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Evolutionary Game Analysis of New Energy Vehicle Battery Swapping Station Construction in China under Low-Carbon Policies

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Abstract: China's dual-point policy has been instrumental in promoting the new energy vehicle industry. However, the adoption of battery swapping stations in the battery-as-a-service (BaaS) model poses significant cost and implementation challenges. To address this, the government has extended its support to the BaaS model. This study employs an evolutionary game model involving new energy enterprises and local governments to assess the impact of the dual-point policy and BaaS model subsidy policy, while also considering the government's environmental concerns, including carbon emissions. The key findings are as follows: Firstly, solely implementing the dual-point policy proves insufficient for widespread BaaS model adoption. Secondly, exclusively implementing the subsidy policy for swapping stations may lead to subsidy fraud. Lastly, the combined effect of the dual-point policy and the BaaS model subsidy policy is positive. Lower subsidy rates and credit prices attract vehicle enterprises towards the BaaS model.

1. Introduction

China aims to reach the peak of carbon dioxide emissions by 2030 and reduce carbon dioxide emissions per unit of GDP by 60%-65% compared to 2005 levels[1]. While positive results have been seen in emission reduction through upgraded greenhouse gas management measures, China's reliance on imported petroleum, reaching 70.9%, poses energy security risks. Additionally, the environmental and climate impacts of fossil fuel consumption, especially in the automotive sector, are a growing concern. New energy vehicles, particularly electric vehicles, are rapidly emerging as a key solution to improve fuel efficiency and reduce petroleum consumption[2].The Energy Research Institute of the National Development and Reform Commission predicts a transformation of powertrain systems in the automotive industry between 2025 and 2030, with many companies, both domestic and multinational, phasing out internal combustion engine vehicles[3]. This shift signifies the inevitable replacement of traditional fuel vehicles by new energy vehicles, and the exit of internal combustion engine vehicles from the market is imminent[4].Among the various models for new energy vehicles, the battery swapping model offers significant advantages over the integrated vehicle-electricity model[5]. Charging stations face challenges in implementation and grid pressure, while battery swapping provides shorter replenishment times (3-5 minutes) and reduces battery degradation. Moreover, the battery cost is not included in the price of battery-swappable models, making them more affordable for consumers. Battery swapping also addresses consumer concerns, boosts sales for automakers, and facilitates centralized battery recycling[6].

However, the development of battery swapping vehicles faces challenges that require capital and policy support. The high investment costs of battery swapping stations and the low market share of battery swapping vehicles hinder profitability. To promote the battery swapping model, the government has implemented supportive policies, such as exempting vehicles adopting this model from certain restrictions and calling for its accelerated promotion and application. Standards and safety requirements for battery swapping systems have also been established[7]. This study focuses on the battery swapping model in the new energy vehicle field, examining the impact of the dual credit policy and battery swapping station subsidy policy on vehicle enterprises' choices between the integrated vehicle-electricity model and the vehicle-electricity separation strategy. The research aims to assess the effectiveness of subsidy policies in promoting the battery swapping model and whether policy synergies or coordination failures occur between the dual credit policy and the battery swapping station subsidy policy. The following problems are worth studying1) How does the dual credit policy influence vehicle enterprises' choices between the integrated vehicle-electricity model and the vehicle-electricity separation strategy? 2) What is the impact of the battery swapping station subsidy policy on vehicle enterprises' choices between the integrated vehicle-electricity model and the vehicle-electricity separation strategy? Does it effectively promote the healthy development of the battery swapping industry? 3) Can the simultaneous implementation of the dual credit policy and the battery swapping station construction subsidy policy synergistically promote vehicle enterprises' vehicle-electricity separation strategy?

2. Model Assumptions and Construction

2.1 Assumptions

This study focuses on the choice of the integrated vehicle-electricity charging model in the dual credit policy by vehicle companies and the subsidy decisions of local governments for battery swapping station infrastructure. Using evolutionary game theory, the study assumes game participants with bounded rationality, which is more realistic in practical scenarios. Evolutionary game theory examines groups rather than individuals, emphasizing the process of group dynamics.[8] It suggests that companies, under the influence of evolving game situations, will choose dynamic behavioral strategies in their interactions within the network. This assumption aligns with the characteristics of this study. Based on these considerations, the following assumptions are proposed:

Assumption 1: This evolutionary game involves two participants, if both parties exhibit bounded rationality. Game participant 1 represents new energy vehicle manufacturers using the integrated vehicle-electricity charging model, excluding those primarily focusing on battery swapping models. Game participant 2 represents local governments, who can choose to subsidize or not subsidize the establishment of battery swapping stations by new energy vehicle companies[9].

Assumption 2: It is assumed that the respective basic returns and social welfare of new energy vehicle manufacturers and governments are represented by R_1 and R_2. Vehicle companies can choose to produce battery swapping models while investing in the construction of battery swapping stations, or they can choose to produce integrated vehicle-electricity new energy vehicles. The cost of producing battery swapping models is represented by C_1, while the cost of producing integrated vehicle-electricity new energy vehicles is represented by C_2. Since battery swapping models do not include battery costs, $C_1 < C_2$.

Assumption 3: Manufacturers choosing the battery swapping model need to invest in battery swapping stations, which can bring them benefits. The cost of investing in battery swapping stations is represented by I_i, ($i = 1, 2, 3$), where I_1 represents the scenario where new energy vehicle companies invest in battery swapping stations and receive government subsidies, I_2 represents the scenario where new energy vehicle companies invest in battery swapping stations without government investment, and I_3 represents the scenario where the government subsidizes battery swapping companies while manufacturers producing integrated vehicle-electricity models choose not to produce battery swapping models. Since battery swapping models are more competitive in the market and can erode the market share of the integrated vehicle-electricity models, the assumption is made that the market size being eroded is $b * I_3 * D_3$, and $I_1 > I_2, I_3$. Furthermore, the improvement of battery swapping station infrastructure can reduce consumer anxiety about range anxiety, thereby increasing additional income for companies. Therefore, it is assumed that the profit from market growth brought about by investments by vehicle companies is represented by D_i, ($i = 1, 2, 3$). Moreover, the more companies invest, the greater the market growth and profit obtained by the vehicle companies, so it can be assumed that $D_1 > D_2, D_3$.

Assumption 4: When vehicle companies choose to invest, it also brings benefits to the government. The government needs to bear the environmental costs brought about by the choice of the integrated vehicle-electricity model by vehicle companies, represented by EC_i, ($i = 1, 2, 3, 4$). These costs include environmental pollution caused by improper battery recycling and additional costs due to peak grid pressure. Since the battery swapping model adopts unified battery management, it can efficiently recycle batteries and reduce peak grid pressure. Therefore, it is assumed that $EC_4 > EC_3$, $EC_2 > EC_1$. Additionally, investment in battery swapping stations can bring benefits to consumers, create related job positions during the operation of battery swapping stations, reduce carbon emissions, and increase land utilization efficiency. Thus, the social welfare brought about by these factors is represented by Ra_i, ($i = 1, 2, 3$), and the greater the investment made by companies, the greater the social welfare obtained. Therefore, $Ra_1 > Ra_2, Ra_3$.

Assumption 5: The government has introduced the dual credit policy to encourage the development of new energy vehicles. Vehicle companies that obtain positive credits can generate additional profits by selling these credits. The specific calculation of positive credits for vehicle companies depends on the number of new energy vehicles produced and the mileage of the produced models. To simplify the model, it is assumed that vehicle companies obtain credit benefits, represented by p, from the profit of each sold new energy vehicle. The size of p is influenced by the scoring efficiency and credit price. Additionally, to encourage more companies to adopt and produce battery swapping models, the government may subsidize battery swapping models or the construction of battery swapping stations. This study primarily discusses the impact of subsidies for battery swapping stations. Therefore, it is assumed that the subsidy rate for battery swapping stations by the government is represented by b (range).

2.2 Model Construction

Under the influence of the dual credit policy and the subsidy policy for battery swapping station construction, and based on the assumptions, the payoff matrix can be obtained as shown in Table 1. The entries in the table represent the expected profits of both vehicle companies and local governments.

Table 1: The payoff matrix for New Energy Vehicle (NEVs) manufacturers and Local Governments(LGs).

Game-agent		**LGs**	
		With subsidy y	Without subsidy 1-y
NEVs	Producing& investing x	$R_1+D_1+p\left(R_1+D_1\right)-C_1-\left(1-b\right)I_1$	$R_1+D_2+p\left(R_1+D_2\right)-C_1-I_2$
		$R_2+Ra_1-EC_1-bI_1$	$R_2+Ra_2-EC_2$
	Not producing& investing 1-x	$R_1+p\left(R_1-D_3\right)-bI_3D_3-C_2$	$R_1+pR_1-C_2$
		$R_2+Ra_3-EC_3-bI_3$	R_2-EC_4

According to the payoff matrix in Table 1, the expected payoff and expected average payoff for the new energy vehicle manufacturer's choices of investing and producing battery swapping or not investing and producing battery swapping are as follows:

$$\pi_{x_1}=-C_1-I_2+R_1+pR_1-D_2\left(1+p\right)\left(y-1\right)+(D_1+\left(-1+b\right)I_1+I_2+D_1p)y$$

$$\pi_{x_2}=-C_2+R_1+pR_1-D_3\left(bI_3+p\right)y$$

$$\pi_x=x\pi_{x_1}+\left(1-x\right)\pi_{x_2}$$

The dynamic replicator equations for the new energy vehicle manufacturer is:

$$F\left(x\right)=dx/dt=y\left(\pi_{x_1}-\pi_x\right)=\left(-1+x\right)x(C_1-C_2+I_2+D_2\left(1+p\right)\left(-1+y\right)-\left(D_1+\left(-1+b\right)I_1+I_2+bD_3I_3+\left(D_3+D_3\right)py\right)$$

Similarly, the expected income and the expected average income of local governments choosing to subsidize and not subsidize electricity replacement can be obtained. The dynamic replication equation of the government can be obtained in the same way:

$$F\left(y\right)=dy/dt=y\left(\pi_{y_1}-\pi_y\right)=\left(EC_3-EC_4+bI_3-Ra_3+\left(EC_1-EC_2-EC_3+EC_4+bI_1-bI_3-Ra_1+Ra_2+Ra_3\right)x\right)\left(-1+y\right)y$$

By setting $dx/dt=0$ $dy/dt=0$, we can obtain the equilibrium points: $E_1\left(0,0\right)$, $E_2\left(1,0\right)$, $E_3\left(0,1\right)$, $E_4\left(1,1\right)$, $E_5\left(x^*,y^*\right)$.

Where $x^*=\dfrac{EC_3-EC_4+bI_3-Ra_3}{-EC_1+EC_2+EC_3-EC_4-bI_1+bI_3-Ra_1+Ra_2-Ra_3}$.

And $y^*=\dfrac{(-C_1+C_2+D_2-I_2+D_2p)}{(-D_1+D_2+I_1-bI_1-I_2-bD_3I_3-D_1p+D_2p-D_3p)}$.

$E_5\left(x^*,y^*\right)$ exists if:

$$0<EC_3-EC_4+bI_3-Ra_3<-EC_1+EC_2+EC_3-EC_4-bII_1+bI_3-Ra_1+Ra_2-Ra_3$$

$$0<-C_1+C_2+D_2-I_2+D_2p<-D_1+D_2+I_1-bI_1-I_2-bD_3I_3-D_1p+D_2p-D_3p \quad .$$

Equation (1) is a Jacobian matrix. Equation (2) is The trace of the Jacobian matrix. They are both used to judge the stability of evolutionary game points. If the local equilibrium point satisfies $det(J)$>0 and $tr(J)$<0, If the local equilibrium point satisfies >0 and tr <0, it indicates that the point is an evolutionarily stable strategy of the system[9]. The five local stable equilibrium points are shown in Table 2.

$$det(J)=\begin{vmatrix}\frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y}\\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y}\end{vmatrix} \tag{1}$$

$$\mathrm{tr(J)}=\frac{\partial \mathrm{F(x)}}{\partial \mathrm{x}}+\frac{\partial \mathrm{F(y)}}{\partial \mathrm{y}} \tag{2}$$

Table 2: Equilibrium Point Analysis

Equilibrium Point	$det(J)$	$tr(J)$	Stability
$E_1(0,0)$	+	-	Stable
$E_2(1,0)$	+	-	Stable
$E_3(0,1)$	+	-	Stable
$E_4(1,1)$	+	-	Stable
$E_5(x^*, y^*)$	\	0	Unstable

3. Case Analysis under Different Policies

Based on the constraints of Proposition 1, we simulate the trend of car manufacturers' investment in battery swapping systems towards (1, 0) under different policies and analyze the impact of policy variables on the evolutionary game results. The evolutionary data is based on publicly available data from the battery swapping industry for parameter settings.

NIO, in 2021, invested heavily in battery swapping stations and received a favorable market response. From January 2021 to December 2021, NIO established 589 battery swapping stations, a year-on-year increase of 351%9. Car sales reached 91,000 units, a year-on-year increase of 109%. In the entire battery swapping market, the number of swapping stations increased by 847, a growth of 152% compared to 2020. The market size of battery swapping vehicles reached 160,000 units, with a year-on-year growth rate of 162%. In terms of manufacturing costs, battery swapping vehicle production does not include battery costs, which account for 30-40% of the total vehicle cost. Additionally, due to government subsidies for battery swapping vehicles, the price difference between battery swapping vehicles and conventional electric vehicles can reach 50%. On average, one battery swapping station requires three operational staff, so the increase in battery swapping stations in 2021 directly created 2,541 job positions. Furthermore, in terms of environmental governance, the carbon emissions per kilometer for gasoline vehicles is approximately 176 grams of CO2, while for electric vehicles, it is 70 grams of CO_2. It is estimated that by 2035, the carbon emissions per kilometer for electric vehicles can be reduced to 20 grams of CO_2[10]. Based on the current carbon pricing of 30 yuan per ton and an average vehicle lifespan of 8 years or 160,000 kilometers, the newly added battery swapping vehicles in 2021 can directly contribute to a carbon emissions control cost of 100 million yuan. Moreover, due to the advantages of rapid energy replenishment and the ability to operate without stopping, battery swapping stations indirectly improve land utilization efficiency. In terms of peak grid pressure, the price difference between peak and off-peak electricity can be considered. Currently, the average price difference between peak and off-peak electricity in the national grid is around 0.6-0.7 yuan, with an increase of 40-65%. The specific parameter settings for simulation based on the investigated case data are as follows: $D_1=7$, $D_2=3$, $D_3=3$, $C_1=1$, $C_2=1.8$, $I_1=10$, $I_2=7$, $I_3=6$, $EC_1=2$, $EC_2=5$, $EC_3=5$, $EC_4=8$, $Ra_1=0.6$, $Ra_2=0.3$, $Ra_3=0$.

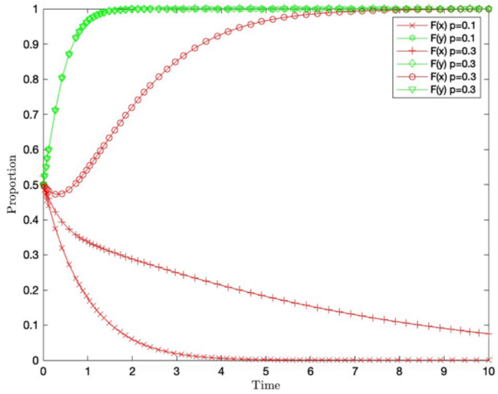


Figure 1: Without the subsidies of the local government case ($b=0$)

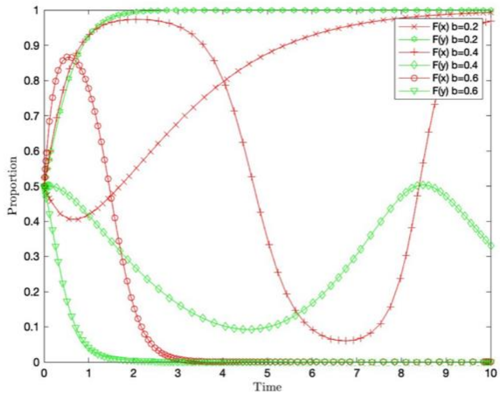
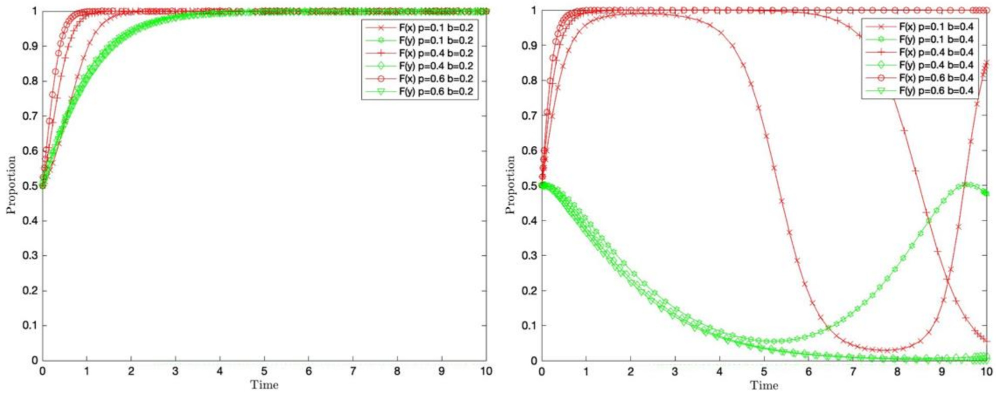


Figure 2: With the dual-credit policy case ($p=0$)



(a). With low credit price ($b=0.2$)　　(b). With middling credit price ($b=0.4$)

Figure 3: With the dual-credit policy and the subsidies of the local government cases

3.1 Impact of Dual-Credit Policy

Currently, the dual-credit prices in China's new energy vehicle market are relatively low. In 2021, the overall positive credits in the market were three times higher than the negative credits, and the credit price dropped to below 1,000 credits per unit. In 2020, the peak price reached 4,000 yuan per credit. NIO sold approximately 200,000 credits of new energy vehicles in 2021, generating revenue of 517 million yuan, equivalent to 2,585 yuan per credit. Considering the impact of credit prices alone, with $b=0$, assuming credit prices(p) of 0.1, 0.2, and 0.3, the evolutionary path of the battery swapping market under the dual-credit policy is shown in Figure 1. By comparing the evolutionary simulation results with different credit prices, the following conclusions can be drawn: (1) When the credit price is too low, the dual-credit policy fails to promote the development of the battery swapping industry. (2) As the credit price increases, the rate at which companies decide to abandon BaaS models significantly slows down. (3) When the credit price is high enough, as the income generated by credits gradually covers the investment costs of battery swapping stations, car manufacturers will choose to produce and invest in BaaS models.

3.2 Impact of Subsidy Policy

The simulation results are shown in Figure 2. Without considering the influence of the dual-credit policy, by comparing the evolutionary simulation results with different subsidy rates, the following conclusions can be drawn: (1) When the subsidy rate is low, car manufacturers initially do not produce or invest in BaaS models. However, with continuous government subsidies, car manufacturers produce and invest in BaaS models, and the government provides continuous subsidies for battery swapping station construction. (2) As the subsidy rate increases, there is a phenomenon of subsidy fraud. (3) When the subsidy rate is sufficiently high, it can quickly promote car manufacturers to produce and invest in BaaS models. However, since the government's subsidies do not bring corresponding social welfare benefits, the proportion of local governments choosing to provide subsidies gradually decreases. Eventually, subsidies are phased out, and the number of car manufacturers choosing to invest and produce BaaS models rapidly decreases, leading the system to evolve towards (0, 0).

3.3 Impact of Dual-Credit Policy and Subsidy Policy

Both the dual-credit policy and subsidy policies have a combined impact on the development of the battery swapping industry. Therefore, it is necessary to discuss the evolutionary game path under the influence of combined policies. This section discusses the influence of high, medium, and low credit prices on the evolutionary game path under low and medium subsidy rates. The results of the evolutionary game are shown in Figure 3(a). Scenario 1 considers the impact of high, medium, and low credit prices on the system under a low subsidy rate ($b=0.2$), and p is set to 0.1, 0.4, and 0.6, respectively. It can be observed that when the subsidy rate is low, due to the significant social welfare brought by the battery swapping industry, the government chooses to subsidize the basic construction of battery swapping stations. Car manufacturers also choose to invest and produce BaaS models.

The results of the evolutionary game are shown in Figure 3(b). Scenario 2 considers the impact of high, medium, and low credit prices on the system under a medium subsidy rate ($b=0.4$), and p is set to 0.1, 0.4, and 0.6, respectively. It can be observed that (1) when the credit price is low, subsidies encourage car manufacturers to invest and produce BaaS models, but as the subsidy rate increases, there is still a phenomenon of subsidy fraud. The proportion of local governments choosing to subsidize battery swapping decreases due to social welfare considerations. (2) When the credit price increases, subsidies encourage car manufacturers to invest and produce BaaS models, but as subsidies are phased out, car manufacturers struggle to sustain profitability from battery swapping, and subsidy fraud cannot be eliminated. (3) When the credit price is sufficiently high, an increase in the subsidy rate can prompt car manufacturers to choose to invest and produce BaaS models. It is worth noting that even if local governments choose to withdraw subsidies, car manufacturers, with the support of the dual-credit policy, will still choose to produce and invest in BaaS models. The entire system ultimately evolves towards (1, 0), with continued development of the battery swapping industry supported by initial local government assistance.

4. Conclusion

Implementing the dual-credit policy alone does not effectively promote the battery-swapping model. A high credit price and investment in infrastructure are necessary for the policy to have a positive impact. When the credit price is low, enterprises cannot afford the deployment cost of battery-swapping stations without government subsidies, leading them to opt out. Similarly, implementing only the subsidy policy without the dual-credit policy does not foster healthy development. Continuous low-rate subsidies encourage enterprises to invest in battery-swapping vehicle production, but they rely on ongoing government support. High subsidies from local governments attract initial investment but result in enterprise withdrawal when the proportion of subsidies decreases. Excessive subsidies exceeding local government capacity also lead to disinvestment. The combined effect of the dual-credit policy and subsidy policy effectively promotes battery-swapping development. Lower subsidies and credit prices incentivize enterprises to invest, and as credit prices rise, choosing the battery-swapping model becomes easier. Higher subsidies influence enterprise investment, but they may withdraw from vehicle production after subsidies are phased out. When credit prices are sufficiently high and supported by local governments, the battery-swapping market expands, and enterprises invest in production. However, high subsidy costs eventually force local government withdrawal.

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References

[1] Dong, F., Hua, Y. and Yu, B., "Peak Carbon Emissions in China: Status, Key Factors and Countermeasures—A Literature Review," Sustainability 10(8), 2895 (2018).

[2] Hao, H., Liu, Z., Zhao, F., Li, W. and Hang, W., "Scenario analysis of energy consumption and greenhouse gas emissions from China's passenger vehicles," Energy 91, 151–159 (2015).

[3] Gong, H., Shi, X. and Zou, X., "The Impact of China's New Energy Vehicles on the Realization of Carbon 'Zero-emission' and Future Trend Analysis:," presented at 2022 7th International Conference on Financial Innovation and Economic Development (ICFIED 2022), 2022, Zhuhai, China.

[4] Zhili, D., Boqiang, L. and Chunxu, G., "Development path of electric vehicles in China under environmental and energy security constraints," Resources, Conservation and Recycling 143, 17–26 (2019).

[5] Sarker, M. R., Pandzic, H. and Ortega-Vazquez, M. A., "Optimal Operation and Services Scheduling for an Electric Vehicle Battery Swapping Station," IEEE Trans. Power Syst. 30(2), 901–910 (2015).

[6] Adegbohun, F., Von Jouanne, A. and Lee, K., "Autonomous Battery Swapping System and Methodologies of Electric Vehicles," Energies 12(4), 667 (2019).

[7] Feng, Y. and Lu, X., "Construction Planning and Operation of Battery Swapping Stations for Electric Vehicles: A Literature Review," Energies 14(24), 8202 (2021).

[8] Keivanpour, S., Ait-Kadi, D. and Mascle, C., "Automobile manufacturers' strategic choice in applying green practices: joint application of evolutionary game theory and fuzzy rule-based approach," International Journal of Production Research 55(5), 1312–1335 (2017).

[9] Yuan, J.-H., Zhou, S., Peng, T.-D., Wang, G.-H. and Ou, X.-M., "Petroleum substitution, greenhouse gas emissions reduction and environmental benefits from the development of natural gas vehicles in China," Pet. Sci. 15(3), 644–656 (2018).