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ORIGINAL PAPER

Technology development for electric vehicles under new energy vehicle credit regulation in China: scenarios through 2030

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Abstract

The newly launched new energy vehicle credit regulation scheme is expected to have a dramatic impact on the development of the Chinese and global new energy vehicle markets. This paper establishes a bottom-up framework to estimate the impacts of regulation on the technological trends of battery electric vehicles based on the most up-to-date data from the market in China. The results suggest that mini-electric cars will always be the most credit cost-effective. Moreover, 350 km will be the optimal driving range under the credit regulation. With the development of energy-saving technologies, midsize electric vehicles will increase in popularity before 2020 and be the first to receive the highest credit of 6. Additionally, promoted by the regulation, the investment in energy-saving technologies will reduce the cost of batteries and lead to higher credits, especially for large-class and high electric range vehicles. However, the regulation likely faces the risk of losing this positive effect in 2025 or even earlier. To avoid such a circumstance, the relevant policies should be modified before such a scenario occurs.

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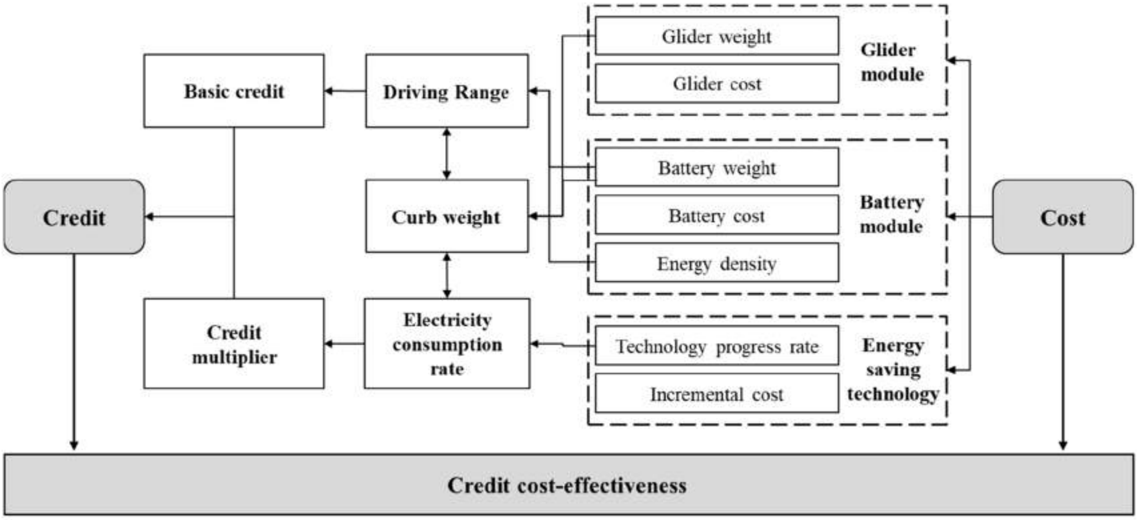
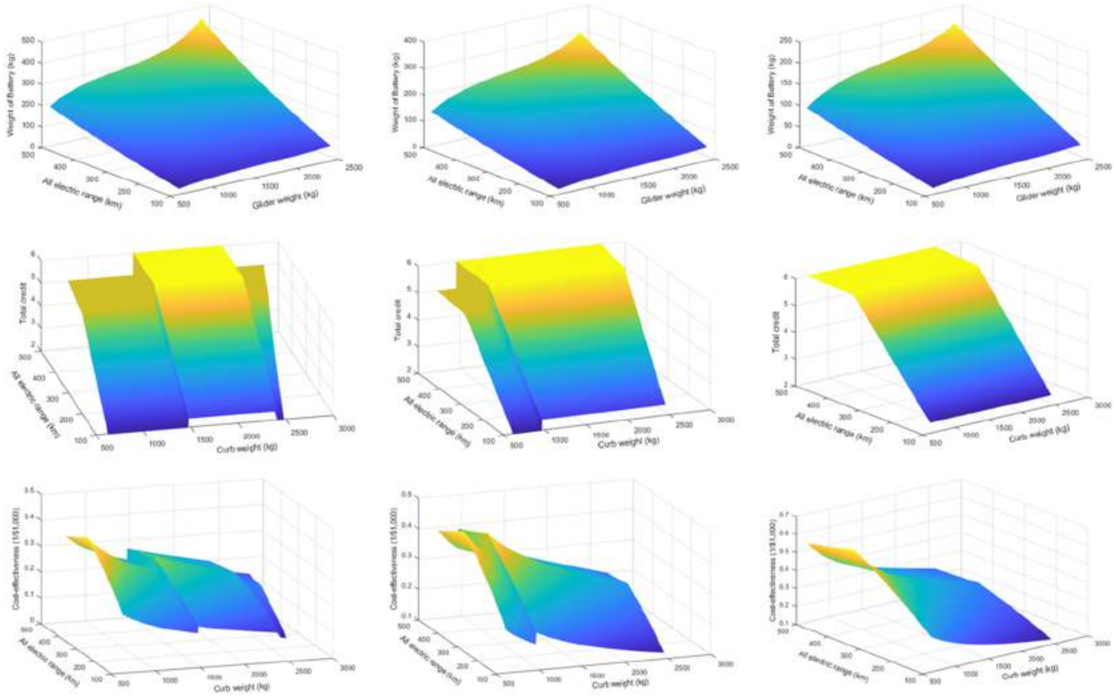
Graphical abstract





Keywords New energy vehicle credit regulation · Battery electric vehicle · Technology tendency · Cost-effectiveness · Scenario analysis

Abbreviations

BAU	Business-as-usual
BEV	Battery electric vehicle
BEVx	Range-extended electric vehicle
CAFC	Corporate average fuel consumption
CAFE	Corporate average fuel economy
CATC	China automotive test cycle
EPA	Environmental protection agency
FCV	Fuel cell vehicle
HICE	Hydrogen internal combustion engine vehicle
MIIT	Ministry of industry and information technology
MPV	Multi-purpose vehicle
MSRP	Manufacturer's suggested retail price
NEDC	New European Driving Cycle
NEV	New energy vehicle

NHTSA	National highway traffic safety administration
OEM	Original equipment manufacturer
PHEV	Plug-in electric vehicle
TZEV	Transitional zero emission vehicle
ZEV	Zero emission vehicle

Introduction

The automobile market in China has grown dramatically over the past few decades. In 2017, automobile sales in China reached over 28.9 million (CAAM 2018a), which accounted for approximately 30.1% of total global vehicle sales (WardsAuto 2018) and ranked first in the world for the ninth consecutive year. However, in 2017, the vehicle ownership level in China was only approximately 156 vehicles per 1000 people (NBS 2018; MPS 2018), which is much lower than the average level of 500 vehicles per 1000 people in most developed countries (the vehicle ownership level in America is more than 800 vehicles/1000 people). So, great growth potential is expected for the Chinese automobile market. Nevertheless, China is simultaneously facing severe energy and environmental problems (Hao et al. 2014a; Wang et al. 2015). Over the past few years, China's external dependence on oil has continually increased from 30.0% in 2000 to 67.4% in 2017 (ETRI 2018), which far exceeds the international safety warning level. The transportation sector is responsible for more than half of the total petroleum consumption in the country (IEA 2012; iCET 2017) and for the emission of hundreds of pollutants that threaten the health of residents (Pathak et al. 2016) and is a major cause for societal concern.

Due to the mounting pressure related to energy and environmental concerns, several measures have been taken by the Chinese government to promote the development of new energy vehicles (NEVs) and shift the vehicle power source from petroleum to other clean energies, thereby coping with the issues of energy security and emissions (Zhao et al. 2016; Hao et al. 2017). According to the Ministry of Industry and Information Technology (MIIT) of China, NEVs include plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell vehicles (FCVs). Among these vehicles, BEVs are the most promising clean vehicle technology, and they have accordingly been given high priority in China and the rest of the world. In 2017, China's NEV sales reached 0.78 million, with BEV sales reaching over 0.65 million and constituting 83.9% of all new energy vehicles (CAAM 2018b). NEV sales increased by nearly 60% in 2017 compared with the level in 2016 and by a factor of 13.5 compared to the level in 2014 (CAAM 2016, 2017).

The booming sales of NEVs have largely been promoted by a series of incentive policies. The objective of the Chinese government is to reach a total BEV and PHEV production level of 2 million by 2020 (State Council 2012), with the sales of NEVs accounting for 7% of the entire vehicle market in 2020 and 20% and 40% in 2025 and 2030, respectively (MIIT 2016). In the past decade, China has issued a series of preferential policies and regulations, including subsidies, tax exemptions, and regulatory incentives, to promote the development of NEVs (Hao et al. 2014b; Wang et al. 2017). Among these policies and regulations, the parallel scheme of corporate average fuel consumption (CAFC) and NEV credit regulation, which was newly issued by the MIIT of China in September 2017, is considered a notable impetus for the development of NEVs accompanied by a decrease in subsidies (MIIT 2017; Wang et al. 2018). Thus, China has taken the global leader in establishing a nationwide credit management scheme for energy savings and new energy passenger vehicles.

Essentially, the parallel CAFC and NEV credit regulation scheme, also widely called dual-credit regulation, is a combination of former CAFC and NEV credit regulations based on credit compensation. The aim of NEV credit regulation is to promote the penetration of NEVs and guarantee the market size of NEVs by setting a proportional NEV credit requirement for traditional automobile manufacturers. The design concept of NEV credit regulation is similar to the zero emission vehicle (ZEV) mandate passed in California (iCET 2017). However, there are significant differences between these schemes in policy design and implementation, as shown in Table 1.

The policy design has a considerable impact on the development of products and largely determines the technical tendency. The NEV credit has become extremely valuable because it can not only be sold to other manufacturers but can also unilaterally compensate for CAFC credits in China's dual-credit scheme. According to the rules of the NEV credit regulation, different vehicles have different credits with different evaluation indicators. Furthermore, the final credit for vehicles in the NEV credit regulation consists of the basic credit and multiplier, as Eq. (3) shows. The basic credits of different type of vehicles are shown in Table 2.

Besides, the multiplier is another determining element that is significantly different for different type of vehicles. BEVs have three kinds of multipliers, namely, 0.5, 1 and 1.2, as Eq. (2) shows, and PHEVs and FCVs have two kinds of multipliers, 0.5 and 1 (MIIT 2017; Ou et al. 2018). Specifically, according to the regulation, the upper limit of basic credits for all NEVs is 5. So the maximum final credits of BEVs, PHEVs, and FCVs are 6, 2 and 5, respectively, which reflect the strong support for BEVs from the Chinese government.

Until now, few studies have focused on China's NEV credit regulation because of its recent inception. Shen et al. (2017) projected the influence of the dual-credit regulation

Table 1 Comparison between China's NEV and California's ZEV credit regulations

Features	China's NEV credit regulation	California's ZEV credit regulation
Associated with CAFC/CAFE	Yes	No
Scope	Nationwide	California and 9 other states
Applicable manufacturer	Production of traditional cars per year > 30,000	Average sales of traditional cars in the previous 3 years > 4500
Credit proportion requirement	2019: 10%; 2020: 12%	2018: 4.5%; 2019: 7%; 2020: 9.5%; 2025: 22%
Encouraging vehicle	BEV/PHEV/FCV	ZEV (BEV, FCV)/BEVx/TZEV (PHEV, HICE)/NEV
Credit trading	Free trading	Free trading
Expiry date	1 year, cannot be carried over except in 2019	Allowed to be carried over annually
Punishment	Administrative punishment: suspension of production	Financial punishment: penalty

(1) BEVx in California refers to range-extended electric vehicles, which are considered PHEVs in China. (2) NEV in California means neighborhood electric vehicle, which is called a low-speed electric vehicle and not included in NEVs in China

Table 2 The basic credits of different passenger vehicles

Vehicle type	Basic credit
BEV	$0.012 \times \text{AER} + 0.8$
PHEV	2
FCV	$0.16 \times P$

(1) AER denotes the all-electric range (based on a mode method of the NEDC cycle) (km). The AER of BEVs and PHEVs should not be less than 100 km and 50 km, respectively. (2) P denotes the power rating of the fuel cell system (kW). (3) The upper limit of basic credits for all NEVs is 5

and analyzed the Chinese NEV credit market based on the CAFC and NEV credit model. The relationship among the CAFC, NEV and carbon credit regulations was analyzed by Liu et al. (2017), who projected the development of NEVs based on the dual-credit regulation. Moreover, Wang et al. (2018) analyzed different compliance scenarios based on the dual-credit regulation for four typical automakers and summarized the most cost-effective strategies for those automakers. However, these studies were all based on the draft of the dual-credit regulation, which is different from the official version. Zou et al. (2017) established a corporate compliance model based on the official dual-credit regulation. The principle of the model is to meet the requirements of the dual-credit regulation with a minimum number of NEVs and fix the trading price of NEV credits. Ou et al. (2018) also quantitatively analyzed the impacts of the dual-credit regulation on plug-in electric vehicle (PEV) sales and industry profits based on a newly constructed energy and oil consumption model, and different policy scenarios (CAFC only, NEV only, CAFC and NEV) from 2016 to 2020 were simulated and compared. However, these published studies all focused on the compliance of the dual-credit regulation and the impacts on the market. Few have systematically and quantitatively analyzed the impacts on technology development of BEVs. Moreover, the long-term estimate of the impact is lacked.

Additionally, numerous studies have focused on the adoption of electric vehicles in China. Zhou et al. (2015) reviewed the market trends together with policies in China and concluded that major policies such as incentives and regulations can have strong positive impacts on the market penetration of electric vehicles. Hao et al. (2014b) estimated the impacts of two-phase subsidy scheme on BEV market penetration and found that BEVs could become less or not reliant on subsidy to compete with conventional internal combustion vehicles prior to 2020 with the decrease in BEV manufacturing cost. Moreover, 150 km might become the bottom-line of electric range for major BEVs in the future. Ou et al. (2018) also quantified the penetration of BEVs and PHEVs in China and concluded that battery electric sedans with a range higher than 250 km will be popular under the dual-credit policy. Zhang et al. (2017) analyzed 175 NEV policies including national policies and those from Beijing, Tianjin, and Hebei, and revealed that the public sector is the first breakthrough to promote NEV adoption.

The cost and driving range are considered to be the main barriers to the penetration of BEVs. Egbue and Long (2012) analyzed the potential barriers to the adoption of BEVs and found that driving range is the biggest concern followed by cost. Helveston et al. (2015) developed a consumer preferences model for different vehicles in China and suggested that Chinese consumers are willing to adopt BEVs and mid-range PHEVs similarly relative to conventional gasoline vehicles, whereas American consumers prefer low-range PHEVs. However, the conclusions of these studies mainly focused on the sales and percentage of BEVs. Few studies involved the technologies, such as driving range of BEVs and the conclusions, are vague and lack a quantitative basis.

As for the impacts of the credit regulation on technology, there is still a major deficit of existing studies. Such policies largely guide product characteristics and technological trends, including those related to the optimal vehicle class, driving range, energy-saving technologies and new energy technologies, which need to be elaborated quantitatively. To fill such research gaps, a bottom-up model based on the credit cost-effectiveness method is established to provide comprehensive policy insights regarding the NEV credit regulation and estimate the associated effect on the technological trends of BEVs. Additionally, two scenarios with and without progress in energy-saving technologies are developed with the aim of evaluating the benefit of energy-saving technology under the new credit scheme. This study includes a policy simulation, predictions of technical trends, and an explicit assessment of policy implications associated with the NEV credit regulation. The paper is organized as follows: the following section describes the accounting framework, key assumptions, and data. Then, the research results for the business-as-usual (BAU) and alternative scenarios are compared and discussed. Finally, the policy implications are deduced, and some recommendations are made for regulation planning and technological development for the government and manufacturers.

Methodology and data

In this section, the overarching methodology and data are introduced. Figure 1 presents the scope and accounting framework of this study. As previously mentioned, this study focuses on the technological trends of BEVs based on a credit cost-effectiveness analysis and the NEV credit regulation. The vehicle classification used in this study based on the Chinese BEV market is introduced firstly. Then the NEV credit scheme is interpreted and the battery sizing methodology is discussed. After that, the methods of calculating the costs of glider, batteries and energy-saving technologies are presented. Finally, the definitions of credit cost-effectiveness and incremental credit cost-effectiveness are explained.

Vehicle classification based on the Chinese BEV market

Because of the obvious distinction between electric vehicles and conventional internal combustion vehicles, the classification of conventional vehicles is not suitable for BEVs. However, due to the limited data, there is no official classification of BEVs. In this paper, the appropriate baseline and classification were established first.

The MIIT had issued 15 catalogs of NEVs that were exempt from purchase taxes from 2014 to 2017 and 12 catalogs of NEVs that were subsidized in 2017 (MIIT 2017), which contain a large number of vehicles and detailed technical attributes of different vehicle models, such as the curb weight, all-electric range, battery capacity, electricity consumption rate and so on. Based on these catalogs, and the market prices as well as sales investigated, a large database covering all BEVs in the Chinese market was established, and the basic features of BEVs were analyzed in this study. The distribution of vehicles in the Chinese market is shown in Fig. 3, and this figure exhibits a skewed normal feature, which suggests that the BEVs in China are mainly small and midsize class vehicles. Moreover, with rapid progress in the development of battery technology, the driving range of electric vehicles in the Chinese market has increased. Notably, the minimum range of vehicles was 120 km in 2016 and 150 km in 2017.

Based on the distribution shown in Fig. 2, this study classified BEVs into six classes, namely A00, A0, A, B, C, and D, based on different glider weights, respectively, 800 kg, 1000 kg, 1200 kg, 1600 kg, 1800 kg and 2000 kg. The classification covers almost all mainstream BEVs in the Chinese market and the analysis based on that can reflect the trends of technologies and the market.

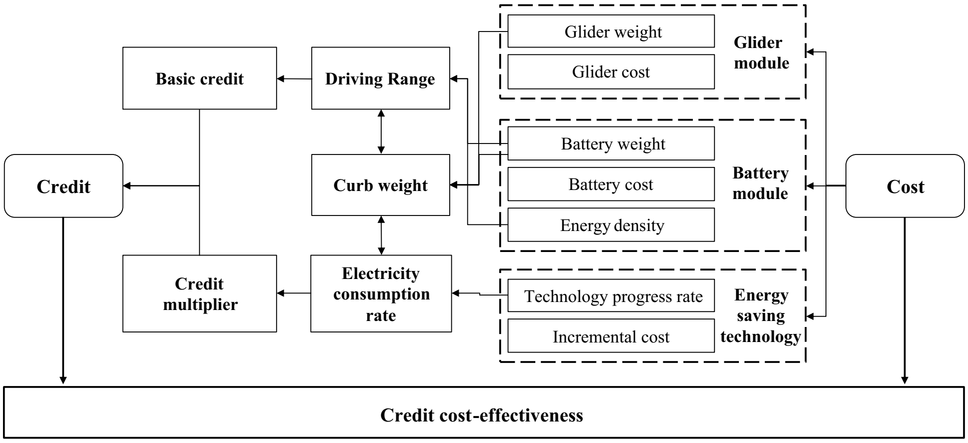


Fig. 1 Scope and accounting framework of this study

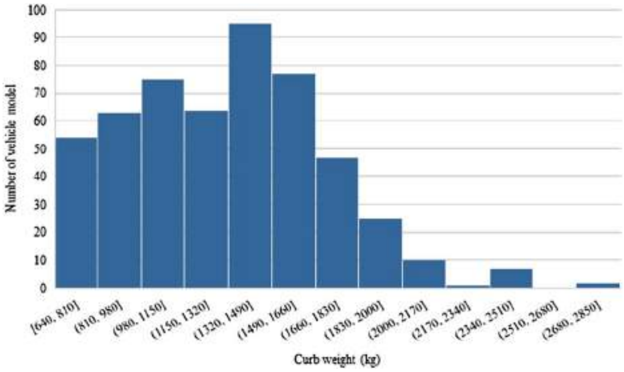


Fig. 2 Distribution of vehicle models in the Chinese market

NEV credit

The basic calculation framework of the credit

The final credit for vehicles in the NEV credit regulation scheme consists of a basic credit and a multiplier, which depends on the curb weight, battery weight, battery capacity, energy-saving technology, etc. According to the NEV credit scheme, the basic vehicle credit is determined by the electric range of BEVs, and the credit multiplier is determined by the electricity consumption rate. The credit calculation methods are shown in Eqs. (1)–(3):

$$\mathrm{CS} = 0.012 \times \mathrm{AER} + 0.8 \tag{1}$$

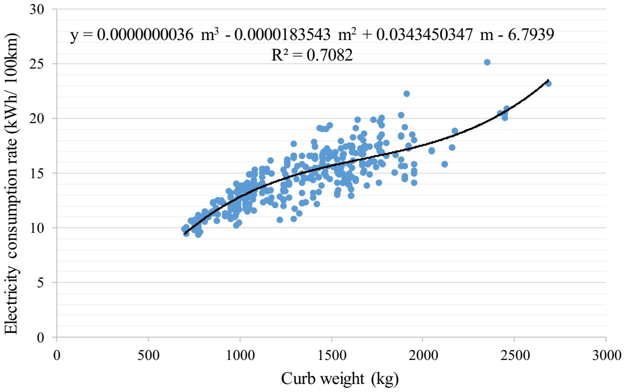


Fig. 3 Polynomial regression of the electricity consumption rate and curb weight for the Chinese BEV market in 2017

Battery sizing methodology

For BEVs with different glider weights, the curb weight is determined by the weight of the battery, and battery matching depends on the battery density. Furthermore, the driving range depends on the electricity consumption rate (Y) and the battery capacity, which is determined by the battery density and battery weight. The relationship among the electricity consumption, capacity of the battery, weight and the electric range is shown in Eqs. (4)–(6):

$$m_\mathrm{b} = m - m_\mathrm{g} \tag{4}$$

$$\alpha = \begin{cases} \begin{cases} 1.2, & Y \le 0.7 \times (0.014 \times m + 0.5) \\ 1, & 0.7 \times (0.014 \times m + 0.5) < Y \le 0.014 \times m + 0.5 \\ 0.5, & Y > 0.014 \times m + 0.5 \end{cases} & m \le 1000 \\ \begin{cases} 1.2, & Y \le 0.7 \times (0.012 \times m + 2.5) \\ 1, & 0.7 \times (0.012 \times m + 2.5) < Y \le 0.012 \times m + 2.5 \\ 0.5, & Y > 0.012 \times m + 2.5 \end{cases} & 1000 \le m \le 1600 \\ \begin{cases} 0.2, & Y \le 0.7 \times (0.005 \times m + 13.7) \\ 1, & 0.7 \times (0.005 \times m + 13.7) < Y \le 0.005 \times m + 13.7 \\ 0.5, & Y > 0.005 \times m + 13.7 \end{cases} & m \ge 1600 \end{cases} \tag{2}$$

$$C = \mathrm{CS} \times \alpha \tag{3}$$

where CS denotes the basic credit, AER (based on the mode method of the NEDC cycle) denotes all-electric range of the vehicle (km), α denotes the credit multiplier, Y denotes the electricity consumption rate of BEVs (kWh/100 km), m denotes the curb weight of the vehicle (kg), and C denotes the final credit of the vehicle. As mentioned above, the driving range of a BEV cannot be less than 100 km; otherwise, the vehicle will not receive the credit.

$$C_\mathrm{b} = \rho \times m_\mathrm{b} \tag{5}$$

$$\mathrm{AER} = \frac{C_\mathrm{b}}{1000 \times Y} \times 100 \tag{6}$$

where m_b denotes the weight of the battery (kg), m_g denotes the weight of the glider (kg), ρ denotes the energy density of the battery (Wh/kg), and C_b denotes the capacity of the battery (Wh).

In addition, the electricity consumption rate depends heavily on the curb weight, and the energy-saving technologies influence the final results (Hao et al. 2017). However, little research has elucidated the relationship between the electricity consumption rate and the curb weight of BEVs. Due to vehicle model and data limitations, the United States Environmental Protection Agency (US EPA) previously used a polynomial regression formula derived from the model year 2008 vehicles to estimate all conventional light-duty vehicle fuel economy trends, characterize the relationship between the curb weight and fuel economy, and convert the fuel economy to gross energy consumption to estimate the values for BEVs (EPA 2016; EPA & NHTSA 2016). However, the data the EPA used are old, and the regression formula is not precise for BEVs.

Almost all global BEV manufacturers have entered the Chinese BEV market due to the electric vehicle boom in recent years, with large quantities of BEVs being produced and sold. In this study, the data from the Chinese BEV market in 2017 are derived from the catalogs of NEVs exempted from purchase taxes and NEVs that are subsidized. Based on the data, the average level of energy-saving technology implementation and the relationship between the electricity consumption rate and the curb weight in China's BEV market can be derived, as shown in Fig. 3. For BEVs with a maximum speed that less than 120 km/h, the electricity consumption rates are relatively low, as they cannot reach the maximum speed in the NEDC test (SAC 2017). However, currently, most large BEVs in China, with curb weight greater than 2300 kg, are multi-purpose vehicles (MPVs), and the energy-saving technology employed is laggard. Therefore, in this study, a cubic polynomial regression is used to derive the relationship. The regression formula is shown in Eq. (7).

$$Y = 0.0000000036 \cdot m^3 - 0.0000183543 \cdot m^2 + 0.0343450347 \cdot m - 6.7939 \tag{7}$$

All the coefficients in Eq. (7) represent the average level of energy-saving technology employed in the Chinese BEV market in 2017. Figure 3 presents the trendline of the average electricity consumption rate of BEVs in the 2017 Chinese market. Note that the industry-wide average multiplier of BEVs in 2017 was 1.

Furthermore, to predict the relationship in the near future, a conservative annual technological progress rate of 3% was established for China. According to the fuel economy and greenhouse gas emission standards of America and Europe (ICCT 2013; EPA 2016), technological progress rates between 3 and 6% are reasonable, so a conservative scenario is used in this study. In addition, two scenarios, one with and one without future energy-saving technological progress, are established to assess the influence of energy-saving technology.

For a BEV with a certain gilder weight and range, the levels of energy-saving technology and battery technology implementation determine the average battery matching level, and the results can be obtained via an iterative procedure.

Vehicle cost

The total vehicle cost consists of the basic glider cost, battery cost, and the incremental energy-saving technology cost based on the electricity consumption rate.

Glider cost

As with the analysis of the US EPA, the costs of BEVs are separated into battery and non-battery costs, namely, the glider cost, in this study. However, because of BEV model and data limitations, the US EPA simply estimated the costs of battery and non-battery systems based on several BEVs in different classes and studied the direct manufacturing costs versus the mass cost reduction according to linear regressions (EPA 2016). Therefore, it is necessary to calculate the glider costs of BEVs more accurately. Vyas et al. (2000) determined that the direct manufacturing costs and indirect costs included in the processes of manufacturing and selling vehicles. The indirect costs included research and development (R&D) and engineering, business-related costs, retail sales-related costs, etc., and the costs associated with profits are recovered by allocating the above costs to vehicles. The cost multipliers from the manufacturing cost to the manufacturer's suggested retail price (MSRP) for components manufactured internally and outsourced are 2.0 and 1.5, respectively. These multipliers are also used by the US EPA (2016).

For most Chinese original equipment manufacturers (OEMs), the reality is that the battery system is usually outsourced, with the retail price estimated at 1.5 times the manufacturing cost. Non-battery components are typically manufactured internally, and the retail price is estimated at 2 times the manufacturing cost. Based on the MSRP and parameters of all BEVs in the Chinese market, the relationship between the glider cost and glider weight is linearly fit, and the regression formula for the glider cost trendline is shown in Eq. (8):

$$c_g = 6.5625 \cdot m_g + 3769.063 \tag{8}$$

where c_g denotes the cost of the glider (US$).

Moreover, the learning curve factor is applied to the glider cost. The learning curve factor addresses the anticipated reduction in manufacturing costs that results from improvements in the product design or manufacturing process. According to the learning factor developed by the US EPA (EPA & NHTSA 2012), a fixed value of 3 percent per year is applied through 2030.

Battery cost

As the heart of BEVs, the battery influences the development of BEVs and the entire NEV industry. In the past several years, various types of batteries have been used in NEVs, such as a lead acid, nickel metal hydride (NiMH), lithium-ion, and fuel cell batteries (Dhameja 2002). Among them, the lithium-ion battery has considerably attention for applications in BEVs due to its excellent properties, such as a high energy density, high power density, low self-discharge rate, no memory effect, capacity to accept high charging and discharging rates, and other factors (Zhang 2007; Saw et al. 2013). The Chinese market for BEVs is also dominated by lithium-ion batteries.

According to the technological roadmap for energy saving and new energy vehicles in China (MIIT&SAE-China 2016), the battery pack densities and unit costs are shown in Fig. 4. The industry-wide unit cost of a battery pack will be reduced to \$156.25/kWh in 2020 and \$125/kWh in 2030, which is similar to the forecasts from major international agencies and analysts (IEA 2017; Nykvist and Nilsson 2015). All manufacturers are likely to based development on the battery technology roadmap and reach the goals in the following analysis because of the impetus of the government and the electric range requirements of customers.

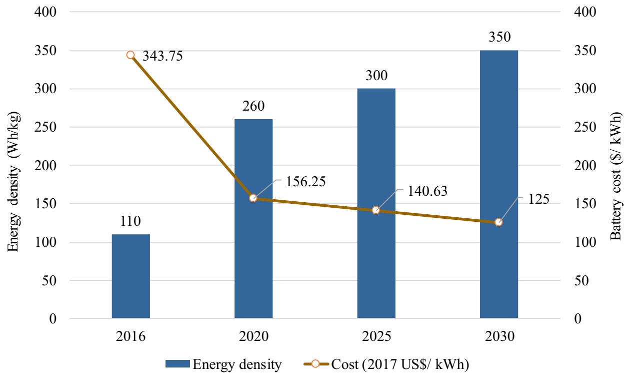


Fig. 4 Battery technology roadmap issued by the Chinese government

The relationship among the total battery cost, battery density and unit cost of the battery pack is shown in Eq. (9):

$$c_{\mathrm{b}} = \frac{m_{\mathrm{b}} \cdot \rho \cdot \tau}{1000} \tag{9}$$

where c_{b} denotes the total cost of the battery (\$) and τ denotes the unit cost of the battery pack (\$/kWh).

Incremental energy-saving technology cost

Table 3 presents the estimates of the incremental energy-saving technology costs associated with progressively reduced electricity consumption for a single BEV relative to the level in 2017. Differences exist in the technology cost per a given percentage improvement in electricity consumption for vehicles in different classes. The National Highway Traffic Safety Administration (NHTSA) estimated that the industry-wide average levels as approximately \$77 per % for passenger cars, \$95 per % for light trucks, and \$86 per % for the combined light-duty vehicle fleet (EPA & NHTSA 2016). Two main assumptions in this study are that the annual improvement in the electricity consumption rate and the technology cost per a given improvement in electricity consumption for certain class remain constant. Additionally, the cost is modified based on large quantities of BEVs from automakers in the Chinese market.

Credit cost-effectiveness and incremental credit cost-effectiveness

Credit cost-effectiveness

The credits and costs associated with all BEVs with different weights and ranges are calculated and compared based on

Table 3 Incremental energy-saving technology costs for different BEVs

Class	Glider weight (kg)	Technology cost per % electricity consumption improvement (\$/ %)	Incremental technology cost in 2020 (2017\$)	Incremental technology cost in 2025 (2017\$)	Incremental technology cost in 2030 (2017\$)
A00	800	70	609	1512	2289
A0	1000	75	652.5	1620	2452.5
A	1200	80	696	1728	2616
B	1600	90	783	1944	2943
C	1800	95	826.5	2052	3106.5
D	2000	100	870	2160	3270

the calculation framework to determine the optimal product features and technologies, as shown in Eqs. (10)–(11):

$$C_{ij} = CS_{ij} \cdot \alpha_{ij} \tag{10}$$

$$c_{ij} = c_{g,ij} + c_{b,ij} + c_{t_{es},ij} \tag{11}$$

where CS_{ij} denotes the basic credit for a vehicle with glider weight i and range j, α_{ij} denotes the credit multiplier for glider weight i and range j, and C_{ij} denotes the final credit for a vehicle with glider weight i and range j. Similarly, $c_{g,ij}$ denotes the glider cost ($), $c_{b,ij}$ denotes the battery cost ($), $c_{t_{es},ij}$ denotes the energy-saving technology cost ($), and c_{ij} denotes the total cost of a vehicle with glider weight *i* and range *j* ($).

Additionally, the credit cost-effectiveness is defined as the NEV credit for a unit cost in this study, as shown in Eq. (12):

$$\mathrm{CE}_{ij} = \frac{1000 \cdot C_{ij}}{c_{g,ij} + c_{b,ij} + c_{t_{es},ij}} \tag{12}$$

where CE_{ij} denotes the credit cost-effectiveness for vehicles with glider weight *i* and range *j* (credit/$1000). The subsequent results are used to determine the most economic technology pathway for receiving credits.

Incremental credit cost-effectiveness

In reality, when BEVs employ more advanced energy-saving technologies, the cost of the battery will be reduced because it will consume less electricity. The amount of reverse benefit can determine the strategy of energy-saving technology implementation in the future.

In this study, the incremental cost is defined as the difference in the total cost with and without improvements in energy-saving technology, as shown in Eq. (13):

$$\Delta c \ = \ c_n^{\mathrm{T}} - c_n^0 \tag{13}$$

where c_n^0 denotes the total cost in year *n* without an improvement in energy-saving technology ($) and c_n^{T} denotes the total cost in year *n* with an improvement in energy-saving technology ($). Moreover, a negative incremental cost indicates that the reduced battery cost associated with the application of energy-saving technology is greater than the increased cost of the energy-saving technology.

The incremental credit cost-effectiveness is defined as the incremental NEV credit related to the unit incremental cost relative to that of the baseline scenario. When the incremental cost is positive, the incremental credit cost-effectiveness is calculated by Eq. (14).

$$\mathrm{ICCE}_p = \Delta C / \Delta c \tag{14}$$

When the incremental cost is negative, the incremental credit cost-effectiveness is calculated by Eq. (15). This scenario is preferred because the application of energy-saving technology not only reduces the total cost but also yields credit.

$$\mathrm{ICCE}_n = \Delta C \cdot \Delta c \tag{15}$$

In this equation, ΔC denotes the incremental credit, namely the difference between the final credit in the two scenarios; ICCE_p is the positive incremental credit cost-effectiveness (credit/$); and ICCE_n is the negative incremental credit cost-effectiveness (credit·$). The larger the value of ICCE_p is, the higher the benefit obtained by the application of energy-saving technology. Additionally, the larger the absolute value of ICCE_n is, the higher the reverse benefit obtained by the application of energy-saving technology.

Results and discussion

To predict and assess the product and technological trends of BEVs under the new NEV credit scheme, two scenarios, one with and one without improvements in the electricity consumption rate in the future, are established. The BAU scenario reflects the total cost and cost-effectiveness of different BEVs without improvements in the electricity consumption rate. Furthermore, the alternative scenario reflects the total cost and cost-effectiveness with improvements in the electricity consumption rate. The impact of energy-saving technology can be assessed by comparing these scenarios. Moreover, the preferred vehicle class and driving range of BEVs under the NEV credit regulation scheme will be estimated.

BAU scenario

Figure 5 presents the battery weights of BEVs with different gliders ranging from 600 to 2400 kg and different driving ranges ranging from 100 km to 500 km under the 2020 BAU scenario. For the vehicles with low driving ranges,

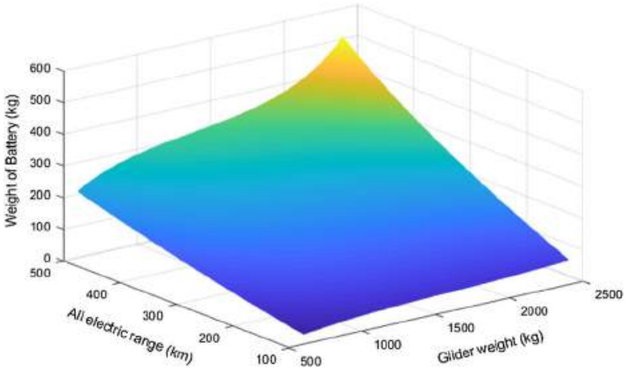


Fig. 5 Battery weight in 2020 under the BAU scenario

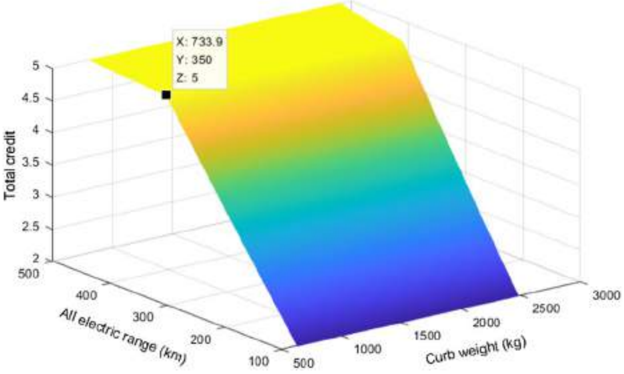


Fig. 6 Final credit in 2020 under the BAU scenario

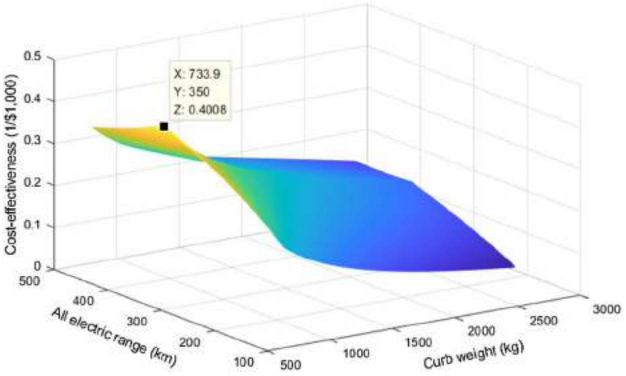


Fig. 7 Credit cost-effectiveness in 2020 under the BAU scenario

the vehicle class has a small effect on the weight of the battery. The battery weight increases with the vehicle class and the driving range and when the glider weight is more than 2000 kg. When the driving range is higher than 400 km, the battery weight sharply increases.

Figure 6 shows the final credits for BEVs with different gliders and driving ranges under the 2020 BAU scenario. As mentioned above, the industry-wide average multiplier of BEVs in 2017 is 1. Without improvements in the electricity consumption rate, the industry-wide average multiplier will always be 1, and the credit is only determined by the driving range. Therefore, the credits acquired in 2025 and in 2030 under the BAU scenario are the same as that in 2020.

Figure 7 shows the credit cost-effectiveness of BEVs with different gliders and driving ranges under the 2020 BAU scenario. As is shown in the figure, the smaller the vehicle is, the higher the credit cost-effectiveness, which is one of the reasons why the Chinese BEV market has witnessed a mini-electric vehicle boom. Moreover, 350 km is the optimal driving range for vehicles under the NEV credit regulation, and both larger and smaller ranges exhibited lower cost-effectiveness. Therefore, to some degree, the development of BEVs with other ranges will be limited by the regulation.

Additionally, the credit cost-effectiveness trends in 2025 and 2030 under the BAU scenario are similar to that in 2020, but these trends will increase with time due to progress in battery technologies.

Alternative scenario

The battery matching in 2020, 2025 and 2030 under the alternative scenario is presented in Fig. 8a–c. Under the same level of battery technology implementation, the battery weight is sharply reduced with improvement in energy-saving technology compared to that in the BAU scenario.

As Fig. 8d–f shows, with improvements in the electricity consumption rate, the multiplier of a vehicle with a curb weight of 1500–2400 kg will increase from 1 to 1.2 in 2020; specifically, the BEVs in the B, C, and D classes will receive the highest credit of 6 for the first time, and the lowest credit among classes will be 2.4. In 2025, more BEVs will be able to receive a credit of 6. In 2030, the levels of all vehicles will be 1.2 times the level in 2020, and vehicles will receive the highest credit of 6 when the driving range is higher than 350 km.

The credit trend driven by regulation reflects the encouragement of midsize BEVs in the future prior to 2020. Still, the multiplier of mini-electric vehicle requires considerable progress to reach 1.2. Progress in energy-saving technology will be greatly propelled by the regulation prior to 2025, and after that, new incentive measures should be introduced.

Figure 8g–i presents the credit cost-effectiveness in 2020, 2025 and 2030 under the alternative scenario, and the results exhibit a step feature similar to that observed for the final credit. From the perspective of cost-effectiveness, mini-electric vehicles always have the largest credit cost-effectiveness, which indicates that they will be the most economical BEVs for OEMs to produce in the A00 and A0 classes under the NEV credit regulation. However, as noted above, small vehicles cannot earn a credit of 6 in the short term. It is worth mentioning that the cost-effectiveness of BEVs in the B class is larger than that of BEVs in the A class in 2020, and the BEVs in the A0 class have the highest cost-effectiveness in 2025.

Simultaneously, 350 km is still the optimal driving range for vehicles under the alternative scenario, which is different from the predictions of previous studies (Hao et al. 2014b; Ou et al. 2018) and the higher range is not always the better. The largest credit cost-effectiveness of BEVs in 2020, 2025 and 2030 is 0.4009, 0.4537 and 0.6038 points per $1000, respectively, all obtained at 350 km.

Benefit evaluation of energy-saving technology

Figures 9, 10 and 11 present the incremental credit cost-effectiveness between the BAU and alternative scenarios in

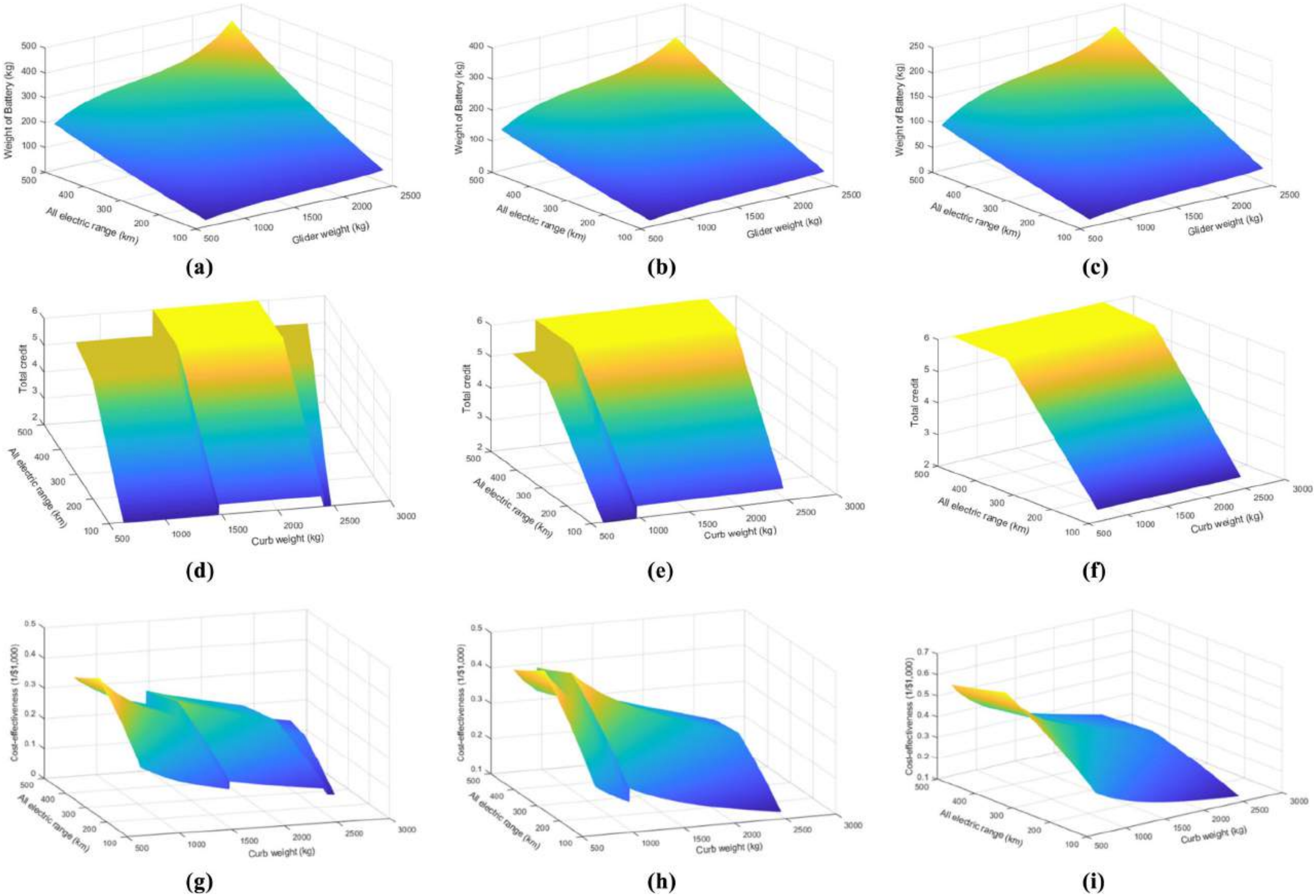


Fig. 8 **a**–**c** Battery weight in 2020, 2025 and 2030 under the alternative scenario; **d**–**f** Final credit in 2020, 2025 and 2030 under the alternative scenario; **g**–**i** Credit cost-effectiveness in 2020, 2025 and 2030 under the alternative scenario

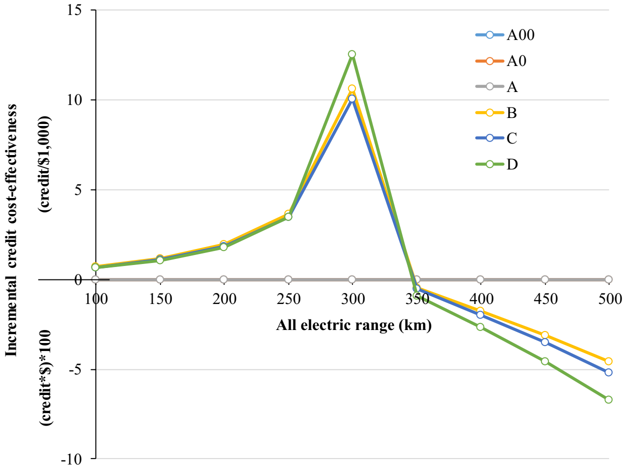


Fig. 9 Incremental credit cost-effectiveness between the BAU and alternative scenarios in 2020

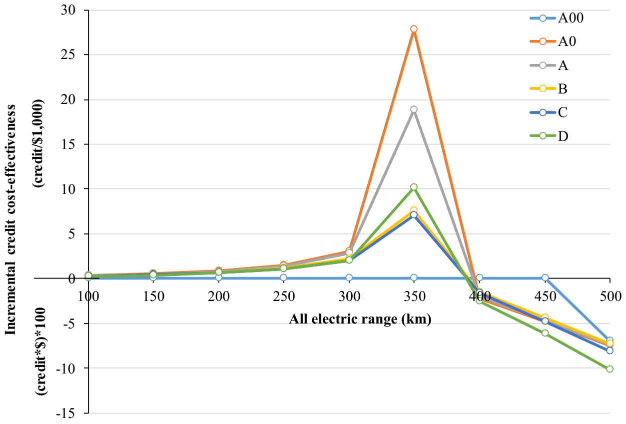


Fig. 10 Incremental credit cost-effectiveness between the BAU and alternative scenarios in 2025

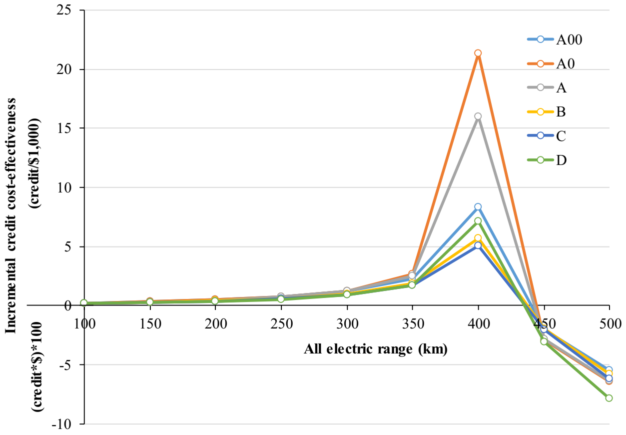


Fig. 11 Incremental credit cost-effectiveness between the BAU and alternative scenarios in 2030

2020, 2025 and 2030, respectively. The incremental credit cost-effectiveness reflects the effect of improvements in energy-saving technology, as mentioned above, by comparing the BAU and alternative scenarios. In many cases, although more energy-saving technology investment is required, the cost of batteries will be reduced due to the decrease in electricity consumption, which creates an extra benefit.

As Fig. 9 presents, the employment of advanced energy-saving technology (annual technology progress rate of 3%) in the B, C, and D classes will have a significant effect in 2020, and BEVs in the D class will receive the highest benefit. Moreover, when the driving ranges of these vehicles are greater than or equal to 350 km, an extremely large benefit will be obtained; therefore, the application of energy-saving technology will not only reduce the total cost but also lead to higher credits. Nevertheless, no effect will be gained by the employment of advanced energy-saving technology in the A00, A0 and A classes in 2020.

In 2025, the BEVs in the A0 and A classes will obtain the most significant benefit when the driving range is less than or equal to 350 km. When the range is greater than 350 km, the largest significant benefit will still be obtained by BEVs in the D class due to the sharp decrease in the battery weight.

In 2030, the most significant benefit will be gained by BEVs in the A0 and A classes when the range is 400 km. Similar to the trends in 2020 and 2025, when the range is greater than 400 km, the largest significant benefit will be obtained by the BEVs in the D class; therefore, energy-saving technology is most suitable for application to large BEVs with large ranges. However, when the driving range is 350 km or 400 km after 2020, energy-saving technology will be the most cost-effective for implementation in BEVs in the A0 and A classes. Moreover, the policies, especially the credit allocation, show a great influence on the benefit of technology and the preference of vehicles.

Policy implications

The NEV credit regulation is considered a milestone for the development of the Chinese automobile market, a promoter of the development of NEVs, and a revolutionary change for the Chinese energy structure (Liu et al. 2018). It is widely believed that the regulation will dramatically accelerate the pace of vehicular electrification in China and even worldwide (Ou et al. 2017), which will initiate the deep changes in the energy matrix. As promising technologies for addressing oil security, air pollution, and greenhouse gas emissions, NEVs will transfer part or all of the input from the use of gasoline or diesel to grid electricity. Therefore, with the penetration of electric vehicles, the consumption of oil is going to be gradually reduced. During this process, policies will not only influence the speed of technological innovation but also determine the direction of clean technologies.

Compared with previous studies, this paper focuses on calculations associated with the most recent NEV credit regulation in China and estimates the related impacts on BEV technologies from the perspective of credit cost-effectiveness. This approach fills a major gap in existing studies. Based on the latest data from the Chinese electric vehicle market, the trends in the electricity consumption rate, manufacturing cost and technical parameters of BEVs are derived and estimated in a more accurate way than in previous studies. For instance, because of data limitations, the US EPA estimated the relationship between the electricity consumption rate and the curb weight of BEVs using the trendline of all conventional fuel economy light-duty vehicles derived from MY 2008 vehicles and converted the fuel economy to electricity consumption (EPA 2016; EPA & NHTSA 2016); however, this approach is not suitable for current BEVs.

Different from the existing studies, from the interpretation of the NEV credit regulation and the analysis of different scenarios, we find that the regulation benefits midsize BEVs in the short term and small BEVs in the long term. Under the NEV credit regulation, midsize BEVs will obtain the highest credit of 6 first in 2020. Compared to small BEVs, midsize BEVs have greater potential to employ advanced technology and will further promote the development of technology in the early stage. However, the results also show that mini-electric cars will always be the most credit cost-effective passenger cars under the regulation. Moreover, miniaturization is one of the most important trends to reduce vehicle resource waste (Zhang et al. 2009). In this regard, mini-BEVs will be preferential in the long term.

Additionally, developments in energy-saving technology and battery technology are becoming increasingly important under the NEV credit regulation. Improvements in battery technology will reduce the battery weight and increase the driving range, thereby leading to higher credits. Moreover, improvements in energy-saving technology will directly decrease the electricity consumption rate of BEVs and lead to higher credit multipliers. In addition, the weight and cost of batteries can be reduced, which can lead to benefits such as reducing the total cost and gaining more credit. However, the regulation will face the risk of losing the effect of promoting energy-saving and battery technology because all vehicles will obtain the same multiplier of 1.2 after 2025 based on our conservative estimate; therefore, all vehicles will receive the highest credit value of 6 when the range is higher than 350 km.

In addition, our estimation shows that the optimal driving range under the NEV credit regulation is 350 km, which shows that the higher driving range is not always the better under credit regulation. Larger or smaller ranges will all have lower cost-effectiveness than that observed for a range of 350 km. In this regard, the regulation will limit the development of BEVs with other ranges in the future. Additionally, the NEV credit regulation scheme only extends through 2020 and is undefined after that.

From the government's perspective, policies can be developed in three major directions. First, it is necessary to establish long-term planning for the stable and orderly development of the Chinese vehicle market. Second, it is critical that the rationale for calculating credit regulations be modified after 2020 due to the risk of losing the promoting effects of energy-saving and battery technology in the long term. Third, it is appropriate to change the test cycle of BEVs from the NEDC to China Automotive Test Cycles (CATC), which has been researched since 2015 and will be issued in the near future (CATARC 2018). The evaluation of Chinese BEVs is still based on the NEDC test cycle. Numerous studies have shown that the electricity consumption in the NEDC cycle deviates from the actual driving cycle in China and is overestimated because the NEDC cycle is not suitable for evaluating energy recovery with start-stop technologies (Gong et al. 2017, 2018). The regulation based on the new test cycle will improve the robustness and reliability of guiding policies.

From the manufacturer's perspective, appropriate strategies should be implemented for the short and long terms. In the short term, midsize BEVs may be a good choice if credits are lacking for a given enterprise, as midsize vehicles can obtain the highest credit of 6. In the long term, mini-electric vehicles will have the highest credit cost-effectiveness and follow the miniaturization trend. More importantly, it is unwise to focus on battery technology and ignore the development of energy-saving technology in BEVs. The results show that investments in energy-saving technology will lead to larger incremental credit benefits, especially in large-class vehicles with high ranges.

Conclusions

This paper focuses on the newly issued NEV credit regulation in China and establishes a systematic bottom-up framework to estimate the effects on the technological trends of BEVs from the perspective of credit cost-effectiveness. By developing and comparing BAU and alternative scenarios, the optimal vehicle class and driving range, as well as the benefits of energy-saving technology, are estimated at different times through 2030. Compared with existing studies, this paper fills a research gap regarding the effects of technology based on the latest NEV credit regulation. The market structure and the key parameters of BEVs are derived, with technological trends well reflected by employing the most up-to-date data from the entire Chinese BEV market.

The study suggests that small BEVs will always be associated with the highest credit cost-effectiveness and that 350 km will be the optimal range under the NEV credit regulation. Even with an annual improvement in the electricity consumption rate of 3%, a conservative value, midsize BEVs will benefit the most before 2020 and can receive the highest NEV credit of 6 when the range is higher than 350 km. After 2020, BEVs in the A00, A0 and A classes will again be prioritized.

The study also shows that the regulation will greatly promote the short-term development of energy-saving and battery technologies. The investment in energy-saving technology will lead to reductions in battery costs and higher credits, especially for large-class vehicles with high ranges. In some cases, the employment of energy-saving technology can even reduce the total cost and lead to higher credits. However, the regulation will face the risk of losing the associated promotional effect on energy-saving and battery technologies because all vehicles will reach the same multiplier of 1.2 after 2025 or even earlier, and all vehicles with ranges higher than 350 km will equally receive the highest credit.

This study concentrates on evaluating the regulation and estimating the impacts on technological trends. Notably, the final production trends not only depend on the regulation but are also influenced by the choices of consumers. In this regard, the effect of consumer choices on BEV production trends should be considered in future studies.

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