owing to reduced dependence on imported petroleum.

However, mass-market consumer's decisions are not driven by the social cost, but primarily by the private cost. To spur mass adoption of PEVs, the industry must go beyond the early adopters and become appealing to the majority of consumers who care more about price and convenience than environmental policy. Thus, this study also considers the consumer-centric total cost of ownership (TCO), i.e., the lifetime cost to a customer of purchasing and operating a car including taxes, subsidies, fuel, maintenance, insurance, and battery replacement costs for PEVs. We examine the cost attractiveness of PEVs by depicting their localized TCO trajectories relative to ICEVs out to 2030. Supported by various subsidy programs, China's PEVs have been heavily subsidized by the government during the period of 2016-2020, making them more TCO attractive than ICEVs. However, after subsidies are eliminated at the end of 2020, while PHEVs could remain cost-competitive, this TCO parity will no longer be reached for BEVs, probably even out to 2030, if the automakers keep the same price structure as today. The phase-out of the PEV subsidies and the introduction of the dual-credit system mandate will force the automakers to adjust their pricing strategy. Based on the experience in the USA with CAFE (Corporate Average Fuel Economy) standards, carmakers are very likely to raise the price of ICEVs and lower the price of BEVs to make the consumer TCO lower for BEVs, to achieve the mandated targets. On the other hand, for the megacities with car ownership restrictions, the "valuable" ICEV license plates make PEVs much more cost-attractive than ICEVs even with no subsidy, boosting the local PEV sales.

Although TCO-based methodology is applied throughout this study to investigate the impacts of achieving China's aggressive goals for electric transport, several limitations are recognized. First, gasoline prices will be fluctuating rather than staying constant. Second, TCO is not the only factor affecting the new technology adoption; other barriers include limited access to charging infrastructure and consumer familiarity. Third, the effects of policies cannot efficiently be computed by static single-point estimations. For example, the electrified mobility will probably reduce emissions of greenhouse gases and air pollutants, leading to valuable health and climate benefits that are not captured in this direct-cost analysis. Furthermore, the calculation ignores the secondary effects due to reduced petroleum imports and increased electricity generation, and costs of building more recharging infrastructure. Thus, further investigation based on this study is required to improve the policy impact evaluations of private vehicle electrification.

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