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Quantifying the sensitive parameters of the new energy vehicles in China

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Abstract— *To achieve carbon neutrality by 2060, the Chinese government has put effort into decarbonizing the transportation sector. Consequently, China elaborated a new energy vehicle strategy promoting the production of electric vehicles and expanding into hydrogen (H_2) vehicle technologies including fuel cell electric vehicles and H_2 internal combustion engine vehicles. The Transportation Energy Analysis Model (TEAM) projects the market penetration as well as energy demand and greenhouse gas emissions in China up to 2050. By integrating the Monte Carlo simulation, this study tests the robustness of TEAM and investigates the key parameters that will shape passenger vehicle sales and emissions in the future. The results show that fuel cell cost, H_2 price, and battery cost are the most sensitive parameters for H_2 vehicle technologies.*

Keywords—*sensitivity, new energy vehicles, market penetration, hydrogen vehicles, electric vehicles, carbon neutrality*

I. Introduction

Fighting climate change has become an increasingly important task for governments worldwide. In this context, nearly every nation on earth has endorsed the Paris Agreement, a landmark international accord aiming at substantially reducing greenhouse gas (GHG) emissions to limit the global temperature increase in the century to 2 degrees Celsius above preindustrial levels [1]. The pact establishes a framework for transparency, accountability, and the achievements of more ambitious targets. Among other requirements, countries must report their GHG inventories relative to their targets allowing experts to evaluate their success. To achieve the Paris Agreement’s objectives, 186 countries responsible for more than 90 percent of global emissions have committed to fighting climate change by submitting carbon reduction targets [1]. In light of this, China, one of the largest GHG emitters in the world and accounting for 27% of global CO_2 emissions in 2019 as reported by the International Energy Agency (IEA) [2], announced in 2020 an ambitious goal of achieving carbon neutrality by 2060 [3]. One of the major sectors that heavily contributes to GHG emissions is transportation. Hence, the Chinese government enacted numerous policies to ensure an eco-friendly transportation energy transition by promoting the development and market adoption of new energy vehicles (NEVs) [4]. One of the most predominant drivers of the rapid development of the new energy vehicle industry is the Measures on Parallel Administration of Passenger Car Corporate Average Fuel Consumption (CAFC) and NEV Credits (commonly called dual-credit policy). Similar to the corporate average fuel economy (CAFE) standard in the U.S., CAFC sets targets for the production-weighted average fuel consumption for vehicle manufacturers. On the other hand, the NEV rule mandates original equipment manufacturers (OEMs) to produce enough NEVs to meet the NEV credit quota.

In China, battery electric vehicles (BEVs), hydrogen fuel cell electric (FCEVs), and plug-in hybrid electric vehicles (PHEVs) are classified as NEVs [5]. In fact, the development of FCEVs in China can be traced back to 2008. First Automobile Works (FAW), Shanghai Automotive Industry Corporation (SAIC), Guangzhou Automobile Corporation (GAC), and Beijing Automotive Industry Holding Corporation (BAIC) developed passenger FCEVs but did not realize mass production due to the high cost, short fuel cell lifespan, and limited H_2 refueling stations. In the following years, FAW completed the development of a 30-kW fuel cell based on the completion of key technologies. In 2017, FAW took the lead in the major special project "High Specific Power Fuel Cell Engine R&D" of the Ministry of Science and Technology and invested $31.3M (216 million CNY) for positive development [6]. In 2020, MAXUS EUNIQ7 became the first passenger FCEV recommended by the Ministry of Industry and Information Technology (MIIT) [7]. Although the development of passenger FCEVs is still at an early stage in China, it is expected that more OEMs will launch passenger FCEVs.

Considering the promising potential of H_2 in decarbonizing the transport sector, it is crucial to evaluate the market potential of H_2-powered vehicles and their impact on reducing GHG emissions. In addition to FCEVs, hydrogen internal combustion engine vehicles (H_2-ICEVs) technology is also investigated in this study. The development of H_2-ICEV in China can be traced back to 2013. Chang'an Automobile Co. and Beijing Institute of Technology (BIT) jointly developed and demonstrated the first port fuel injection (PFI) H_2-ICEV, cumulatively conducting more than 10,000 km of on-road tests by 2013 [8]. In 2021, incentivized by the carbon neutrality goals, MIIT included H_2-ICEV as a key technology, being supported as part of the national H_2 development strategy [9]. Furthermore, the first Hongqi 2.0L hydrogen engine independently designed and developed by FAW successfully rolled off the production line of the FAW Research Institute [6]. Besides, GAC designed an internal-combustion engine to burn hydrogen in place of gasoline or diesel, which has a brake thermal efficiency of 44%, according to a company press release [10].

Many studies have been conducted to investigate the impacts of government regulations on the transportation sector in China [11] [12] [13]. Future prediction models are not impervious to having incorrect findings due to the uncertainties in assumptions. In this study the Transportation Energy Analysis Model (TEAM) was used to quantify the sensitivities of key parameters on technology market penetration. The innovation behind this work is that TEAM does not assume a pre-defined market technology mix and vehicle fuel economy. TEAM simulates the market penetration of the light-duty vehicle technologies in China using a discrete choice model. A sensitivity analysis adds credibility and integrity to the model because it accounts for variations in the assumptions and parameters.

This paper consists of four sections. The first section introduces China's emissions concerns and targets as well as the interest in H_2 vehicle technologies as a means to help decarbonize the automotive industry. The second section describes the methodology applied to achieve this study. The third section discusses the results and findings. Finally, the fourth section highlights the main takeaways from this study.

In this paper, the yearly average currency exchange rate of $ 1.0 USD = 6.910 CNY in 2016 is used [14].

II. METHODOLOGY

In this paper, the reference projection scenario assumes that China will produce both FCEVs and H_2-ICEVs. Furthermore, the battery cost is projected to decrease from 137 $/kWh in 2020 to 70 $/kWh in 2050.

A. *Assumptions*

Table 1 summarizes H_2 vehicle technologies assumptions as well as battery cost projection. Refueling availability is a key factor that influences the consumer's decision in purchasing a vehicle technology. Consumers are more likely to buy vehicles that will not cause them to have a long trip to a refueling station. In this context, we quantify the refueling inconvenience based on the lifetime refueling time, which is a function of the time spent to/from public H_2 station per trip, H_2 usage, and vehicle tank size as explained in the previous work [15].

This study assumes that H_2 vehicle technologies will be available in the Chinese market starting in 2025 when the H_2 stations are better developed. Moreover, we assume that the fuel cell technology will reach its optimum in 2050 by embracing the ultimate US Department of Energy (DOE) goal of $30/kW [16]. This study also adopts the Chinese government H_2 price target of $5.1/kg (35 CNY/kg) [17]. Besides, the current system volumetric capacity of H_2 is 0.03 kg H_2/L. DOE targets in 2025 and 2050 are 0.04 kgH_2/L and 0.05 kgH_2/L, respectively [18].

To investigate the impact of the dual-credit policy on the light-duty vehicle market in China, up to 2050, we make assumptions on the future CAFC and NEV targets. Based on the vehicle fuel economy improvements proposed by the Chinese Society of Automotive Engineers (SAE-China) in the Technology Roadmap for Energy Saving and New Energy Vehicles [19], a linear decrease in CAFC target from 4.7 to 3.7 L/100 km from 2025 to 2030 is assumed in this study. The CAFC assumption is also assumed to decrease by 1% per year starting from 2030 to reach 3.3 L/100 km by 2040. On the other hand, The NEV quota is assumed to increase linearly from 18% in 2023 to 40% in 2030.

B. *The Transportation Energy Analysis Model*

TEAM is a Python-based model to project market penetration of alternative fuel technologies, energy demand, and greenhouse gas emissions of the light-duty transport sector in China. TEAM models the market dynamics of 18 different vehicle types from both the demand side and supply side. On the demand side, the consumer choice is modeled considering the impacts of technology cost, energy cost, refueling/charging availability, and consumer travel pattern. On the supply side, TEAM simulates the technology evolution by the auto industry to maximize industry profit under the constraints of government policies. The outputs of the market penetration module are served as inputs for the vehicle fleet module, which combines the vehicle fuel economy, vehicle scrappage rate, vehicle kilometers traveled, vehicle sales, and GHG intensities of fuels/electricity to assess energy demand and GHG emissions. A detailed description of TEAM is provided in [20].

The market penetration modeling section in TEAM is a multinomial logit discrete choice model that specifies the purchase probabilities of the consumers based on the utility function by quantifying the total perceived ownership cost of each vehicle technology. The perceived ownership cost considers multiple variables such as the manufacturer's suggested retail price (MSRP), fuel/electricity/ H_2 consumption cost, government subsidies, and industry internal subsidies. The simulation is a multivariable optimization problem, maximizing the industry profit. The optimization is constrained by the dual-credit policy that combines the NEV credit rules and the CAFC credit rules. The decision variables in the market penetration model are the internal subsidies, which are the difference between the cost-based prices (i.e., vehicle production cost multiplied by a markup factor) and the actual prices to consumers. The market complies with the dual-credit policy starting from the year that the internal subsidies are found equal to zero. This situation means that NEVs and fuel-efficient vehicles become cost-competitive compared to conventional vehicles. In the short term, these technologies are not yet cost-competitive. Therefore, their prices to consumers must be reduced, by internal subsidies, to stimulate sufficient demands for policy compliance.

C. *Monte Carlo simulation*

Monte Carlo methods are a class of computational algorithms that use randomness to solve deterministic problems by relying on repeated random sampling to obtain numerical results. Monte Carlo simulation is used to identify the key parameters that shape the light-duty vehicle market in China. The sensitivity analysis gives more credibility to market penetration results, as it allows quantifying the uncertainties of the future projections.

In this study, Monte Carlo is applied in two techniques. The first approach consists in quantifying the impact on BEVs, FCEVs, and H_2-ICEVs market shares caused by an asynchronous uniform distribution within the 20% percent range of the key parameters, including battery cost, H_2 price, gasoline price, H_2 refueling station availability, H_2 storage cost, and fast battery-electric charging possibility. The second approach adopted in this work is conducted by applying the simultaneous normal distribution to the parameters listed above. The purpose is to estimate the standard deviation of every key parameter that will keep the market shares within 1%. 10,000 Monte Carlo iterations are simulated in this work.

III. Results

Under the assumptions adopted in the reference scenario, electric vehicles (BEVs and PHEVs) could dominate the vehicle market by 2039, reaching more than 50% of the annual sales. H_2 vehicles, including FCEV and H_2-ICEV, could reach 24% of the total sales in 2050, as shown in Fig.1.

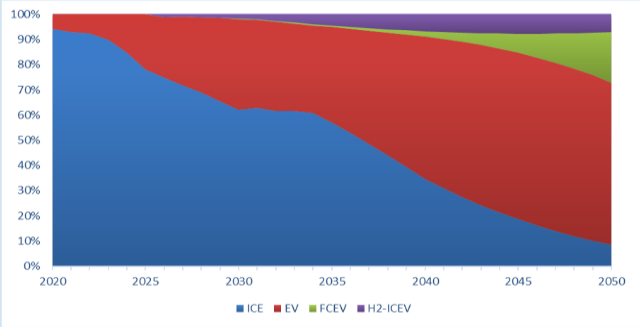

Fig. 1 Market penetration portfolio, 2020-2050

A. *Sensitivity analysis on H_2 vehicles*

a) Market share

To explore the future market opportunities for H_2, it is crucial to identify the key parameters that would shape the market penetration of H_2 vehicles. Fig. 2 shows that H_2-ICEVs will penetrate the vehicle market earlier than FCEVs, starting from 2026. During that period, the production cost of FCEVs would still be high compared to that of other technologies available in the light-duty vehicle market. In 2026, the production cost of FCEVs will be more than $34.7K (240,000 CNY) due to the high fuel cell cost $246/kW, 154% more costly than H_2-ICEVs. Consequently, FCEV wouldn't be an attractive option to consumers. The market share of H_2-ICEVs will keep on increasing until reaching 7% in 2045. Starting from 2026, FCEVs will slowly penetrate into the market, but at a slower rate than H_2-ICEVs before 2045. Under the assumption of achieving the ultimate DOE's fuel cell cost goal of $30/kWh in 2050, the low production cost of FCEV after 2045 makes it a more competitive technology than H_2-ICEVs. As a consequence, the market share of FCEV surpasses H_2-ICEV in 2046, reaching 20% in 2050.

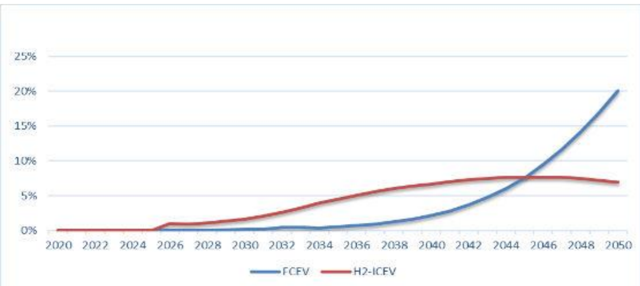

Fig. 2. FCEVs and H_2-ICEVs market penetration

Fig. 3 focuses on the sensitivity of FCEV market share as a function of fuel cell costs, battery pack costs, H_2 price, H_2 storage cost, and H_2 availability. The x-axis represents the 10,000 Monte Carlo iterations. At every iteration, the algorithm randomly picks a value for the key parameters within its uniform distribution range. The y-axis represents the fluctuations in market shares caused by the variations of the key parameters.

We apply the sensitivity analysis on FCEVs in 2040 and 2050, as it is by that time that the technology will start to seriously penetrate the Chinese vehicle market. After 2034, no internal subsidies are needed to incentivize consumers to purchase NEVs; the major driving force towards decarbonization is the consumer purchase selection. Consequently, the total perceived cost of ownership is a linear combination of MSRP, inconvenience cost, and energy cost. MSRP is proportional to the production cost. Since the fuel cell cost accounts for the biggest share of the production cost, it is the most sensitive parameter influencing the FCEV market share in 2040. The assumed fuel cell technology's continuous advancement reaching the ultimate DOE goal for fuel cell cost of $30/kW in 2050 would not only make FCEVs remarkably competitive but also decrease the share of MSRP in the total ownership cost. The energy cost, which is proportional to H_2 price, becomes a key parameter in 2050, as shown in Fig. 3.

Although battery cost directly affects BEV market share, we also include it in this section. Before 2030, FCEVs and H_2-ICEVs would still be expensive to produce compared to BEVs and internal combustion engine vehicles (ICEVs), which results in a big difference in the total cost of ownership. As long as this difference is substantial compared to the H_2 inconvenience cost, the vehicle production cost is still the dominant factor that influences the market penetration of H_2 vehicles. It is also noticeable that the inconvenience cost of BEVs is higher than that of H_2 vehicles. This is due to the H_2 refilling time advantage compared to BEVs. Gradually, H_2 vehicle technologies become more affordable thanks to the technology advancement and the decrease in H_2 storage cost. Moreover, the H_2 energy cost will also decrease proportionally to H_2 price. Consequently, the gap in total ownership cost of H_2 vehicles compared to BEVs and ICEVs will be smaller. Eventually, battery cost becomes a sensitive parameter for FCEVs and H_2-ICEVs as shown in Fig. 3 and Fig. 4.

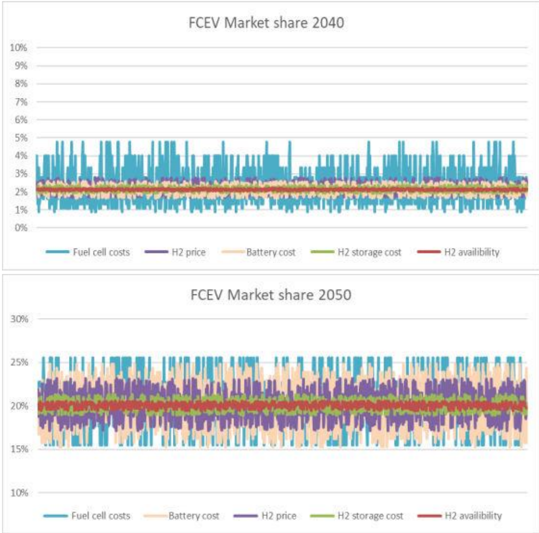

Fig. 3. FCEV market share sensitivity in 2040 and 2050

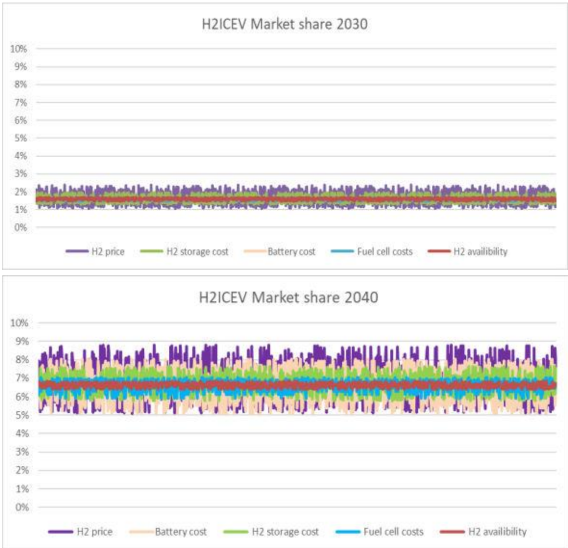

Fig. 4. H_2-ICEV market share sensitivity in 2030 and 2040

b) Dispersion measurement

In this section, a normal distribution for H_2 price, battery cost, and fuel cell system cost was applied when performing Monte Carlo simulation. SD is the measurement of the dispersion of the data set from its mean value. Approximately 99.7% of a data series falls between (MEAN –3 * SD) and (MEAN + 3 * SD). This is called the confidence interval. Therefore, we look for the standard deviations (SDs) that corresponds to the normal distribution of the above parameters to achieve a confidence interval of 1% for FCEVs and H_2-ICEVs market shares in 2040. The optimum combination of SDs, listed in Table 2, is the one that maximizes the industry profit per vehicle. For FCEVs, the fuel cell cost dispersion needs to be within 2.07 $/kW, representing only 3.2% of fuel cell projected cost (64.5

$/kW) in 2040, in order to keep FCEV market share at 1% variation around 3%. This confirms the results shown in Fig. 3, stating that fuel cell costs are the main key parameter for FCEVs. H_2-ICEVs, accounting for a bigger market share (7%) in 2040, are more sensitive to H_2 price and battery cost. A combination of $0.36/kg H_2 price dispersion and 2.37$/kWh battery cost dispersion would shift H_2-ICEV market share by 1% in 2040.

Table 1. Dispersion of key parameters to cause 1% market share variation in 2040

		FCEV	H_2-ICEV
	Mean	*3*SD*	*3*SD*
H_2 Price ($/Kg)	6.75	0.43	0.36
Battery Cost($/kWh)	80.00	3.84	2.37
Fuel cell cost($/kW)	64.50	2.07	7.25

B. Sensitivity analysis on battery electric vehicles

Due to the obligation to satisfy the dual-credit policy and the immature growing H_2 vehicle technologies by 2030, BEVs will be the dominant new energy vehicles, reaching almost 20% of the total sales. As shown in Fig. 5, battery cost and fuel price are the top sensitive parameters for BEVs. In fact, battery cost accounts for 57% of the BEV production cost in 2030. The charging inconvenience cost is directly related to the fast-charging availability and is an additional cost that contributes to the total cost of ownership. However, the charging inconvenience cost is about 15% of MSRP in 2030. Consequently, despite its importance in reducing range anxiety, fast-charging availability is less sensitive than the battery cost. Fuel price is a crucial parameter for ICEVs. The energy cost is a delicate parameter for ICEVs, accounting for 22% of the total perceived cost of ownership in 2030. Since BEVs and ICEVs would be the top two vehicle technologies in 2030, a fuel price fluctuation will directly affect ICEV market share and therefore influence BEV sales.

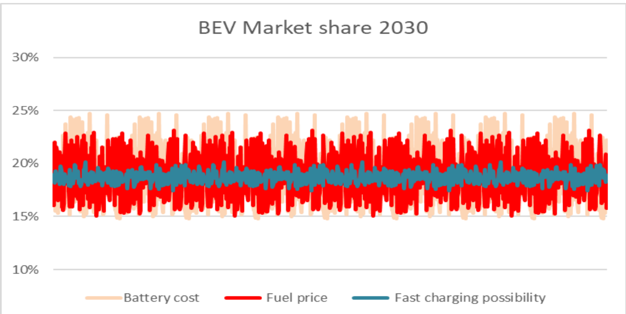

Fig. 5. BEV market share sensitivity in 2030

C. Impact of battery cost on internal investments

In this section, we study the impact of battery cost on the internal subsidies. This study adopts the internal subsidies per vehicle ($) as the measurement for the investment intensity of the industry to comply with the dual-credit policy. The x-axis represents the battery cost values selected in Monte Carlo iterations. As shown in Fig. 6, there is a clear correlation between battery cost and internal subsidies. Cheaper battery cost results in lower internal subsidies. In fact, BEVs will be the most attractive new energy vehicles by 2030. Therefore, it is more profitable for OEMs to invest in BEVs for dual-credit policy compliance.

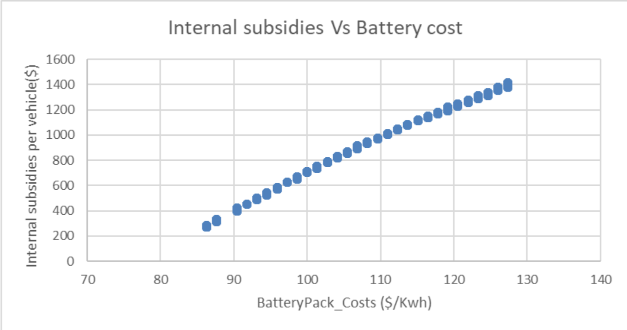

Fig. 6. Battery cost impact on internal investments

IV. CONCLUSION

H_2 could be a promising pathway for China to fulfill the decarbonization mission, especially if the manufacturing complications cause the battery costs not to decrease as expected. In this context, we use TEAM to explore the potential of H_2 vehicle technologies in China's light-duty vehicle market. The goal of this study is to test the robustness of TEAM and investigate the key parameters that will shape passenger vehicle sales and emissions in the future. Below is a list of the key findings:

- Electric vehicles (BEVs and PHEVs) could dominate the vehicle market by 2039. H_2 vehicles, including FCEV and H_2-ICEV, could reach 24% of the total sales in 2050.
- Fuel cell costs, H_2 price and battery cost are the main sensitive parameters for H_2 vehicle technologies. A combination of $0.36/kg H_2 price dispersion and 2.37$/kWh battery cost dispersion would shift H_2-ICEV market share by 1% in 2040.
- Battery cost and fuel price are the top sensitive parameters for BEVs.
- There is a clear correlation between battery cost and internal subsidies as it is more profitable for OEMs to invest in BEVs for dual-credit policy compliance.

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