

Article

Energy and Environmental Impact of the Promotion of Battery Electric Vehicles in the Context of Banning Gasoline Vehicle Sales [†]

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Abstract: This study quantitatively estimates the energy and environmental impacts of China's promotion of battery electric vehicles (BEVs) in the context of banning the sale of gasoline vehicles (GVs). Combining the population ecological growth model and the life cycle assessment method, the potential of BEVs promotion in reducing fossil energy (FE) consumption and greenhouse gas (GHG) emissions under different timings of banning GV sales was dynamically simulated and analyzed. The results show that the current life cycle FE consumption and GHG emissions of BEVs are approximately 40.1% and 26.6% lower than those of GV, respectively. Based on the development of automobile technology and the national energy plan, replacing GV with BEVs can reduce GHG emissions and FE consumption by up to 43.61–55.81% and 46.33–55.45%, respectively. Compared with the scenario without BEV promotion, if sales of GV in China are banned between 2040 and 2060, the point at which the carbon peak of the automobile market will be reached will be advanced by approximately two years, and the corresponding carbon peak value will be reduced by approximately 13.58–28.79 million tons of CO₂-eq (MtCO₂e). In addition, the annual FE savings and GHG emission reductions will reach approximately 2.99–6.35 million TJ and 276.54–488.77 MtCO₂e by 2050. This research work will not only help authorities, managers, and the public to better understand the environmental and energy impacts of promoting new energy vehicles, but also provide a forward-looking reference for formulating comprehensive, systematic, and reasonable industrial planning to better promote a green and sustainable transformation of the automotive sector and solve the relevant energy and environmental problems.

Keywords: banning sales of gasoline vehicles; battery electric vehicles; sustainability; population growth model; life cycle assessment; energy conservation; climate change; carbon peak



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1. Introduction

A global consensus has been reached on speeding up the green and sustainable transformation of the transportation sector to alleviate the increasingly severe energy and environmental issues [1–4]. As a promising way to reduce FE consumption and GHG emissions, the promotion of new energy vehicles (NEVs) has become an irreversible global trend [5–7]. Countries and regions around the world are committing to developing electric vehicles and vehicles powered by other alternative fuels (e.g., compressed natural gas, liquified natural gas, hydrogen, methanol, methane, dimethyl ether, and bioethanol) [8–12].

The development of the NEVs industry is of great significance to China's energy security and the structural adjustment of the automobile industry. Currently, China is the world's second-largest oil consumer [13,14] and the largest oil importer [15,16]. In 2021, China's net oil import was 513 million tons, and the corresponding oil import dependence was approximately 72.05% [17]. Huge oil consumption and a high degree of dependence

on oil imports seriously threaten China's national energy security. Since approximately half of China's oil consumption is attributed to the use of automobiles, the development of NEVs is an important way to alleviate China's energy problems.

At this critical moment in addressing the challenges of global climate change, the Chinese government has set a "dual carbon" goal of reaching a carbon peak by 2030 and becoming carbon neutral by 2060 [18,19]. Currently, GHG emissions from the transportation sector account for approximately 15% of China's total GHG emissions, making it the third largest source of GHG emissions after industry and construction [20,21]. In the transportation sector, carbon emissions from automobiles account for approximately 75% [22]. Therefore, promoting the low-carbon development of the automobile industry is of great significance to achieving the goals of "carbon peak and carbon neutrality" [23,24].

Over the past decade, China has been pushing for the development of NEVs [25–27]. In 2021, China's NEV sales reached 3.334 million, accounting for nearly half of the world's total NEV sales [28]. More than 80% of the NEVs in China are BEVs [28]. From the perspective of market prospects and policy direction, BEVs will occupy a dominant position in China's NEV market for the foreseeable future [29–31].

Currently, academic research in the field of NEVs mainly focuses on industrial theories and policies, development paths, consumer behavior, technological innovations in vehicles and fuels, and comparisons with conventional fossil fuel vehicles in terms of vehicle performance, energy consumption, and environmental impact [32–36]. In order to better solve the problems concerning energy conservation, emission reduction, and the battery health of electric vehicles, scholars have also conducted a series of in-depth studies on energy management strategies and have proposed a variety of optimal control methods [37–39]. In addition, research on the modeling, forecasting, and analysis of the production and sales of NEVs has also been widely carried out [40,41]. However, little effort has been devoted so far to discussing the long-term energy and environmental impacts of promoting NEVs. The market evolution of NEVs is closely related to the government's overall industrial planning for NEVs, and its energy-saving and emission-reducing (ESER) potential also, in turn, depends on the energy structure and the technical level of vehicles and fuels.

Furthermore, the evolution of the NEVs industry is not isolated, but is rather a huge and complex system closely related to the national economy and people's livelihoods. For example, the upstream of the automobile industry chain involves electronics, machinery, metallurgy, and the chemical industry, among others, and the downstream involves transportation, logistics, leasing, and other related services and consumption fields. Therefore, it is necessary to assess the energy and environmental impact of promoting NEVs from the perspective of a long-term time span, which is conducive to optimizing and improving the industrial planning and layout at the macro level.

In particular, due to increasing environmental pressure, many countries in the world have formulated a timetable for banning gasoline vehicle sales (BGVS) [42]. However, little is known about the impact of this policy on the dynamic growth trend of the NEV market, and the potential effects on energy and the environment are still unclear.

With this in mind, based on the development of vehicle technology and national energy planning, this study employs a population growth model and life cycle assessment (LCA) method to systematically and deeply analyze the impact of the promotion of BEVs on China's FE consumption and GHG emissions. We attempt to answer the following two questions from the perspective of long-term dynamic development: what is the FE saving and GHG emission reduction potential of promoting BEVs, and how does the policy of BGVS contribute to the automobile industry's carbon peak and carbon neutrality goals? This research work can not only help authorities, operators, and the public to better understand the environmental and energy impacts of promoting NEVs, but also provide a forward-looking reference for formulating more effective measures to promote the healthy and sustainable development of NEVs and solve the relevant energy and environmental problems.

2. Materials and Methods

This study aimed to quantitatively estimate the ESER effect of China's promotion of BEVs in the context of banning GV sales. First, the life cycle GHG emissions intensity (GHGEI) and FE consumption intensity (FECI) of BEV and GV were estimated and compared using the LCA method. Then, the changes in the market scale of BEVs and GVs under different BGVS scenarios were simulated by a population ecological growth model. Finally, combined with the FECI and GHGEI of BEV and GV, and the number of BEVs and GVs under different BGVS scenarios, the annual FE consumption and GHG emissions from China's automobile market under different scenarios could be calculated. On this basis, the ESER effect of China's promotion of BEVs in the context of banning GV sales is further analyzed and discussed.

2.1. LCA Method

The energy and environmental impact assessment for China's BEV and GV industries in this study followed the standardized LCA framework and process provided by ISO [43,44]. The LCA modeling for BEV and GV was mainly based on the SimaPro 9.0 software and Ecoinvent 3.6 database. The system boundaries for LCA modeling are shown in Figure 1, which includes vehicle life cycle (VLC) and fuel life cycle (FLC). Considering that light-duty gasoline passenger cars account for 90% of China's automobile market [31,45], they were selected as the research object in this study to analyze the ESER potential of replacing GVs with BEVs. Therefore, the analysis of FLC needs to consider both gasoline and electricity. For the VLC of BEV and GV, the main inventory data and processes are summarized in Appendices A–C.

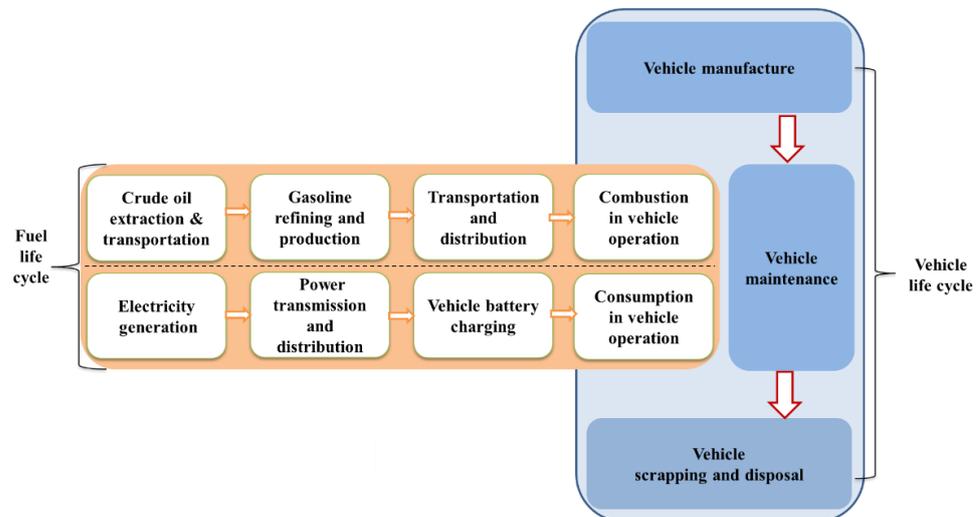


Figure 1. System boundary of LCA modeling for BEVs and GVs.

2.2. The Calculation of the Life Cycle GHGEI and FECI of BEVs and GVs

In this study, the kilometer (km) is used as the functional unit for comparative analysis, and the corresponding measurement unit for the life cycle GHGEI and FECI of BEVs and GVs are g CO₂-eq/km and MJ/km, as shown in Equations (1) and (2).

$$FECI_i = \frac{FECVL_i + FECFL_i}{LVKT_i} \quad (1)$$

$$GHGEI_i = \frac{GHGEVL_i + GHGEFL_i}{LVKT_i} \quad (2)$$

where i refers to the BEVs and GVs (i.e., vehicle type), FECI refers to the total life cycle (including FLC and VLC) FE consumption intensity of the vehicle, and GHGEI refers to the total life cycle (including FLC and VLC) GHG emissions intensity of the vehicle. FECVL

and FECFL refer to the FE consumption from the VLC and FLC, respectively. GHGEVL and GHGEFL refer to the GHG emissions from the VLC and FLC, respectively. LVKT refers to the life cycle vehicle kilometers traveled (VKT). The average annual VKT and lifespan of Chinese passenger cars are approximately 150,00 km and 10 years [46], respectively, which means that the average LVKT for GVs and BEVs in China is approximately 150,000 km.

The FECVL and GHGEVL can be obtained by the LCA modeling of the VLC, and the FECFL and GHGEFL can be calculated by Equations (3) and (4).

$$FECFL_i = FEV_i \times LVKT_i \times FECIF_j \quad (3)$$

$$GHGEFL_i = FEV_i \times LVKT_i \times GHGEIF_j \quad (4)$$

where i refers to the BEVs and GVs (i.e., vehicle type), and j refers to the gasoline and electricity (i.e., fuel type). FEV represents the fuel economy of the GVs and BEVs (i.e., L/100 km for gasoline-powered vehicles and kWh/100 km for electricity-powered vehicles). The FECIF and GHGEIF refer to the FE consumption and GHG emission intensity of the FLC for the automotive fuel (i.e., gasoline and electricity). For gasoline in China, the FECIF and GHGEIF are set to 1.268 MJ/MJ and 2.964 kg CO₂-eq/L, respectively [47]. For electricity, the FECIF and GHGEIF are obtained by Equations (5) and (6), respectively.

$$FECIF_{electricity} = FECIFP \times (1 - \beta)^{-1} \times (1 - \partial)^{-1} \quad (5)$$

$$GHGEIF_{electricity} = GHGEIFP \times (1 - \beta)^{-1} \times (1 - \partial)^{-1} \quad (6)$$

where GHGEIFP and FECIFP refer to the GHG emissions intensity (i.e., g CO₂-eq/kWh) and FE consumption intensity (MJ//kWh) during power production, respectively. ∂ refers to the power loss rate during power transmission and distribution, and β refers to the power loss rate of BEVs power battery during charging. In this study, ∂ and β are set to 5.9% and 9.5%, respectively [48,49]. In addition, FECIFP and GHGEIFP in China can be obtained by Equations (7) and (8), respectively.

$$FECIFP = \sum FECIFP_\gamma \times S_\gamma \quad (7)$$

$$GHGEIFP = \sum GHGEIFP_\gamma \times S_\gamma \quad (8)$$

where γ refers to the type of power source, and S_γ refers to the proportion of the power source γ . Figure 2 presents China's power generation structure in 2020. In addition, $FECIFP_\gamma$ and $GHGEIFP_\gamma$ are presented in Table 1.

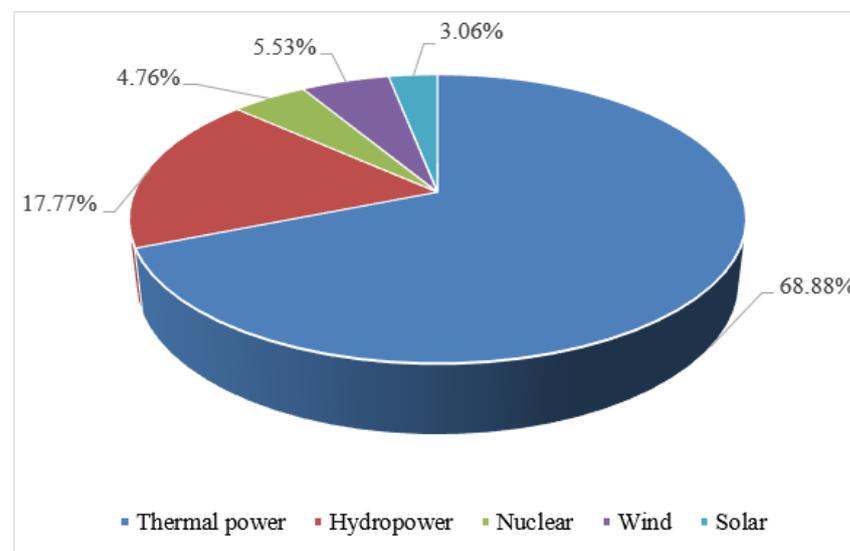
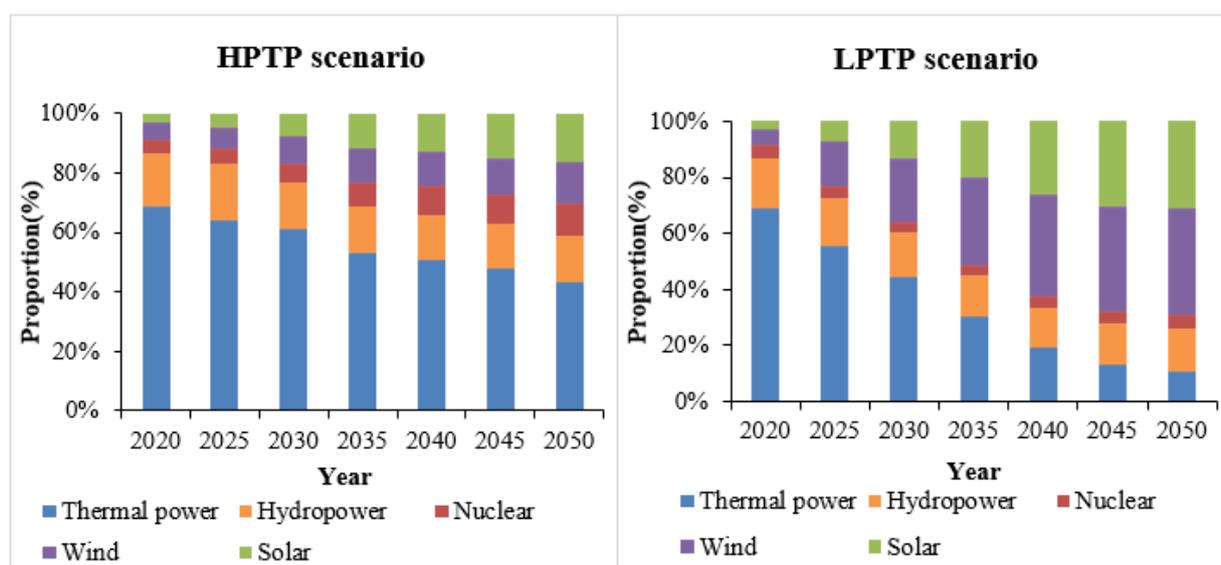


Figure 2. China's power generation structure in 2020 [50].

Table 1. The FECIFP and GHGEIFP of power production in China [51,52].

| | FECIFP (MJ/kWh) | GHGEIFP (g CO ₂ -eq/kWh) |
|---------------------------------|-----------------|-------------------------------------|
| Coal-fired thermal power (CFTP) | 8.97 | 891.5 |
| Hydropower | 0.001 | 18.36 |
| Nuclear power | 0.23 | 23.42 |
| Solar power | 3.42 | 143.56 |
| Wind power | 0.17 | 7.20 |

Considering that the ESER effect of BEV depends on electricity production, two power development scenarios were used to further explore the ESER effect of promoting BEVs in China: the high-proportion thermal power (HPTP) scenario and the low-proportion thermal power (LPTP) scenario (see Figure 3).

**Figure 3.** China's power development scenarios [53].

For the HPTP scenario, the proportion of CFTP is expected to drop to approximately 60% in 2030 and approximately 45% in 2050 [54,55]. As for the LPTP scenario, the proportion of CFTP will decrease to around 45% in 2030 and 11% in 2050 [56,57]. In addition, the FECIFP and GHGEIFP of CFTP production in China will decrease to 8.79 MJ/kWh and 873.92 g CO₂/kWh by 2030, and 8.13 MJ/kWh and 801.11 g CO₂/kWh by 2050 [54,58].

For the current FEV in China, the average FEV of BEVs is 15 kWh/100 km, while the FEV of GVs is approximately 7.8 L/100 km [59,60]. In addition, the FEV of BEVs can be expected to decrease to 12.0 kWh/100 km in 2025, 10.0 kWh/100 km in 2030, and 6 kWh/100 km in 2050 [59,60], and the FEV of GVs in 2020, 2030, and 2050 can be expected to decrease to 6.5, 5.8, and 4.0 L/100 km, respectively [59,60].

2.3. Population Growth Model and Simulation of Automobile Market Scale

This study employs the population ecological growth model to simulate the market evolution of BEVs and GVs in China. In population ecology, two typical population growth models are J-shaped and S-shaped. The J-shaped curve corresponds to the growth mode under ideal conditions. If the population is growing in an environment with abundant food (nutrients) and space conditions, no predators, and suitable climate, the population will grow continuously [61,62]. However, in reality, the resources and space in nature are limited. Therefore, the population cannot grow infinitely. When the population size reaches the maximum allowed by environmental conditions, it will stop growing, approximating an S-shaped growth curve [63,64]. The logistic curve, an S-shaped growth

curve named by Pierre Francois Viller [63,64], has been widely used to study population growth, technology diffusion, and product promotion and has achieved good application effects [65–67]. Therefore, we use it to simulate the development trend of the BEV and GV markets in China.

In the study of the market diffusion of products, the differential equation for the logistic growth curve can be described as shown in Equation (9).

$$\frac{dx}{dt} = kx(A - x) \quad (9)$$

where A refers to the market maximum capacity value, and x refers to the value of the market scale at time t . The growth rate of the market scale (i.e., $\frac{dx}{dt}$) is proportional to the product of the market scale (i.e., x) and the degree to which it is close to the saturation level (i.e., $A - x$). The proportional coefficient is denoted as k .

$x(t)$ can be solved by integrating the following Equation (9):

$$x(t) = \frac{A}{1 + Be^{-Ct}} \quad (10)$$

where B and C are positive constants, which can be determined by the initial conditions. Based on the actual data of China's automobile market from 1985 to 2017 (see Appendix D), the nonlinear least square method (NLS) and SPSS 26.0 software were used to estimate the value of A , B , and C .

2.4. The Annual FE Consumption and GHG Emissions from China's Automobile Market

The annual FE consumption (AFEC) and annual GHG emissions (AGHGE) from China's automobile market can be estimated by Equations (11) and (12).

$$APEC = MS_{BEV} \times VKT \times FECEI_{BEV} + MS_{GV} \times VKT \times FECEI_{GV} \quad (11)$$

$$AGHGE = MS_{BEV} \times VKT \times GHGEI_{BEV} + MS_{GV} \times VKT \times GHGEI_{GV} \quad (12)$$

where MS refers to the market scale of BEVs or GVs, which can be calculated by the population growth model. VKT refers to the average annual vehicle kilometer traveled (i.e., 15,000 km). In addition, $FECEI$ and $GHGEI$ can be obtained by Equations (1)–(8).

Based on the above methods and materials, the ESER effect of China's promotion of BEVs under different scenarios can be compared and analyzed.

3. Results

3.1. The Life Cycle GHGEI and FECEI of BEV and GV

The FECEI and GHGEI of BEV and GV under China's current electric power mix and vehicle fuel economy are presented in Figure 4. As for the FECEI and GHGEI of GVs, the FLC and the VLC account for approximately 84% and 16%, respectively. For the full life cycle of BEV, the FECEI and GHGEI from the VLC account for approximately 38%, while the FECEI and GHGEI from the FLC account for approximately 62%. Although the additional battery equipment makes the FECEI and GHGEI of BEVs during the VLC greater than that of GVs, the FECEI and GHGEI of BEVs from FLC are significantly lower than those of GV. The FECEI and GHGEI of BEV are approximately 2.17 MJ/km and 197.35 CO₂-eq/km, respectively. Compared with GV, BEV could reduce the GHG emissions intensity by approximately 26.6%, a reduction of 71.52 g CO₂-eq/km. As for FEC, the FECEI of BEV is approximately 40.1% lower than that of GV, a decrease of 1.45 MJ/km.

Based on the changes in vehicle fuel efficiency and China's energy planning, the FECEI and GHGEI of future BEVs and GVs were further calculated and compared. The detailed results are shown in Figures 5 and 6. It can be seen that the potential of BEV in ESER will gradually increase.

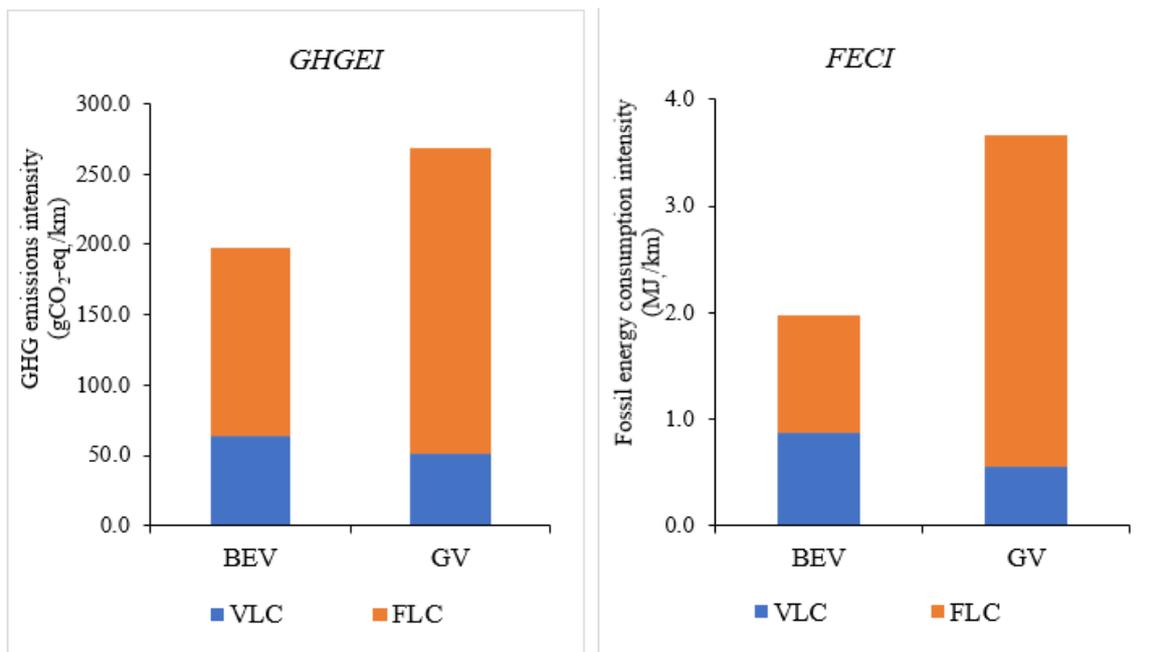


Figure 4. FECI and GHGEI under the current power structure.

For GVs, the GHGEI could be reduced to approximately 207.33 g CO₂-eq/km by 2030 and 162.57 g CO₂-eq/km by 2050, while the FECI could be reduced to 2.75 MJ/km by 2030 and 2.12 MJ/km by 2050.

Under the HPTP scenario, the GHGEI of BEV could be reduced to approximately 133.81 g CO₂-eq/km (2030) and 91.67 g CO₂-eq/km (2050), and the FECI could be reduced to approximately 1.55 MJ/km (2030) and 1.14 MJ/km (2050). This shows that compared with using GV, using BEV can reduce GHG emissions by up to 35.46% in 2030 and 43.61% in 2050, and can also reduce fossil energy consumption by up to 43.69% in 2030 and 46.33% in 2050.

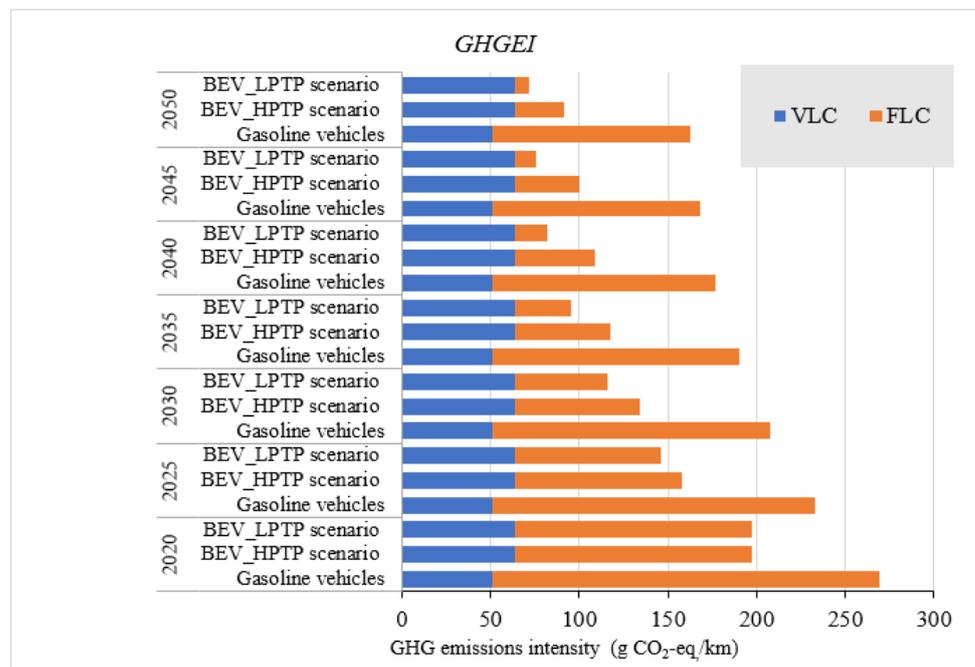


Figure 5. GHGEI of BEVs and GVs under different scenarios.

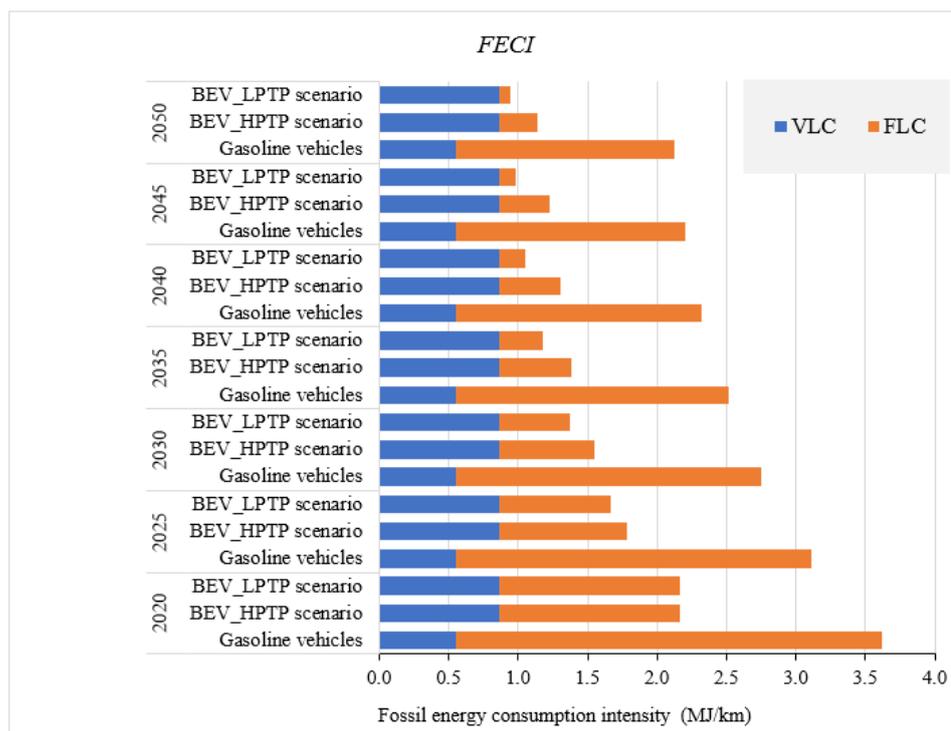


Figure 6. FECI of BEVs and GVs under different scenarios.

Under the LPTP scenario, the GHGEI of BEVs is expected to drop to 115.61 and 71.84 g CO₂-eq/km by 2030 and 2050, respectively. The FECI of BEVs would be 1.37 and 0.95 MJ/km by 2030 and 2050, respectively. In this case, using a BEV instead of a GV can reduce GHG emissions by up to 44.24% in 2030 and 55.81% in 2050 and reduce fossil energy consumption by up to 50.12% in 2030 and 55.45% in 2050.

In addition, it is worth noting that the proportion of the fuel life cycle will gradually decrease. For GVs, the share of the fuel life cycle will decline from around 80% in 2020 to around 70% in 2050. For the GHGEI of BEVs, the proportion of the fuel life cycle can be reduced from 67.87% in 2020 to 52.62% (low-proportion thermal power scenario) and 45.16% (HPTP scenario) in 2030, and to 30.84% (LPTP scenario) and 11.74% (HPTP scenario) in 2050. For the FECI of BEVs, the proportion of the fuel life cycle can be reduced from 60.00% in 2020 to 44.05% (LPTP scenario) and 36.83% (HPTP scenario) in 2030, and to 23.92% (LPTP scenario) and 8.33% (HPTP scenario) in 2050. It can be found that, from around 2030, VLC will become the primary source of the FC consumption and GHG emissions of BEVs.

3.2. Market Scale of BEVs and GVs

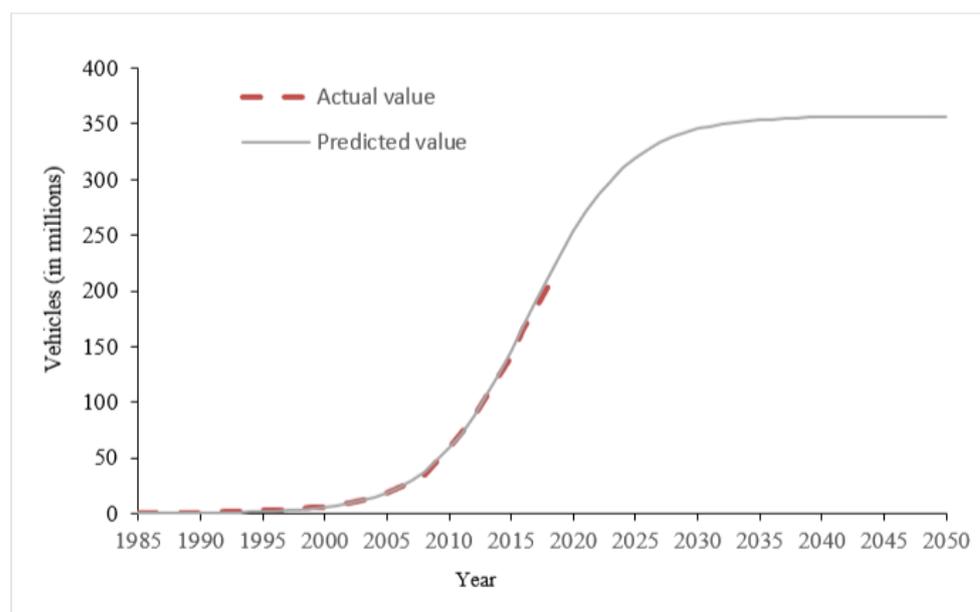
The estimated values of the parameters in the logistic equation are shown in Table 2. R² and the adjusted R² of the model are 0.986 and 0.951, respectively. All parameter values are significant at the 0.001 probability level (see Table 2). Table 3 and Figure 7 present the goodness-of-fit results for the obtained Logistic equation for China’s automobile market in this study.

Table 2. Estimated values and goodness-of-fit of the logistic equations.

| | Estimated Value | Significance (p-Value) |
|---|-----------------|------------------------|
| A | 35,691.60 | 0.001 |
| B | 3561.16 | 0.000 |
| C | 0.25 | 0.000 |

Table 3. The comparison of actual and estimated values.

| Year | Actual Value (in Millions) | Estimated Value (in Millions) | Error |
|------|-------------------------------|----------------------------------|-------|
| 2018 | 205.554 | 212.8365 | 3.54% |
| 2019 | 226.35 | 233.8661 | 3.32% |
| 2020 | 243.93 | 253.3203 | 3.85% |
| 2021 | 262.46 | 270.8309 | 3.19% |

**Figure 7.** The actual and predicted value of the overall scale of China's automobile market.

As shown in Table 3, considering that the prediction errors are all within 5%, this model can be used to simulate the development trend of the GV and BEV markets (see Figure 7). In addition, it can also be found from Figure 7 that the overall scale of China's automobile market (including GVs and BEVs) is expected to reach a maximum of 360 million vehicles.

Many countries across the world have formulated a timetable for BGVS [42]. Since China has not yet proposed a clear plan, in order to better explore the ESER potential of the promotion of BEVs, three scenarios were set up in this study, namely, banning GV sales in 2040, 2050, and 2060.

The market evolution of BEVs can be calculated and simulated based on the following assumptions: firstly, the maximum scale of China's automobile market is approximately 360 million. Second, since the lifespan of passenger cars is approximately 10 years in China [46], it can be assumed that the market share of BEVs will reach around 90% 10 years after the ban on the sale of GVs. Third, there were approximately 5 million BEVs in China in 2020 (i.e., the initial value at $t = 0$) [68,69]. Fourth, according to China's NEV Development Plan (2021–2035), the NEV sales will account for 20% of total new car sales in the entire automobile market [70]. Based on the given assumptions, we utilized the logistic equation (see Table 2 and Equation (10)) to estimate the changing trend of GVs and BEVs in the market scale under different BGVS scenarios in China, as shown in Figure 8.

If the sales of GVs are banned starting in 2060, the number of BEVs in China could reach 21.38 million in 2030, 79.38 million in 2040, and 201.26 million in 2050. If sales of GVs are banned starting from 2050 on, the market size of BEVs could rise to 33.93 million in 2030, 156.49 million in 2040, and 306.12 million in 2050. In particular, if China starts banning GV sales in 2040, the BEV market will reach 73 million by 2030 and 300 million by 2040. Under the scenario of banning GV sales from 2060 on, the market size of BEVs will

exceed that of GVs around 2049. When the time points for BGVS are set to 2050 and 2040, this critical point can be advanced to 2042 and 2035, respectively.

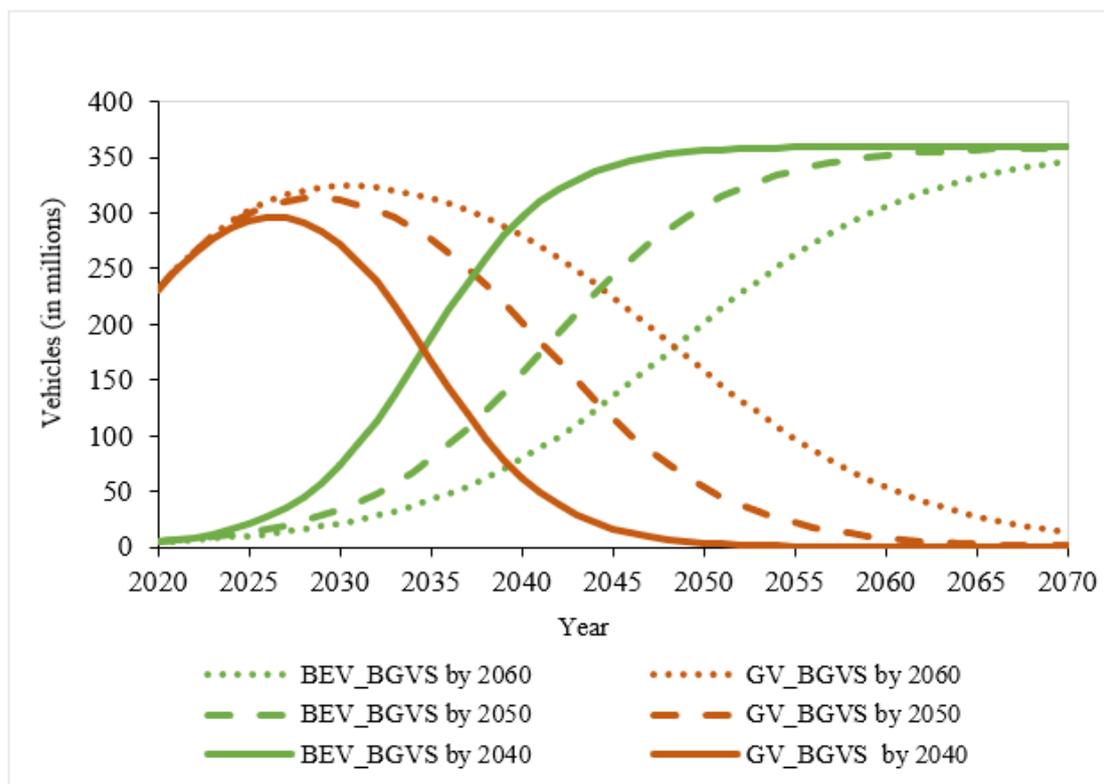


Figure 8. Market evolution of BEVs and GVs in China.

3.3. The ESER Effect of China's BEVs Promotion under Different BGVS Scenarios

Combined with the FECEI and GHGEI of BEVs and GVs in Section 3.1 and the development trends for BEVs and GVs in Section 3.2, the annual FE consumption and GHG emissions from China's automobile market under different scenarios can be calculated, as shown in Figures 9 and 10.

As shown in Figures 9 and 10, promoting BEV can significantly reduce FE consumption and GHG emissions from China's automobile market. If sales of GVs are banned starting in 2060, under a high-proportion thermal power scenario, annual GHG emission reductions can reach 24.33 million tons of CO₂-eq (MtCO₂e) in 2030, 83.14 MtCO₂e in 2040, and 214.94 MtCO₂e in 2050. The FE consumption can also be reduced by 0.40 million TJ in 2030, 1.24 million TJ in 2040, and 2.99 million TJ in 2050. Furthermore, under the LPTP scenario, annual GHG emission reductions can reach 30.35 MtCO₂e in 2030, 115.10 MtCO₂e in 2040, and 276.54 MtCO₂e in 2050. In addition, annual fossil energy consumption can be reduced by 0.46 million TJ in 2030, 1.56 million TJ in 2040, and 3.60 million TJ in 2050.

If the sale of GVs is banned from 2050 on, the annual reduction in fossil energy consumption by 2030 will reach 0.63 million TJ under the HPTP scenario and 0.72 million TJ under the LPTP scenario, and the annual GHG emissions reduction by 2030 can reach 38.47 MtCO₂e under the HPTP scenario and 48.02 MtCO₂e under the LPTP scenario. By 2040, the annual reduction in fossil energy consumption can reach 2.45 million TJ under the HPTP scenario and 3.06 million TJ under the LPTP scenario, and the annual reduction in GHG emissions can reach 163.48 MtCO₂e under the HPTP scenario and 226.48 MtCO₂e under the LPTP scenario. Furthermore, by 2050, the annual reduction in fossil energy consumption can reach 4.55 million TJ under the HPTP scenario and 5.47 million TJ under the LPTP scenario, and the annual reduction in GHG emissions can reach 326.72 MtCO₂e under the HPTP scenario and 420.50 MtCO₂e under the LPTP scenario.

In particular, if GV sales are banned from 2040 on in China, under the HPTP scenario, the annual reduction in GHG emissions can reach 82.86 MtCO₂e, 309.52 MtCO₂e, and 379.68 MtCO₂e in 2030, 2040, and 2050, respectively. The annual fossil energy savings can reach 1.36 million TJ, 4.64 million TJ, and 5.29 million TJ in 2030, 2040, and 2050, respectively. Furthermore, under the LPTP scenario, the annual emissions reduction can reach 103.47 MtCO₂e, 428.95 MtCO₂e, and 488.77 MtCO₂e in 2030, 2040, and 2050, respectively, and the annual fossil energy savings can reach 1.56 million TJ, 5.80 million TJ, and 6.35 million TJ in 2030, 2040, and 2050, respectively.

In addition, it can be found that without BEVs, the Chinese car market will reach its carbon peak in 2027, with a peak value of approximately 1124.23 MtCO₂e (see Figure 9). In the scenario of the promotion of BEVs, if the ban on the sale of GVs in China is set between 2040 and 2060, the carbon peak will be reached in 2025, and the corresponding carbon peak value could be approximately 1095.45–1110.65 MtCO₂e. Although the promotion of BEVs has no significant impact on the point in time at which the automobile market will reach its carbon peak, it can reduce the carbon peak value by approximately 13.58–28.79 MtCO₂e. In particular, after reaching the carbon peak, the promotion of BEVs shows significant potential for reducing FE consumption and GHG emissions.

It can also be found that, although there are significant differences in FE consumption and GHG emissions under different time points of BGVS, the impact of different time points of banning GV sales on the peak time of carbon emissions is not significant.

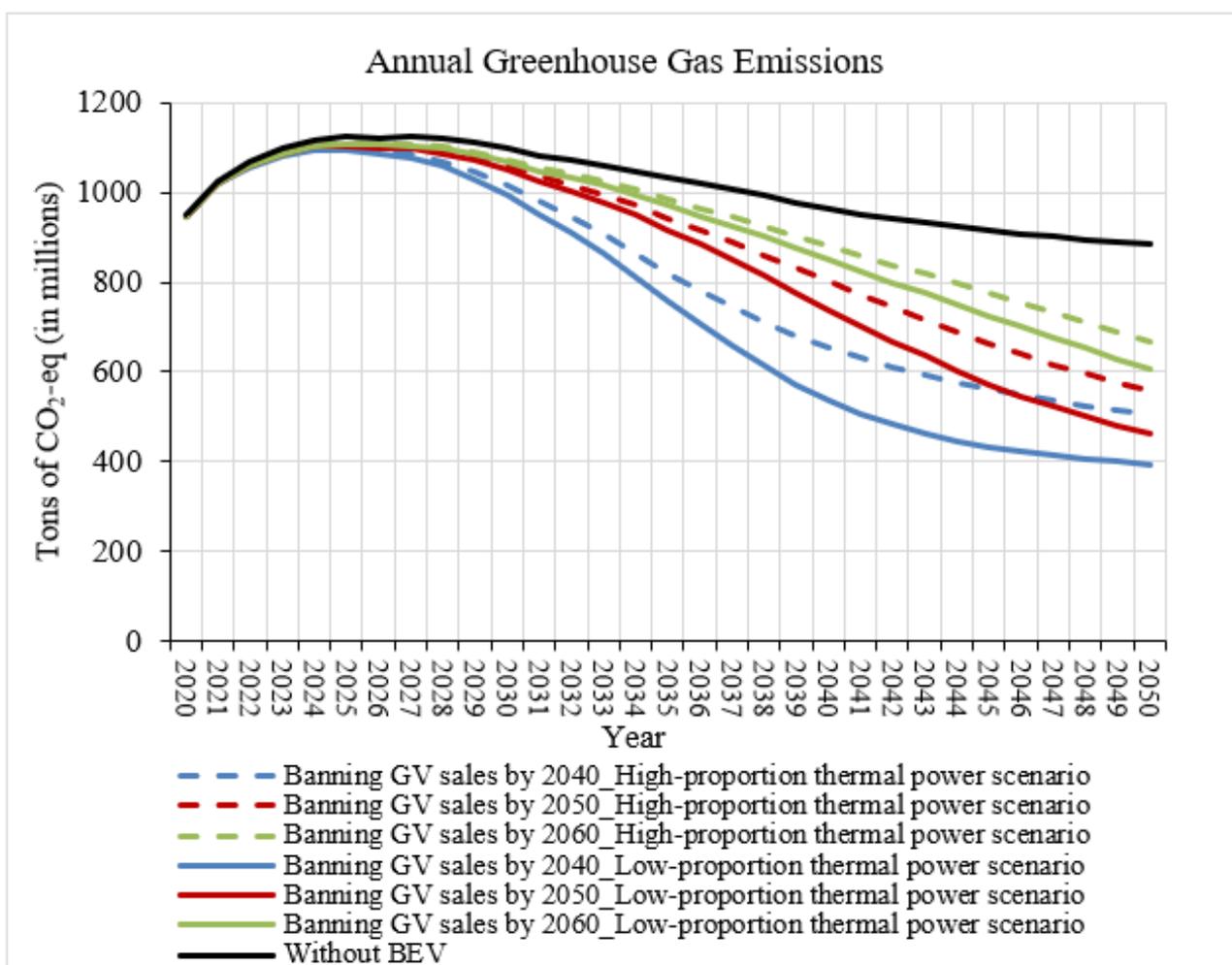


Figure 9. Annual GHG emissions from China’s automobile market under different scenarios.

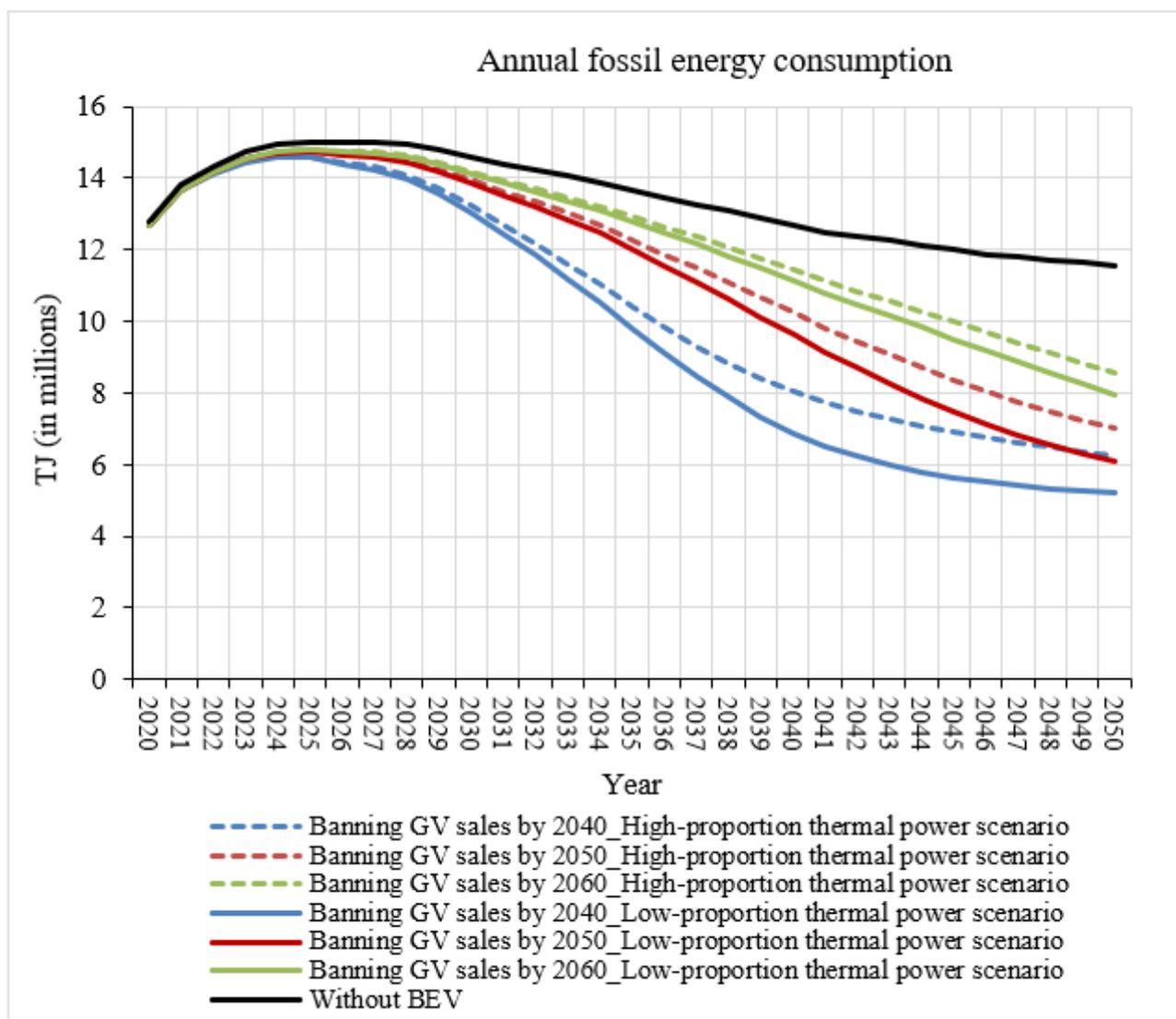


Figure 10. Annual FE consumption of China’s automobile market under different scenarios.

4. Discussion

This study quantitatively estimates the energy savings and emission reduction effect of the promotion of BEVs in the context of banning GV sales. Specifically, using the population ecological growth model, the development trend of China’s GV and BEV markets under different timings of banning GV sales was simulated. Combining national energy planning and automotive technology development, the GHG emission reduction and FE conservation potential of promoting BEVs was further estimated and discussed from the life cycle perspective, making a meaningful contribution to existing research in several ways.

First, existing studies on the field of NEVs mainly focuses on industrial policies and development strategies [25,71–73], consumer behavior and purchase willingness [74–76], vehicle and fuel technology [7,32], and comparisons with conventional fossil fuel vehicles in terms of vehicle performance, energy consumption, and environmental sustainability [47,49,52]. In order to better solve the problems concerning energy conservation, emission reduction, and the battery health of electric vehicles, scholars have also conducted a series of in-depth studies on energy management strategies and have proposed a variety of optimal control methods [37–39]. In addition, research on the modeling, forecasting, and analysis of the production and sales of NEVs has also been widely carried out [40,41]. However, little effort

has been devoted to date to discussing the long-term energy and environmental impacts of promoting NEVs. This study empirically analyzes the impact of the promotion of NEVs on energy and the environment over a long time frame, making up for the deficiencies of the existing literature.

Secondly, although many countries in the world have formulated a timetable for BGVS [42], little is known about the dynamic growth trends of the new energy vehicle market and its corresponding energy and environmental impacts in the context of BGVS. This study first employs the population growth model to simulate the evolution of China's automobile market under different BGVS scenarios and then estimates the ESER potential of promoting BEVs from the life cycle perspective. The findings can not only help authorities, managers, and the public to better understand the changing trends of the entire automobile market and the consequent environmental and energy impacts of BGVS, but also provide a forward-looking reference for formulating comprehensive, systematic, and reasonable industrial planning to better promote the sustainability of the automotive sector and solve the relevant energy and environmental problems.

Thirdly, the ESER effect of NEVs mainly depends on various factors, such as industrial policies, development strategies, power production, energy planning, and vehicle and fuel technology [77–80], while the ESER effect of NEVs also affects the development of related industries and technologies in turn. This study fully considers these influencing factors to explore the ESER potential of BEV promotion, which can provide a valuable reference for promoting healthy and sustainable development in all aspects.

BEVs show great ESER potential. Currently, compared with GVs, BEVs in China have lower GHGEI and FECl. Replacing GVs with BEVs can reduce GHG emissions by approximately 26.6% (71.54 g CO₂-eq/km) and FE consumption by approximately 40.1% (1.45 MJ/km), respectively. With the continuous improvement of the proportion of green electricity and the efficiency of CFTP plants, the ESER effect of BEVs will gradually increase. By 2050, under the HPTP scenario, using a BEV instead of a GV will reduce GHG emissions by approximately 43.61% and FE consumption by approximately 46.33%. Especially in the LPTP scenario, the corresponding reduction rates of GHG emissions and FE consumption can reach 55.81% and 55.45%, respectively.

Under the scenario of banning GV sales from 2060 on, the market size of BEVs will exceed that of GVs around 2049. The annual FE savings and GHG emission reductions could reach approximately 0.40~0.46 million TJ and 24.33~30.35 MtCO₂e by 2030 and 2.99~3.60 million TJ and 214.94~276.54 MtCO₂e by 2050. If China bans GV sales from 2050 on, the market share of BEVs will exceed that of GVs around 2042. The annual ESER could reach approximately 0.63~0.72 million TJ and 38.47~48.02 MtCO₂e by 2030, and 4.55~5.47 million TJ and 326.72~420.50 MtCO₂e by 2050. In particular, if GV sales are banned from 2040 on, BEVs will start to dominate the automotive market around 2035. The annual ESER could reach approximately 1.36~1.56 million TJ and 82.86~103.47 MtCO₂e by 2030, and 5.29~6.35 million TJ and 379.68~488.77 MtCO₂e by 2050.

Compared with the scenario without BEV promotion, if the ban on the sale of GVs in China is set between 2040 and 2060, the time point at which the carbon peak of the automobile market will be reached will be advanced by approximately two years, and the corresponding carbon peak value will also be reduced by approximately 13.58–28.79 MtCO₂e. Although the peak value and peak timing of carbon emissions in the automobile market are not significantly different between the different time points of BGVS, after reaching the carbon peak, the differences in the ESER effect under the different time points of BGVS will become increasingly significant.

Vigorously promoting NEVs is a potential way to alleviate the increasingly severe energy and environmental problems. In order to better promote the sustainable development of the NEV industry, it is necessary to constantly optimize and improve the overall industrial planning and layout and strengthen technological innovation to enhance industrial competitiveness. Since the ESER potential of BEVs mainly depends on the power structure and power production technology, effective plans and measures should be formulated

and implemented, such as increasing the amount of clean electricity and reducing energy consumption and emissions from thermal power production. In addition, with the continuous improvement of automobile fuel economy and the green degree of the electricity grid, the VLF will surpass the FLF to become the primary source of FE consumption and GHG emissions of BEVs. Therefore, accelerating technological innovation to reduce vehicle weight, adopting more environmentally friendly and energy-saving materials, and optimizing manufacturing processes to improve the sustainability of VLC are also important paths to enhance the ESER potential of BEVs.

However, this study still has some limitations that need to be improved in the future. First, the road transportation sector is a complex and diversified system that includes many different types of vehicles, such as passenger cars, buses, heavy-duty trucks, and commercial vehicles. The specific process of promoting the green and sustainable transformation of the automobile industry also involves the substitution of traditional gasoline and diesel vehicles with diversified electric vehicles (e.g., BEV, PHEV, and FCEV) and other vehicles powered by alternative fuels (e.g., compressed natural gas, liquified natural gas, hydrogen, methanol, methane, dimethyl ether, and bioethanol). In this research work, only passenger cars were selected as the study object to analyze the ESER potential of BEVs replacing GVs. Therefore, a more systematic and comprehensive analysis of the ESER effect on the promotion of NEVs needs to be conducted in the future. In addition, this study did not pay attention to the advancement of vehicle manufacturing technology and the application of environmentally friendly and renewable materials, which can also reduce the energy and environmental impact of BEVs. Finally, this study did not take into account the FE-saving and GHG-reducing potential brought about by advances in power battery technology, which needs to be further supplemented in future studies.

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Appendix A

Table A1. Inventory data for the vehicle life cycle of BEVs.

| | Ecoinvent Unit Process | Unit | Value |
|------------------------|---|------|--------|
| Vehicle manufacture | Glider | kg | 1046.5 |
| | Powertrain | kg | 103.5 |
| | Lithium batteries | kg | 285.6 |
| Vehicle maintenance | Maintenance of passenger cars (BEVs) | p | 1 |
| | Dismantling of used BEVs | p | 1 |
| Scrapping and disposal | Treatment of used gliders | kg | 1046.5 |
| | Treatment of used powertrains for electric passenger cars | kg | 103.5 |
| | Treatment of used lithium batteries | kg | 285.6 |

Appendix B

Table A2. Inventory data for the vehicle life cycle of GVs.

| | Ecoinvent Unit Process | Unit | Value |
|------------------------|---|------|--------|
| Vehicle manufacture | Glider | kg | 913.16 |
| | Internal combustion engine | kg | 320.84 |
| Vehicle maintenance | Maintenance of passenger cars (GVs) | p | 1 |
| | Treatment of used gliders | kg | 913.16 |
| Scrapping and disposal | Treatment of used internal combustion engines | kg | 320.84 |
| | Dismantling of used passenger cars with internal combustion engines | p | 1 |

Appendix C

Table A3. Inventory data for lithium-ion battery production [81,82].

| | Material | Mass (Unit: kg) | FE Consumption (Unit: MJ/kg) | GHG Emissions (Unit: kg CO ₂ -eq/kg) |
|-------------------------------|-----------------------------|--------------------|---------------------------------|--|
| Electrode active material | Graphite | 43.03 | 15.02 | 272.30 |
| | NMC | 68.99 | 31.48 | 448.59 |
| Electrolyte material | Dimethyl carbonate | 11.86 | 1.31 | 47.60 |
| | Ethylene carbonate | 11.90 | 1.65 | 34.08 |
| Electrode supportive material | Lithium hexafluorophosphate | 4.46 | 26.43 | 360.13 |
| | Cu foil | 22.22 | 3.01 | 45.09 |
| | N-Methyl-2-pyrrolidone | 92.91 | 2.48 | 82.09 |
| | Al foil | 9.56 | 17.87 | 288.16 |
| | Polyvinylidene fluoride | 5.80 | 11.47 | 183.21 |
| Separator | Polyethylene membrane | 3.08 | 8.84 | 149.22 |
| Packaging | Al housing | 4.12 | 15.75 | 254.35 |
| | Cu tab | 7.51 | 3.42 | 27.88 |

Appendix D

Table A4. Historical data on the scale of China's passenger car market.

| Year | Vehicles (in Millions) | Year | Vehicles (in Millions) |
|------|------------------------|------|------------------------|
| 1985 | 0.2849 | 2004 | 14.8166 |
| 1986 | 0.3471 | 2005 | 18.4807 |
| 1987 | 0.4229 | 2006 | 23.3332 |
| 1988 | 0.6042 | 2007 | 28.7622 |
| 1989 | 0.7312 | 2008 | 35.0139 |
| 1990 | 0.8162 | 2009 | 45.7491 |
| 1991 | 0.9604 | 2010 | 59.3871 |
| 1992 | 1.1820 | 2011 | 73.2679 |
| 1993 | 1.5577 | 2012 | 88.3860 |
| 1994 | 2.0542 | 2013 | 105.0168 |
| 1995 | 2.4996 | 2014 | 123.3936 |
| 1996 | 2.8967 | 2015 | 140.9910 |
| 1997 | 3.5836 | 2016 | 165.9900 |
| 1998 | 4.2365 | 2017 | 184.6954 |
| 1999 | 5.3388 | 2018 | 205.5540 |
| 2000 | 6.2533 | 2019 | 226.3543 |
| 2001 | 7.7078 | 2020 | 243.9336 |
| 2002 | 9.6898 | 2021 | 262.4640 |
| 2003 | 12.1923 | | |

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