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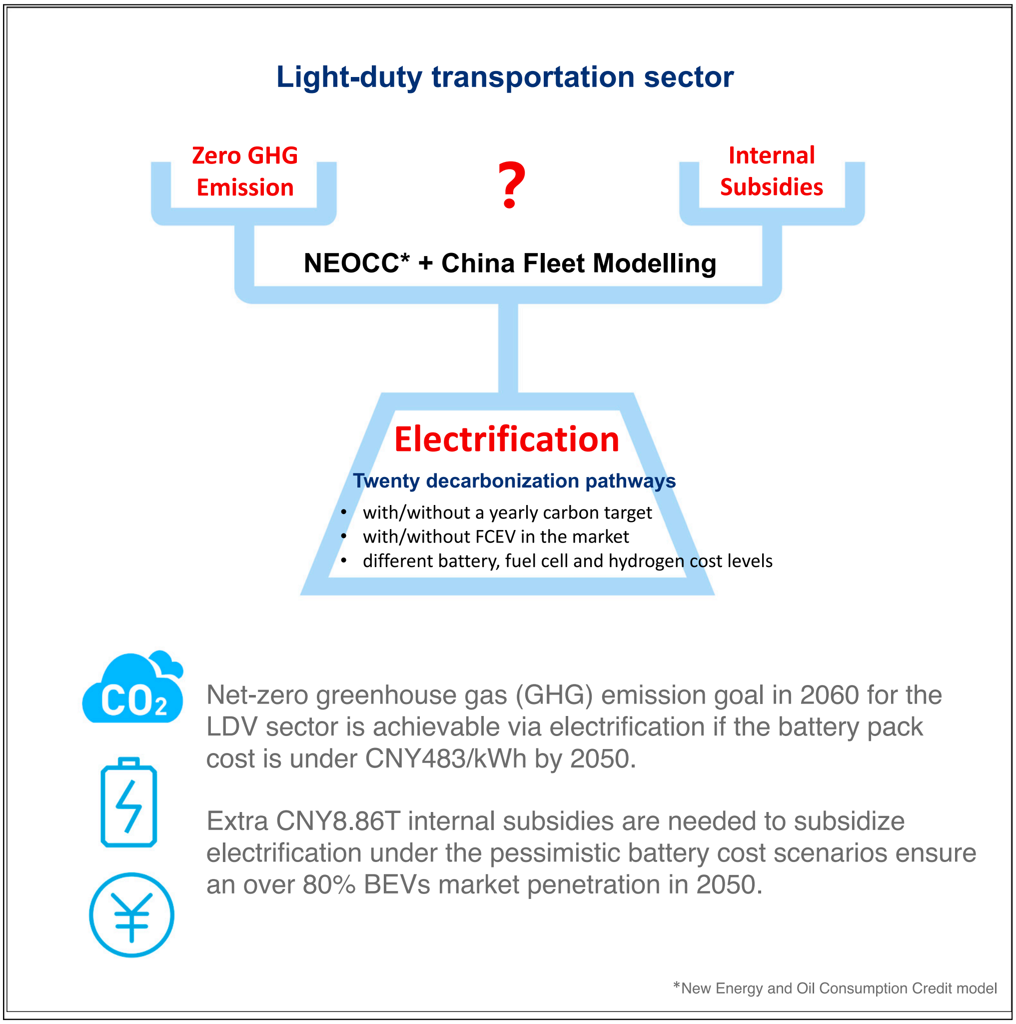


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## Highlights

LDV sector zero-GHG by 2060 via affordable electrification (CNY483/kWh by 2050)

Subsidies drive 80%+ BEV market share by 2050, achieving carbon neutrality

CNY8.86T subsidies for e-mobility needed under CNY759/kWh scenario

FCEVs cut up to 55% abatement costs, aiding carbon mitigation

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# Assessing the cost-effectiveness of carbon neutrality for light-duty vehicle sector in China

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## SUMMARY

**China's progress in decarbonizing its transportation, particularly vehicle electrification, is notable. However, the economically effective pathways are underexplored. To find out how much cost is necessary for carbon neutrality for the light-duty vehicle (LDV) sector, this study examines twenty decarbonization pathways, combining the New Energy and Oil Consumption Credit model and the China-Fleet model. We find that the 2060 zero-greenhouse gas (GHG) emission goal for LDVs is achievable via electrification if the battery pack cost is under CNY483/kWh by 2050. However, an extra of CNY8.86 trillion internal subsidies is needed under pessimistic battery cost scenarios (CNY759/kWh in 2050) to eliminate 246 million tonnes of $CO_2$-eq by 2050 ensuring over 80% market penetration of battery electric vehicles (BEVs) in 2050. Moreover, the promotion of fuel cell electric vehicles is synergy with BEVs to mitigate the carbon abatement difficulties, decreasing up to 34% of the maximum marginal abatement internal investment.**

## INTRODUCTION

In October 2016, more than 55 countries representing at least 55% of global emissions ratified the Paris Agreement aiming to limit global warming below 1.5°C compared to pre-industrial levels by mid-century.[1] To attain the climate goal under the framework of the Paris Agreement as well as avoid further environmental disruptions, by the end of 2020, more than 110 countries have committed to a net zero carbon emissions goal, and some of their plans are highly ambitious. For example, the European Union (EU) endeavors to achieve climate neutrality by 2050 and at least a 55% reduction of GHG emissions compared to its level in 1990 by 2030 through financial investments and policy reforms in various sectors of the energy economy.[2] Followed by the ambitious goal of the EU, Japan committed to reaching net zero GHG emissions from all sectors by mid-century.[3] Furthermore, as one of the world's largest $CO_2$ emitters, China has pledged to reach a $CO_2$ emissions peak before 2030 and be carbon neutral by 2060.[4] Achieving these far-reaching targets requires many structural adjustments in all sectors of the energy economy, particularly in the transportation sector,[5] which accounts for 24% of direct $CO_2$ emissions from fuel consumption in 2020 globally[6] and is predicted to account for over 40% by 2030.[7]

According to the National Bureau of Statistics of China, the transport sector produced about 10% of total GHG emissions.[8,9] Nevertheless, Zheng et al. (2019) showed that the on-road transportation sector, which accounts for 80% of the energy consumed in the transport sector, has been rapidly expanding in energy consumption and GHG emissions in recent decades.[10,11] Since 1980, both freight and passengers' turnover by vehicles have increased by more than ten times, and vehicle stock has risen 14% annually.[12] However, vehicle ownership in China (less than 300 per thousand people) was far away from that in the U.S. (840 per thousand people) by 2021.[13,14] Consequently, it is expected that the total vehicle population in China will continuously grow, which would further amplify the energy demand. GHG emissions from vehicles will probably increase accordingly if the levels of vehicle miles traveled and vehicle fuel economy remain the same. Therefore, to enhance national energy security and reduce emissions, the government has implemented vehicle policies and incentives to transition from conventional vehicles to electric vehicles in the last decade,[15] which is considered an effective solution to decrease carbon and other GHG emissions.[16] The Chinese government launched the dual-credit policy, *Measures for Passenger Cars Corporate Average Fuel Consumption and New Energy Vehicle Credit Regulation*, to promote plug-in electric vehicles (PEVs) in September 2017 and revised in June 2020.[17,18] With more stringent vehicle fuel economy standards and generous monetary incentives, the vehicle industry is transitioning its propulsion technology to hybridization, electrification, and hydrogen-powered systems. The PEV sale in 2021 has reached 3.52 million, over a 20-fold increase compared to

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2013.[19] The China Society of Automotive Engineers (China SAE) expects that in the 2035 light-duty vehicle market, 50% of new vehicle sales will be PEVs, and all internal combustion engine vehicles (ICEVs) will be hybrid electric vehicles (HEVs).[20]

Achieving carbon neutrality by 2060 in China demands tremendous research and development investments in all sectors to form a low-carbon ecosystem. More importantly, it requires more strategic studies to evaluate technologies from the life cycle perspective so that China can achieve the target sustainably. Otherwise, China may suffer from additional irreversible social problems. For instance, Huo et al. claimed that battery electric vehicles (BEVs) could increase sulfur dioxide emissions by 3–10 times more than internal combustion engine vehicles (ICEVs) in China under the 2008 electricity grid structure.[21] Thus, without significant decarbonization of the grid, rapid road transport electrification may not lead to the desired reduction in emissions of GHG and air pollutants. According to China's climate envoy, Zhenhua Xie, "carbon neutrality" in China before 2060 refers to the neutralization of all GHG emissions not just carbon dioxide ($CO_2$).[22] Therefore, reaching carbon neutrality requires comprehensively reducing all GHG emissions for vehicles. On the other hand, in the overall energy balance sheet, the transport sector only accounts for 8% of China's total $CO_2$ emissions between 1980 and 2018, while the industrial and building sectors contribute more than 80%.[23] Then a critical question is whether it is necessary and how much effort is needed for China to achieve carbon neutrality in the transport sector, especially the on-road transportation and light-duty vehicle (LDV) sectors, under the overall economic-wise carbon neutrality goals? And then, what are the additional investments needed to achieve zero net emissions in 2060? To sum up, what is the cost-effective pathway to reach net zero carbon emissions in this context?

There are multiple decarbonization pathways to achieve carbon neutrality in the LDV sector by 2060, among which electrification and fuel cell (FC) are the most promising technologies encouraged by the Chinese government in the LDV sector. The Chinese government has gradually promoted vehicle electrification in the last decade, combined with grid decarbonization.[17] From a life cycle perspective, BEVs and plug-in hybrid electric vehicles (PHEVs) are believed to reduce $CO_2$ emissions by 18% and 1%, respectively, relative to conventional ICEVs by comparing three top-selling vehicle models produced in 2018.[24,25] Meanwhile, deep decarbonization via large-scale vehicle electrification requires a sustainable and resilient electricity grid. Therefore, Mallapaty believes this pathway can be accessible only if China can double its electricity production by 2060 compared to its level in 2020, with the new capacity mainly on clean sources instead of coal.[4] In addition, the academia and the industry consider the hydrogen fuel cell electric vehicles (FCEVs) as another possible pathway for decarbonizing the transport sector.[26,27] A well-to-wheel (WTW) analysis of GHG emissions conducted by Wang et al. showed that FCEVs powered by renewable hydrogen could reduce GHG emissions by 90% compared to gasoline-powered ICEVs.[28] However, if hydrogen is produced by coal gasification, Wang et al. also found that the WTW GHG emission of FCEVs could be around 3% higher than that of gasoline-powered ICEVs.[28] Therefore, similar to the electrification pathway, a clean and efficient hydrogen production process should also come along with the large-scale adoption of FCEVs. Besides the aforementioned, there are more potential pathways such as nuclear-powered electricity production, synthetic fuels (or E-fuels), advanced high-efficiency internal combustion engines, onboard solid oxide fuel cells using biofuel in FCEV, etc.[29,30] Most likely, these pathways will coexist. For example, the combination of vehicle electrification and promotion of FCEVs and their combined impacts are worth further research. PEVs and hydrogen-power vehicles are two of the promising technologies to decarbonize China's transport sector[20]; therefore, these two or combined pathways are extensively discussed in this study. Moreover, zero emissions are not the sole pathway to achieve carbon neutrality. In addition to this, negative emissions technologies could also play a role in reaching carbon neutrality. For instance, the automotive industry has been exploring mobile carbon capture (MCC) technologies,[31] and other industries have been utilizing carbon capture, utilization, and storage (CCUS) methods to assist in achieving carbon neutrality in LDV sector.[32]

Given those major pathways, it is necessary to use a series of quantitative models to compare the different pathways, and potentially identify the most effective pathway. Many comprehensive bottom-up energy models have evaluated road transport energy consumption and GHG emissions, such as the Asia-Pacific Integrated Model (AIM)/Enduse,[33] the Transportation Mode-Technology-Energy-$CO_2$ (TMOTEC) model,[34] the Integrated MARKAL-EFOM System (TIMES),[35] and so on. These models made a series of predictions of the carbon emission in the transportation sector, and investigated what efforts are implemented to reach the carbon targets; for example, Zhang and Hanaoka found that the influence of the financial subsidies on emission reduction varied spatially among the different provinces.[33] However, these existing models rarely quantify the costs needed to reach net-zero carbon emissions, especially internal investments from original equipment manufacturers (OEMs) for policy compliance, which is vital for understanding the costs and barriers of the energy transition. Considering the battery cost, fuel cell, and hydrogen cost fluctuation, much cost uncertainty exerts to reach carbon neutrality in the LDV sector. The extra investments in different scenarios provide an essential reference for the government and OEMs to evaluate different carbon emission reduction pathways in the LDV sector.

Therefore, this study investigates the feasibility of electrified and hydrogenized decarbonization pathways in the light-duty vehicle market if economic-wise carbon neutrality is to be achieved by 2060 in China, i.e., evaluating the extra investments needed to reach carbon targets. The methodology integrates two quantitative models, the New Energy and Oil Consumption Credit (NEOCC) model and the China Vehicle Fleet (China-Fleet) model in a bidirectional way as shown in Figure 1. The NEOCC model, developed in compliance with multiple policy scenarios, projects the market penetration of various vehicle technologies in China by 2050.[17,36,37] The China-Fleet model estimates the corresponding WTW energy use and GHG emissions under different vehicle technology and energy structure scenarios.[38–40] The combination of the two models can not only derive the GHG emission pathway toward carbon neutrality but also calculate the corresponding internal investment and the market penetration as well (see STAR methods). This could have significant implications for OEMs to develop technologies meeting government policies while achieving higher returns, and it also helps quantify the possible internal investments to be carbon neutral in complicated future predictions.

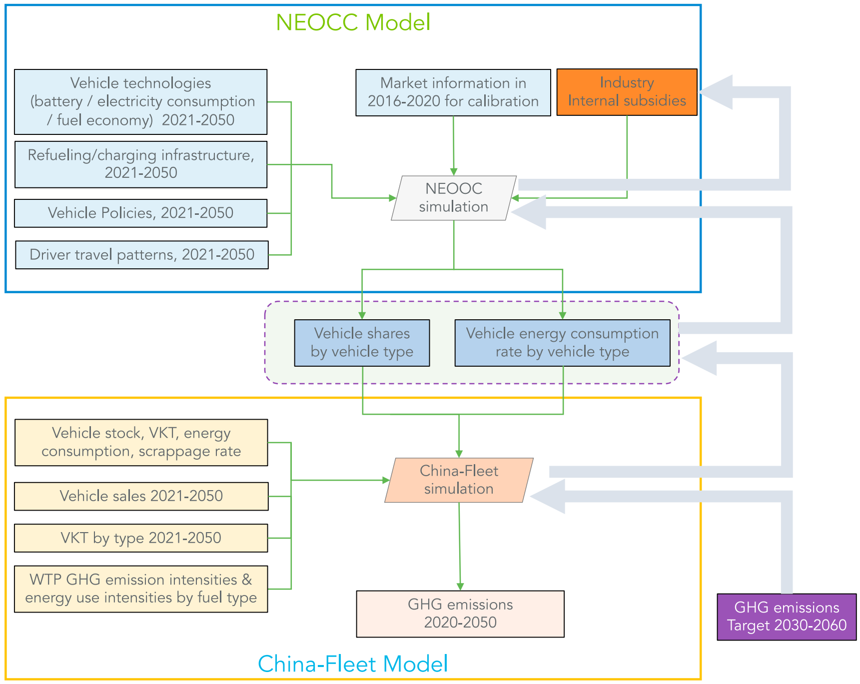


**Figure 1. The integrated model framework to reach carbon neutrality**

The green arrows show the forward simulation, the NEOCC model maximizes the industry profit with a multivariable optimization to derive the market penetration, and then the China-Fleet model estimates the WTW GHG emissions in China's vehicle market from 2020 to 2050 based on the market shares and fuel consumption values delivered by the NEOCC model. The gray arrows illustrate the backward simulation, i.e., the amounts of carbon emissions produced by the light-duty vehicle industry in 2030–2060 are pre-defined, and then the NEOCC model optimizes the internal industry subsidies for each vehicle type, maximizing the total industry profits while meeting the government policy requirements and the pre-defined specific GHG emissions targets.

## RESULTS AND DISCUSSION

### Design of scenarios

The combined model merges the internal subsidies calculation and integrates the carbon neutrality target into three-level hierarchical scenarios, which comprehensively consider the electrification with BEV, PHEV, and the marketization of FCEVs. The three-level hierarchical structure consists of (1) with 2060 carbon neutrality goal or not, (2) the marketization of FCEV or not, and (3) prices of the key components, e.g., battery packs,[41,42] fuel cell packs, and hydrogen costs. Here the "marketization" refers the presence and competition of vehicles as products available for sale in the market. It signifies the commercial availability and adoption of vehicles. A total of 20 scenarios are designed to evaluate the carbon neutrality pathways and the impacts on the light-duty vehicle market dynamics. (see Table 1).

The reference scenario (1) defines the reference projections on the light-duty vehicle market dynamics like the annual sales shares and stocks, the energy demands, and the GHG emissions by vehicle type from 2021 to 2050. The model is calibrated based on historical market information (sales, stocks, prices, vehicle technology features, households, travel patterns, etc.) from 2016 to 2020. The other 19 scenarios are assumed based on the reference scenario. The first level of the three-level hierarchical structure is with/without carbon target. A fixed yearly carbon target is set to decrease emissions linearly from the peak value to zero as a constraint to reach zero GHG emissions in 2060, in line with China's carbon neutrality goals. We make comparisons between the scenarios with carbon targets (Scenario (11)-(20)) and without carbon targets (Scenario (1)-(10)) to evaluate the difference in market share and extra subsidies needed to follow the artificial carbon target pathway strictly. Scenarios (1)-(10) adopt the forward simulation, while Scenarios (11)-(20) adopt the backward simulation. The specific GHG emission targets of Scenarios (11)-(20) are decided by the year and value of the peak GHG. Note that the carbon target in this research constrains the yearly GHG emission, over 85% of which is $CO_2$; however, we use the term carbon target to keep in line with the carbon neutrality goal in China.

In each scenario, the evolution of the battery pack cost, vehicle prices and fuel consumption rate, and charging infrastructure in 2021–2050 can be referred to in Figure S1.[43–45] The scenarios, including FCEVs in the LDV sector, assume that the FCEV will be on the market starting in 2025. The major assumptions of FCEV attributes, hydrogen prices, and infrastructure availability, used in Scenario (4) are listed in Figure S2 and Table S1. Moreover, the GHG emission intensity (g $CO_2$-e/MJ) of electricity consumed by BEVs and PHEVs is generated based on the assumption that the electricity grid structure will continue to improve under the 2°C scenario in China, consistent with the Paris Agreement.[46] Under the 2°C scenario, renewable energies such as hydro, solar, and solar will be the largest source, accounting for about 59% of Chinese electricity generation, while coal will drop to 10% in 2050. (see Figures S3 and S4). Note the prices discussed in this paper are all at the 2020 level, and 1 U.S. dollar equals 6.9 Chinese Yuan (CNY).[47]

Table 1. Scenario definitions for GHG analysis of China's light-duty vehicle market

| Scenarios | Carbon Target or not | FCEV or not | Different costs | | |
|---|---|---|---|---|---|
| | | | Battery cost | FC cost | H2 cost |
| (1) Ref | No | No | Ref. | – | – |
| (2) BatOpt | No | No | Optimistic | – | – |
| (3) BatPes | No | No | Pessimistic | – | – |
| (4) FCEV | No | Yes | Ref. | Ref. | Ref. |
| (5) FCEV+FCOpt | No | Yes | Ref. | Optimistic | Ref. |
| (6) FCEV+FCPes | No | Yes | Ref. | Pessimistic | Ref. |
| (7) FCEV+BatOpt | No | Yes | Optimistic | Ref. | Ref. |
| (8) FCEV+BatPes | No | Yes | Pessimistic | Ref. | Ref. |
| (9) FCEV+H2Opt | No | Yes | Ref. | Ref. | Optimistic |
| (10) FCEV+H2Pes | No | Yes | Ref. | Ref. | Pessimistic |
| (11) Ref+CT | Yes | No | Ref. | – | – |
| (12) BastOpt+CT | Yes | No | Optimistic | Ref. | Ref. |
| (13) BatPes+CT | Yes | No | Pessimistic | – | – |
| (14) FCEV+CT | Yes | Yes | Ref. | Ref. | Ref. |
| (15) FCEV+FCOpt+CT | Yes | Yes | Ref. | Optimistic | Ref. |
| (16) FCEV+FCPes+CT | Yes | Yes | Ref. | Pessimistic | Ref. |
| (17) FCEV+BatOpt+CT | Yes | Yes | Optimistic | Ref. | Ref. |
| (18) FCEV+BatPes+CT | Yes | Yes | Pessimistic | Ref. | Ref. |
| (19) FCEV+H2Opt+CT | Yes | Yes | Ref. | Ref. | Optimistic |
| (20) FCEV+H2Pes+CT | Yes | Yes | Ref. | Ref. | Pessimistic |

See also Figure S6.

### LDV cannot reach carbon neutrality without forced carbon targets if battery cost is higher than CNY483/kWh

The WTW GHG emissions by the light-duty vehicle market under different scenarios are presented in Figure 2 and Table S2. In Scenario (1) Ref, the WTW GHG emission in the LDV sector will peak at 798 million tonnes (Mt) $CO_2$-e with an LDV stock of 405 million in 2032. This reference scenario peak value of the LDV sector is close to the predictions in the previous paper.[46] By 2050, it is projected that there will be 383 Mt $CO_2$-e with an annual sale of 26.4 million LDVs and a stock of 439 million LDVs, representing 48% of the peak GHG emission value. Note that the modeling results from the integrated model only extend to 2050. Therefore, the carbon emission trend toward 2060 is assumed by Figure 2 to depict the feasibility of reaching zero GHG emissions by 2060. The GHG emission in the reference scenario is possible to reach zero according to the analysis. In the ten scenarios without the carbon target, two scenarios with pessimistic battery pack cost assumptions are projected to have difficulty achieving zero GHG emissions by 2060. In 2050, these scenarios are expected to have 531 to 466 Mt $CO_2$-eq GHG, respectively. On the other hand, two scenarios with optimistic battery pack cost assumptions, are projected to achieve carbon neutrality by 2060 with smaller annual decrease rates, with 257 to 249 Mt $CO_2$-eq GHG in 2050, respectively. A comparative analysis with other studies in the field of carbon reduction in road transport reveals a minor variation in the time of peak emissions for relevant decarbonization pathways. In different scenarios, the road transport sector is projected to reach its peak emissions around 2028–2032. However, variations in the peak emission levels occur due to differences in the calculation methods for individual vehicle emissions and the research boundaries for carbon emissions.[46,48,49]

These findings highlight the high sensitivity of LDV carbon neutrality pathways to battery pack costs. To quantify this sensitivity, the simulation of the battery cost threshold for achieving zero GHG emissions, or the tipping point, is performed using four different battery pack cost levels (refer to Figure S5). The extended trajectories of GHG emissions in 2050–2060 assume the average decrease rate in 2040–2050 is continued in 2050–2060, and other assumptions are kept the same as the reference scenario, without FCEVs in the market. Without FCEVs and a carbon target, the battery pack cost needs to be less than CNY483/kWh ($70/kWh) in 2050 to achieve carbon neutrality by 2060.

A group of ten scenarios with yearly carbon target constraints is one-by-one compared to those without the carbon targets shown in the green lines presented by Figure 2. The yearly carbon targets for each scenario are calculated by linear reduction from the peak value to zero in 2060. The constraint ensures the achievement of the carbon neutrality goal in 2060 for all the scenarios, especially for the scenarios that are difficult to reach zero-emission naturally (Scenarios (3) and (8)). Furthermore, strict yearly carbon targets can speed up the carbon emission reduction soon after the carbon peaking before 2040, and reduce the cumulative carbon emission for all scenarios. For example, the LDV sector keeps a steady GHG emission reduction rate at 28.5 Mt $CO_2$-eq per year in the reference scenario with carbon target, while the

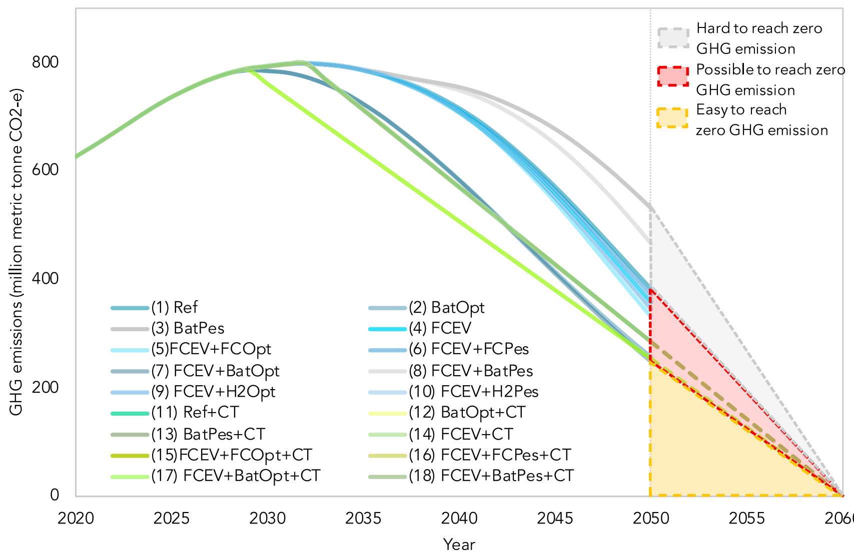


**Figure 2. Projections of GHG emissions in 2020–2050, and de-carbonization paths needed to reach net zero in 2050–2060**

To better understand the feasibility of reaching zero GHG emissions by 2060, we divide the required yearly GHG reduction amounts in 2050–2060 into three areas, based on the decrease rate range of twenty scenarios in 2040–2050 (25.3–42.3 Mt CO2-eq per year), marked with the red shadow. If GHG emissions in 2050 exceed 423 Mt CO2-eq (gray shadow), it would be challenging to reach zero emissions by 2060 as larger yearly carbon reduction amounts would be required. However, if GHG emissions in 2050 fall within the range of 253–423 Mt CO2-eq, achieving zero emissions by 2060 would be possible, as a similar decrease rate would have been achieved in 2040–2050. If GHG emissions in 2050 are smaller than 253 Mt CO2-eq (yellow shadow), it will be relatively easier to achieve zero GHG emissions in 2060. See also Figures S1–S5, Tables S1, and S2.

GHG emission reduction rate in the reference scenario is less than 10 Mt $CO_2$-e per year before 2035. The cumulative emitted GHG in the LDV sector with carbon targets is 18–19 billion tonnes $CO_2$-eq, 6%–17% less than the corresponding scenarios without carbon targets.

## High battery cost may hinder BEV market penetration, leading to up to 242 million $CO_2$-eq

As shown in Figure 2, high battery cost will hinder carbon neutrality, leading to remaining GHG emissions in 2060. The failure is mainly due to the low BEV market penetration at high battery cost scenarios. BEVs are estimated to gain significant market share in the passenger vehicle market in China regardless of the scenarios, as shown in Figure 3. In the reference battery cost scenarios, the BEV share can reach as high as 82% of LDV sales without FCEV in the market and 62% with FCEV in the market in 2050, as the solid lines shown in Figures 3A and 3B. BEV shares under the optimistic and pessimistic battery cost scenarios are depicted as the light shadows in Figure 3. In the scenarios without FCEV and carbon targets, BEV shares vary from 64% to 90% in 2050 (see Figures S8 and S9). With FCEV in the LDV market, the BEV market share varies from 39% to 78% in 2050. The BEV market share is most sensitive to the battery pack cost. High battery cost reduces the BEV market penetration. Besides, the introduction of FCEVs into the market appears to have a limited impact on the combined market share of EVs and FCEVs in both the reference and optimistic battery scenarios, with figures such as 82% in Scenario (1) Ref and 86% in Scenario (4) FCEV by the year 2050. However, the situation changes in the pessimistic battery scenario, where the market share reaches 64% without FCEV and attains 78% with FCEV by 2050, representing a 14% increase.

Yearly carbon targets can improve the BEV market penetration. The carbon target can significantly narrow the BEV share variation range in the pessimistic battery cost scenario. For example, the 2050 BEV share in Scenario (18) FCEV+BatPes+CT is 54%, only 8% lower than the corresponding reference battery cost scenario, while Scenario (8) FCEV+BatPes is 39%, 23% lower than the corresponding reference battery cost scenario (62%). The carbon target ensures an over 50% BEV market penetration despite battery pack cost scenarios.

## Carbon neutrality of China's light-duty vehicle sector requires up to CNY9 trillion without cheap batteries, and FCEV can help mitigate the cost

Reaching carbon neutrality on time is not effortless for the LDV sector in China, especially in the pessimistic battery cost scenario. This study compares the amount of investment needed under different decarbonization pathways in the LDV market, which are used for measuring the difficulties of policy success. In order to achieve the desired carbon targets, internal subsidies will be added by the industry to lower the sales prices of BEVs, PHEVs, and FCEVs in the market and to increase their market shares. In the scenarios without carbon emission targets, the internal subsidies are mainly due to the policy constraints, including the dual credit policy, as shown in Figure 4A. It assumes the current dual-credit policy will continue to be implemented after 2023, which is the last year of the $2^{nd}$ phase of the dual-credit policy in all scenarios. In these scenarios, the simulation results show that no more internal subsidies are needed for PEVs to help the industry meet the requirements of the policy constraints after 2038. The major driving force toward electrification is consumer purchase selections. In the scenarios with

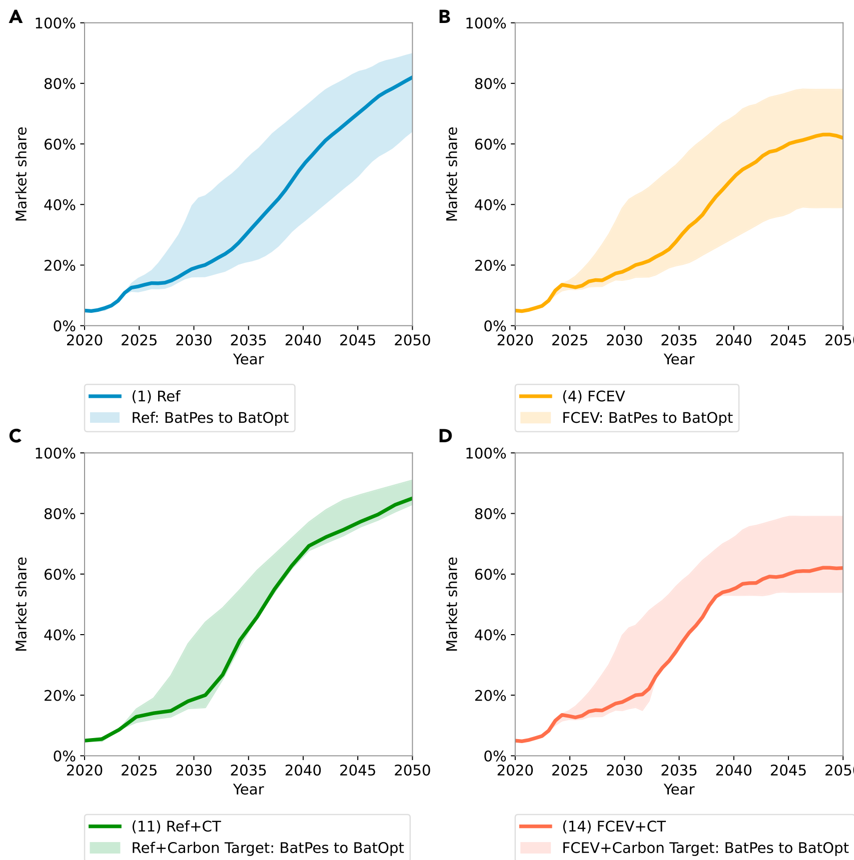


**Figure 3. Projected BEV shares in multiple scenarios with different battery cost affected by FCEV in the market and carbon targets**

The solid lines are the BEV shares with reference battery cost, the shadows are the BEV share ranges from pessimistic to optimistic battery cost. (A) relates to reference scenario, (B) realtes to FCEV scenario, (C) relates to reference scenario with carbon target, and (D) relates to FCEV scenario with carbon target. See also Figures S8 and S9.

carbon emission targets, the internal subsidies are due to the combination of policies and the strict yearly carbon targets, as presented in Figure 4B. It is obvious that the government or the industry must subsidize more to realize the yearly carbon targets for each scenario.

This study adopts the internal subsidies difference with and without the carbon target as the measurement for the extra investment intensity of the industry to achieve the carbon emissions target. Using the investment intensity in 2020 as the benchmark, this study quantifies and presents the extra investment intensities for each vehicle in Figure 4 (the values in (B) minus the corresponding values in (A)) and the whole LDV sector in Figure 4C. Massive subsidies help achieve carbon neutrality for pessimistic battery cost scenarios, and the promotion of FCEV can mitigate the subsidy quantities. For reference and pessimistic battery cost scenarios, the extra subsidies generally increase from 2032 to 2039 and then decrease variously in different scenarios. The BatPes and FCEV+BatPes scenarios require the most extra subsidies to reach carbon neutrality. The yearly subsidies can reach up to a maximum of CNY28,225/vehicle-year in 2040 for BatPes and are projected up to CNY24,993/vehicle-year in 2050. Consequently, a cumulative amount of CNY8.86 trillion for BatPes and CNY5.21 trillion for FCEV+BatPes are needed, as shown in Figure 4C, indicating a heavy financial burden in the LDV sector for the government and the automotive industry. The huge subsidies are mainly to subsidize the development of BEVs due to the pessimistic battery pack cost prediction. Moreover, the development of FCEV can effectively reduce the subsidy intensity in different scenarios. In the pessimistic battery cost scenarios, the promotion of FCEV can reduce over 29%–60% of the subsidy per vehicle yearly after 2040. However, compared to the sensitive battery pack cost, FC and hydrogen prices have smaller impacts on the extra investment intensities, possibly due to limited market share prediction.

In addition, extra subsidies are also constructive for battery reference scenarios to speed up the electrification after carbon peaking, although the extra subsidies are not necessary to reach carbon neutrality. The market shares of PEVs and FCEVs increase slowly from 2030 to 2032 for the reference and pessimistic battery cost scenarios and enter a development stagnation period after carbon peaking. The carbon target can clearly shorten the stagnation period. The combined market share of PEVs and FCEVs in the BatPes scenario remains around 35% till 2038. With yearly carbon targets (Scenario (13)), their combined market share is projected to increase by 3% points after 2033.

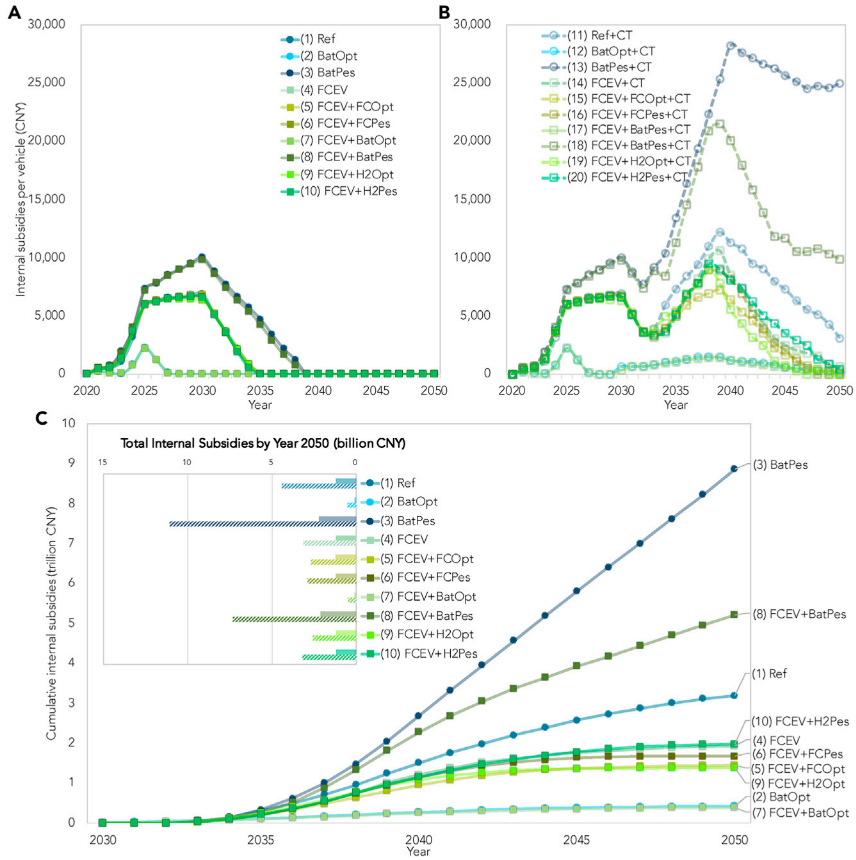


**Figure 4. Investment intensities of different scenarios**

(A) Projections of investment intensities under scenarios without carbon targets.

(B) with carbon targets.

(C) Projections of cumulative extra investment and cumulative investment in 2050 under scenarios for their achieving carbon targets.

See also Figure S7.

To shorten the development stagnation period of PEVs and FCEVs, a total of 1.38–3.19 trillion CNY extra subsidies will be needed to realize the yearly carbon targets for the reference battery cost scenarios from 2021 to 2050.

Furthermore, the marginal abatement internal investment (MAII, unit: CNY/tonne $CO_2$-eq) for GHG emissions is defined as the extra annual internal investment cost per tonne $CO_2$-eq GHG emission reduced from the new PEVs and FCEVs, compared to those scenarios without carbon targets. MAII is an indicator to evaluate the difficulty of decreasing GHG emissions from the internal investment perspective. In general, MAII increases in Scenarios (11)-(20) with carbon targets due to increasing difficulties in reaching the carbon targets (see Figure S7 and STAR methods). In the scenarios with carbon targets, optimistic battery, FC system, and hydrogen cost can effectively decrease the MAII. For example, the MAII of GHG surges sharply to 116 CNY/tonne $CO_2$-eq in 2046 for the pessimistic battery cost scenario, while the MAII for the optimistic battery cost scenario is less than 16 CNY/tonne $CO_2$-eq, which indicates that the technology progress in the aforementioned essential components and hydrogen production can effectively decrease the carbon abatement difficulties. Moreover, the promotion of FCEV can mitigate the high MAII for the pessimistic battery cost scenario. The maximum MAII for BatPes decreases from 116 CNY/tonne $CO_2$-eq to 77 CNY/tonne $CO_2$-eq with carbon target, cutting 34% of that for Scenario (13).

## Reflections on the China's light-duty vehicle sector carbon neutrality and research limitations

To sum up, achieving zero greenhouse gas (GHG) emissions in the LDV sector by 2060 is heavily dependent on the cost of battery packs. Electrification can make this goal achievable if the cost of battery packs is under CNY483/kWh by 2050. However, in pessimistic battery cost scenarios (CNY759/kWh in 2050), an extra of CNY8.86 trillion internal subsidies is required to achieve this goal, eliminating from 531 to 285 Mt $CO_2$-eq by 2050 in the LDV sector. These subsidies ensure an over 80% BEV market penetration in 2050 to meet carbon neutrality, despite battery cost scenarios. In addition, promoting FCEVs could be synergistic with BEVs to mitigate carbon abatement difficulties, reducing up to 34% of the maximum marginal abatement internal investment. However, it should be noted that FCEVs are not the exclusive means to address this challenge. Other potential strategies such as a deceleration in carbon target objectives, exploration of negative emissions technology, and providing subsidies for battery technology research could also be beneficial. Nevertheless, further research is required to thoroughly examine and compare these different approaches.

Considering the huge subsidies needed to reach zero GHG emissions, it is reasonable to identify key factors and promote various pathways to decarbonization, instead of a forced zero GHG emissions for the LDV sector. For further decarbonization, there are several measures that can help mitigate the internal subsidies investment. Firstly, reducing the battery pack cost is a critical factor in increasing the market share of BEVs and enabling the decarbonization of the LDV sector. There are several measures that can be taken to reduce the comprehensive cost of the entire life cycle of electric vehicle batteries, such as improving battery technology, promoting battery recycling, and exploring new battery business models like battery banks. By reducing the battery pack cost, the market share of BEVs can increase, making them more competitive with conventional vehicles and furthering the decarbonization of the LDV sector. Moreover, incorporating BEVs into carbon trading or adopting carbon credits in China can help mitigate the internal subsidies, considering the carbon emissions of BEVs compared to conventional vehicles. In addition, in special cases where internal combustion engines are necessary, e-fuel may also be a potential technology to consider.

### Limitations of the study

However, there are still some limitations to the current research. Currently, some assumptions (such as the trends of FC technology and the availability of hydrogen refueling stations) are made. In NEOCC modeling, potential assumptions may introduce fluctuations in the results. The technology development assumptions in this research are based on the current technology route; the disruptive innovations in battery, charging technology, FC,[50] and hydrogen production are not taken into consideration, which may also lead to unpredictable carbon emission pathways in the future. And the carbon emission of BEV is largely decided by the grid carbon intensity, which remains uncertain toward 2060. Assumptions are made regarding policy continuity and automakers' optimization strategies aimed at profit maximization. However, it should be noted that real-world automaker strategies are characterized by greater flexibility and complexity, which can potentially lead to variations in actual internal investment and market penetration rates. Moreover, some calculations are simplified for the data analysis, e.g., the linear extrapolation of the carbon emission reduction pathway is assumed from 2050 to 2060. As more is learned about the data and the technology innovation evaluation, the analysis and the model will be updated and improved.

## STAR★METHODS

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

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
  - Lead contact
  - Materials availability
  - Data and code availability
- METHOD DETAILS
  - Integrated model framework
  - Parameters assumption and scenarios setting
  - Marginal abatement internal investment

## SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.108203.

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## AUTHOR CONTRIBUTIONS

Study conception and design: S. Ou, X. Hao; Data collection: S. Ou, R. Yu; Model development: S. Ou, M. Saafi, X. He, Y. Gan, Z. Lu, and Y. Jiang; Analysis and interpretation of results: X. Hao, S. Ou, and M. Saafi, X. He; Draft manuscript preparation: S. Ou, X. Hao, X. He, and Z. Lin. All authors reviewed the results and approved the final version of the manuscript.

## DECLARATION OF INTERESTS

M. Saafi and X. He are employees of Aramco, whose business interests include the sale of crude oil and refined products.

## INCLUSION AND DIVERSITY

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

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## STAR★METHODS

### KEY RESOURCES TABLE

| REAGENT or RESOURCE | SOURCE | IDENTIFIER |
|---|---|---|
| Deposited data | | |
| China historical vehicle market information in 2016–2020. | China Automotive Technology and Research Center | www.catarc.ac.cn |
| China macroeconomics statistics | National Statistics Yearbook | http://data.stats.gov.cn/english |
| Energy sources for electricity generation, and WTW GHG emissions intensity for electricity and hydrogen in China | China Fleet Model | https://www.osti.gov/biblio/1483998/ |
| Software and algorithms | | |
| Excel® | Microsoft | www.microsoft.com |
| Python | Python | https://www.python.org/ |

### RESOURCE AVAILABILITY

#### Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Shiqi Ou (sou@scut.edu.cn).

#### Materials availability

This study did not generate new unique materials.

#### Data and code availability

- China historical vehicle market information in 2016–2020 achieved from China Automotive Technology and Research Center. They are available upon request if access is granted. To request access, contact Shiqi Ou. Energy sources for electricity generation, and WTW GHG emissions intensity for electricity and hydrogen in China are from China Fleet Model. They are available upon request if access is granted. To request access, contact Shiqi Ou. Vehicle cost, battery prices, hydrogen prices prediction are from NOECC model. They are available upon request if access is granted. To request access, contact Shiqi Ou. China macroeconomics statistics from National Statistics Yearbook. They are publicly available. These above accession numbers are all listed in the key resources table.
- This paper does not report original code.
- Any additional information required to reanalyze the data reported in this work paper is available from the lead contact upon request.

### METHOD DETAILS

#### Integrated model framework

The NEOCC model projects the market dynamics by vehicle class and powertrain type under the impact analysis of vehicle technologies, policy constraints, and costs of vehicle ownership in China from 2021 to 2050.[36] The model assumes that, under the constraints of government policies such as fuel economy standards or plug-in electric vehicle quotas, the industry provides internal subsidies for multiple vehicle technologies to adjust their prices, which influences their sales in the market, and ultimately maximizes the overall benefits.[17] In each vehicle type, the internal subsidies are the difference between the cost-based and actual prices to consumers. The model assumes the internal subsidies are no less than zero. Those vehicle types with internal subsidies could lower their actual prices to consumers, leading to higher market shares due to their promoted cost-competitiveness. By adjusting the internal subsidies to specific vehicle types, the industry is able to optimize its total profit while complying with the regulations. Moreover, in the backward simulation, each year's internal subsidies for each vehicle type are adjusted to meet the specific market shares, which lead to the specific GHG emissions target by 2060.

The updated version of the NEOCC model includes a total of 16 different vehicle types with technologies ranging from ICEVs, HEVs, PHEVs, to BEVs and FCEVs. ICEVs are categorized into three types: high fuel consumption vehicles (HigFC-ICEV), medium fuel consumption vehicles (AvgFC-ICEV), and HEVs. According to current BEV models on the market, BEVs are further classified based on their electric range. In the sedan segment, BEVs with three different electric ranges are considered: less than 300 km (BEV-sht), between 300 and 500 km (BEV-mid), and over 500 km (BEV-lng). In the SUV/crossover segment, BEVs are divided into BEVs with three different electric ranges: less than 300 km (BEV-sht), between 300 and 400 km (BEV-mid), and over 400 km (BEV-lng). NEOCC takes into account: PEV sales share and sales-weighted average fuel consumption requirements, the incremental cost of fuel efficiency, range limitation of battery electric vehicles, charging infrastructure, consumer choice and central and local government subsidies, and other monetary or nonmonetary incentives for PEVs.[37] It considers EV driving range and the correlated charging infrastructure availability according to various battery sizes. For example, the total vehicle manufacturing cost can be described in relation to battery size (energy capacity in kWh):

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

where $C_{BEV}$ is the total manufacturing cost of a BEV, $C_B$ is the manufacturing cost of a base car for BEV, $C_{bat}$ is the battery pack cost; $E$ is the battery size (energy capacity in kWh); and $\beta$ is a coefficient added into the above equation so to consider the costs for both the auxiliary electric propulsion systems in addition to the battery system. The discrete choice model is adopted as the methodology for computing the vehicle's market sales.

The China-Fleet model was developed to estimate the energy consumption and GHG emissions of China's light-duty vehicle fleet on a life cycle basis.[38,46] The inputs of the China-Fleet model are detailed historical and projected vehicle types/technologies data, including vehicle inventory, sales volume, market share, fleet turnover, mileage, fuel economy, etc. The WTW GHG emission research includes two stages: the well-to-pump (WTP) and the pump-to-wheels (PTW).[38,39] WTP includes processes related to the production and distribution of fuel. PTW involves energy consumption and emissions during vehicle operation in its lifetime. The energy consumption of a vehicle fleet's PTW in a year is determined by the vehicle stock, vehicle kilometers traveled (VKT), and vehicle fuel consumption rate (FCR).[38] Considering the difference between the vehicle labeled FCR and real-world FCR, we adjust the labeled FCR to the real-world FCR by multiplying a ratio of 1.2 for ICEVs[38] and 1.4 for BEVs in their labeled FCR.[40] According to the China-Fleet model, over 85% of the LDV WTW GHG emissions are carbon emissions.

## Parameters assumption and scenarios setting

Considering the several vehicle decarbonization pathways, including vehicle electrification, fuel cell electric vehicles, synthetic fuels, and so on, BEVs and hydrogen-power vehicles are considered two of the most promising technologies to decarbonize China's transport sector.[20] Therefore, these two or combined are discussed in this study. A three-level hierarchical structure and a total of 20 scenarios are designed to evaluate the carbon neutrality pathways and the impacts on the light-duty vehicle market dynamics. The three-level hierarchical structure considers the carbon reduction pathways with/without a yearly carbon target, with/without FCEV, and different battery, fuel cell, and hydrogen cost levels. The descriptions of the scenarios are summarized in Table 1 and Figure S6.

The reference scenario (1) defines the reference projections on the light-duty vehicle market dynamics like the annual sales shares and stocks, the energy demands, and the GHG emissions by vehicle type from 2021 to 2050. Then the model is calibrated based on the historical market information (sales, stocks, prices, vehicle technology features, households, travel patterns, etc.) from 2016 to 2020. Other 19 scenarios are assumed based on the reference scenario. The first level of the three-level hierarchical structure is with/without carbon target. A fixed yearly carbon target is set to decrease emissions linearly from the peak value to zero as a constraint to reach zero GHG emission in 2060, in line with China's carbon neutrality goals. We make comparisons between the scenarios with carbon targets (Scenario (11)-(20)) and without carbon targets (Scenario (1)-(10)) to evaluate the difference in market share and extra subsidies needed to follow the artificial carbon target pathway strictly. Scenarios (1)-(10) adopt the forward simulation illustrated in Table 1, while Scenarios (11)-(20) adopt the backward simulation. The specific GHG emission targets of Scenarios (11)-(20) are decided by the year and value of the peak GHG. Note that the carbon target in this research constrains the yearly GHG emission, over 85% of which is CO2; however, we use the term carbon target to keep in line with the carbon neutrality goal in China.

To evaluate the impact of FCEV development on carbon emission reduction, the future LDV market with and without FCEV in the market is simulated as the second level. Recently there has been a surge of interest in promoting hydrogen and hydrogen-powered transportation in China. The development of FCEV is primarily affected by technology, policy, and the industry, and remains uncertain. The scenarios, including FCEVs in the LDV sector, assume that the FCEV will be on the market starting in 2025.

Table S1 and Figure S2 show the major assumptions of FCEV basic features, hydrogen prices, and infrastructure availability, used in Scenario (4). Time spent from/to a public hydrogen station is based on the station availability.[36] The FC system cost was about 2070 CNY/kW in China in 2020, and the target of the U.S. DOE is 207 CNY/kW ($30/kW), which is assumed to be achieved by China's automakers in 2050.[27] In addition, the third level in the three-level hierarchical structure further assumes different FC system, battery, and hydrogen price scenarios. Based on the literature review, the average hydrogen purchase price (end-use cost) was about 70 CNY/kg in 2020, and the hydrogen price target by the Chinese government is 35 CNY/kg in 2050, which is set as Scenario (4) FCEV.[26] High hydrogen price (Scenarios (10) and (20)) and low hydrogen price (Scenarios (9) and (19)) scenarios are assumed as $+/-20\%$ of the reference hydrogen price of 35 CNY/kg, i.e., 42 CNY/kg and 28 CNY/kg in 2050 according to a series of literature. Similarly, the high FC system cost (Scenarios (6) and (16)) and low FC system cost (Scenarios (5) and (15)) scenarios assume 424 CNY/kW and 172 CNY/kW in 2050.

The evolution of the battery pack cost, the vehicle prices, and the fuel consumption rate, and charging infrastructure in 2021–2050 can be referred to in the descriptions of the reference scenario in a previous publication.[46] The electric vehicle battery pack costs from 2021 to 2050 of reference, optimistic, and pessimistic scenarios are shown in Figure S2. The actual battery pack cost in 2020 is 945 CNY/kWh.[41] In the reference scenario, it is expected to be 828 CNY/kWh in 2025,[42] then assumed to reach the U.S. Department of Energy (DOE)'s goal of 552 CNY/kWh ($80/kWh) by 2040, and assumed to ultimately reduce to 483 CNY/kWh ($70/kWh) by 2050. The battery costs in other years are linearly interpolated between key years. The battery pack cost is expected to reach 310 CNY/kWh for the optimistic battery cost scenario[43,44] and 759 CNY/kWh for the pessimistic battery cost scenario in 2050.[45,46] Similarly, the battery costs in other years are also linearly interpolated between key years.

The WTW life cycle GHG emissions of a vehicle vary not only by vehicle energy efficiency, but also by power sources and their production methods. Although the BEVs and FCEVs are zero-emission vehicles at the PTW stage, their WTP emission cannot be ignored. In this study, the GHG emission intensity (g CO2-e/MJ) of electricity consumed by BEVs and PHEVs is generated based on the assumption that the electricity grid structure will continue to improve under the 2°C scenario in China, consistent with the Paris Agreement.[46] Under the 2°C scenario, renewable energies such as hydro, solar, and solar will be the largest source, accounting for about 59% of Chinese electricity generation, while coal will drop to 10% in 2050. Figure S3 shows the grid mix of electricity generation in China in 2020–2050, adopted by the China-Fleet model.

The GHG emission intensities of hydrogen in 2020–2050 under this renewable situation are based on the following assumption.[51] In 2020, 62% of China's hydrogen was produced by coal gasification. In 2050, the study assumes that hydrogen used by FCEVs will all be produced by renewable energy resources such as solar and wind. This is an optimistic projection while probably viable. Hydrogen is usually produced massively in a single location, which can solely utilize renewable resource systems such as solar panels coupled with the hydrogen storage system. The cumulative number of installed solar capacities in China achieved 204.7 GW in 2019, more than a 48-fold increase compared to 2012, which can accelerate the development of hydrogen production in the upcoming decades.[50] Therefore, the study estimates that hydrogen production produces less GHG emissions than electricity generation after 2040 (Figure S4).

## Marginal abatement internal investment

The marginal abatement internal investment (MAII) for GHG emissions is defined as the extra annual internal investment cost per tonne of CO2-e GHG emission reduced from the new PEVs and FCEVs, compared to those in the reference scenario. MAII (unit: CNY/tonne CO2-e) for Scenario *i* from 2020 to 2060 is:

$$MAII_i = \frac{-(IS_i - IS_j)}{(N_i - N_j)}$$

where,

$IS_i$ refers to the total internal subsidies for Scenario i in Scenarios (11)-(20) with carbon target;

$IS_j$ refers to the total internal subsidies for in Scenarios (1)-(10) without carbon target;

$N_i$ refers to the accumulated WTW GHG of new LDVs sold in Scenarios (11)-(20) with carbon target;

$N_j$ refers to the accumulated WTW GHG of new LDVs sold in Scenarios (1)-(10) without carbon target.

MAII is an indicator to evaluate the difficulty of decreasing GHG emissions from the internal investment perspective. The positive MAII indicates that more internal subsidies are needed to reduce extra GHG emissions compared to the scenarios without carbon targets due to increasing difficulties in reaching the carbon targets.