Developing Hydrogen Infrastructure and Demand

An Evolutionary Game and the Case of China

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Abstract

Diffusion of hydrogen refueling stations (HRS) is key to promotion of hydrogen vehicles. In this paper, we explore the nexus between critical stakeholders in the hydrogen industry from a game perspective. We investigate the proposed policy for promotion of hydrogen vehicles in China. We model the three main actors in hydrogen infrastructure development, i.e. public sectors, private investors, and consumers. The tripartite evolutionary game analyzes the interactive policy process of subsidy provision, infrastructure investment, and fuel consumption. We then examine the evolutionary stable strategy (ESS) of the system. We propose a policy mechanism for how to set values of key parameters to promote active cooperation of the three actors in HRS diffusion. A numerical simulation validates the solution of the game and sensitivity analyses of initial probabilities and key parameters. We find that boosting initial willingness of actors to choose cooperative hydrogen strategies is beneficial to lead the game system to the ideal consequence. We offer some recommendations including establishing regulation standards for the construction of HRS, increasing financial incentives to each actor and decreasing the cost of HRS and retail price of hydrogen.

Keywords: Hydrogen infrastructure; Evolutionary game; Numerical simulation; China

JEL classification: C73, Q42, Q48, R42

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1. Introduction

The transport sector is one of the main contributors to carbon emissions (Kejun et al., 2021). Currently, fuel cell electric vehicles (FCEV) is regarded as an effective way to decarbonize the transportation industry (Gu et al., 2020; Staffell et al., 2019). Many auto manufacturers have announced FCEV commercialization plans: Toyota, Hyundai, General Motors, Honda, Mercedes/Daimler, and others have committed to do the same, some as early as the 2015–2017. Meanwhile developing the hydrogen infrastructure, i.e. hydrogen refueling stations (HRS), is a challenge to commercialization of FCEV (Wu et al., 2021). The diffusion of HRS is believed to generate more impetus to the adoption of FCEV than the price of FCEV (Alazemi and Andrews, 2015; Sdanghi et al., 2019). Thus, it is necessary to plan investment in the HRS construction network (Liu et al., 2018).

The development of HRS is important for achieving the "Carbon Neutrality" goals (van Renssen, 2020). In addition to formulating macro policy road map, subsidies provided by governments are critical for facilitating participation of other actors, because HRS network expansion depends on consumer demand and investors (Köhler et al., 2010; Nistor et al., 2016). Development of HRS also depends on consumer willingness to pay for them (Ono and Tsunemi, 2017). The price of hydrogen at HRS is currently considerably higher than gasoline and diesel and an obstacle for diffusion of FCEV (Grüger et al., 2018; Hardman et al., 2017). For private investors, due to immature industry standards, high costs and uncertain profits, investors need to decide whether to invest in HRS (Bai and Zhang, 2020). A coherent policy for HRS and financial incentives can encourage private investment (Ogden and Nicholas, 2011). In order to promote hydrogen infrastructure, it is necessary to establish a business environment that is conducive to private companies and consumers. Therefore, governmental intervention in the development of HRS is called for (Ren et al., 2015).

There are three salient stakeholders in the diffusion of HRS: public sectors, private investors and consumers. Given the interactions between these actors, game theory provides a powerful means to study their mutual strategic decision-making. The objective of this study is to investigate the interactive nexus for attaining the ideal evolutionary stable strategy (ESS). We focus on the hydrogen vehicle industry in China, which is the world's largest hydrogen producer and plans for the deployment of hydrogen vehicles. China's central government has adopted policies for HRS road map in selected provinces (or cities) as pilot areas. Thus, the promotion of HRS in the pilot regions will influence the development of hydrogen infrastructure in other regions of China.

We aim to (i) investigate the strategies of public sectors in the pilot regions, private investors, and consumers; (ii) build a public-private-consumer tripartite evolutionary game; and (iii) explore how initial probabilities and key parameters of each actor influences the dynamic trajectories of the game, through numerical simulation. It provides a simulation tool for studying the evolutionary trajectories of the main actors in the hydrogen vehicle industry, thereby providing theoretical support for strategies to deploy a hydrogen industry. To our knowledge, this is the first study to explore the diffusion of HRS at the micro level using a dynamic three-actors gaming theoretic approach. This is also the first game analysis of China's recent FCEV industry policy.

The remainder of this paper is organised as follows. Section 2 summarises the literature on the HRS. Section 3 introduces the case in China. Section 4 presents the methodology. Section 5 presents and describes the results. Section 6 conducts the numerical simulation of the game. Section 7 is conclusions and policy implications.

2. Literature Review

Although FCEV have increasingly commercial appeals, there are challenges to overcome. A barrier to FCEV industrialization is lack of hydrogen infrastructure. Public sectors, private sectors and end users are three core actors in diffusion of HRS. There are some relevant strands in the literature concerning their roles in the development of the hydrogen industry.

First, public sectors play a critical role in formulating policies and regulatory frameworks, stimulating investment stakeholders, and implementing subsidies and tax breaks for jump-starting the popularization of HRS (Ambrose et al., 2017; Kim et al., 2019; Lee et al., 2011; Vergragt and Brown, 2007; Wu et al., 2019). Kang and Recker (2014) find that before a profitable hydrogen market is ready for private sectors, public sectors need to contribute to the initial investment in hydrogen infrastructure, for reaching economies of scale while simultaneously attracting private investment. For instance, in California twelve governmental agencies are the largest investors in the HRS (Richardson et al., 2015). Mohideen et al. (2021) review the literature on the hydrogen economy and its end-use sector. They conclude that it is important to support the interplay between governments, car manufacturers, infrastructure suppliers, and consumers. They also emphasize the opportunities of economic rebound in the post Covid-19 era by promoting FCEV industry. Trencher (2020) and Trencher et al. (2020) find obstacles to HRS diffusion from supply-side, demand-side and institutional design. They discuss governance strategies, regulation, market and consumer incentives, and public–private coordination to ramp up the diffusion of HRS.

Second, in order to attract consumers to HRS is important. However, general low-carbon policies can rarely act as a stimulus for consumers' willingness to use HRS (Brey et al., 2017; Fan et al., 2020; Fúnez Guerra et al., 2016; Hardman and Tal, 2018). Kang and Park (2011) and Kim et al. (2019) analyse the nexus between the propagation of governmental "low carbon, green growth" policy and consumers' willingness to adopt FCEV in Korea. They show that the cost of hydrogen retail and fuel availability are key for consumer acceptance and relevant subsidy plan could contribute to HRS diffusion. Likewise, Miele et al. (2020) point out large-scale HRS construction is only a small stimulus to consumers. Strong financial incentives are necessary. Sun et al. (2019) discuss impact of appropriate site and size design of HRS on consumers, for optimal reduction in regional consumers' purchase cost of hydrogen. In contrast, Symes et al. (2014) point to proximity to ensure consumer convenience as the dominant factor in deployment of HRS. However, consumer acceptance is conducive to HRS construction. Campíñez-Romero et al. (2018) consider whether the HRS network can be economically supported if taxi fleets are replaced by FCEV in Madrid city. The result shows that HRS roll-out would only be viable with a subsidy for the cost of construction and operation. Huétink et al. (2010) find consumers possess the small world network attributes, and social network among consumers affects the initial diffusion of HRS. Itaoka et al. (2017) show that consumers have become keener on HRS, but are increasingly concerned with the risk and profits.

Third, the importance of attracting private sectors is emphasized as public sectors are the main investors in HRS placing management and operational burden on them (Richardson et al., 2015). El-Taweel et al. (2019) discuss the economic feasibility of the HRS from the private investor perspective and propose a model to optimally schedule HRS for multiple applications including serving the FCEV and the electricity market operator to increase profits. Houghton and Cruden (2010) analyse the effect of investment in HRS on three competing companies by means of financial tools such as net present value, based on government aiming to stimulate private sector to reduce emissions. Bonilla and Merino (2010) address the subsidies and fares for hydrogen buses and point out that financial leverage can attract private investors, because they offer an acceptable yield of their investments. How the HRS are financed is a key for both public and private sectors. Bai and Zhang (2020) consider public-private-partnership and transfer-operate-transfer as the most appropriate models of financing HRS in China. Engelen et al. (2016) and Li et al. (2020) examine the optimal investment timing of HRS under market and technology uncertainties such as hydrogen retail price and project failure.

China presents significant potential to develop hydrogen infrastructure due to availability of hydrogen supply. The literature mainly focuses on China's hydrogen road map and proposing policy instruments for tackling critical barriers of HRS (Hu et al., 2010; Kendall, 2018; Wu et al., 2021; Xu et al., 2020, 2017; Xu and Su, 2016; Zhang and Qin, 2018; Zhao et al., 2020; Zhou et al., 2021). In September 2020, China announced a landmark policy in the form of hydrogen demonstration city alliances in selected regions. The Ministry of Finance requires each pilot city to build more than 15 HRS by 2023 to qualify for FCEV grants[1].

In sum, the literature discusses the HRS issues only from the perspective of one stakeholder or two stakeholders in hydrogen infrastructure. To the best of our knowledge, only two studies have used a three-actor perspective where public sectors, private investors, and consumers interact to develop a hydrogen infrastructure. Ko et al. (2017) review the approaches to locating refueling stations and refueling demand estimation. They propose that future refueling location models should consider three main actors: government agencies, drivers, and refueling service providers. Haghi et al. (2018) explore the interaction among government, energy hub operator, and energy consumer. They assess the net present value of emission reduction potential in a microgrid coupled with wind power and hydrogen storage infrastructure. The present paper is the first study to quantitatively explore the interplay of three actors in the hydrogen refueling infrastructure. Given the highly interactive relationship among the actors, evolutionary game theory offers a suitable means to study the interplay of their strategic decision-making (Tian et al., 2019). No other study has yet used this method and we provide a new perspective to the analysis of diffusion of HRS and similar infrastructure development analysis.

3. Hydrogen in China

By December 2020, China has built 118 HRS. However, it is not easy for HRS operators to make a profit. More than 70 HRS currently in operation are at a loss. Due to high costs of HRS, the cost recovery period is long. Furthermore, FCEV are in the demonstration stage and have not yet achieved large-scale production, and the cost of purchasing FCEV is high. Due to the fact that currently there are few HRS and they are mainly in the suburbs, this also restricts ordinary consumers from buying hydrogen passenger vehicles. Because the existing HRS are mainly designed for commercial FCEV such as logistics vehicles and buses with fixed driving routes, not suitable for flexible passenger FCEV (Ren et al., 2020). There is still no good profit model for HRS that only provide hydrogen refueling services. In order to achieve a balance of revenue and expenditure and make a profit, it is necessary to form the scale effect of HRS.

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[1] http://www.gov.cn/zhengce/zhengceku/2020-10/22/content_5553246.htm.

Many cities have begun to prepare strategic plans for the hydrogen industry. Table 1 illustrates a roadmap for development of FCEV and hydrogen infrastructure in China. By 2030, China plans to realize the commercial application of one million FCEV and build 1000 HRS. In the capital market, although hydrogen-related firms account for a low proportion of the profit of A-share listed companies, hydrogen is still the key development direction of many listed companies. China is the world's largest hydrogen producer, but the inadequate infrastructure is an impediment to commercial diffusion of the hydrogen vehicle industry.

Table 1

Roadmap for development of hydrogen in China.

Development Goals	Technical Roadmap	Development Focus
Move from pilot to large-scale deployment between 2020 and 2030. ➢ No. of FCEV 2020: 5k; 2025: 50k; 2030: 1,000k ➢ No. of HRS 2020: 100; 2025: 350; 2030: 1k	➢ Key fuel cell materials ➢ Fuel cell stack technology ➢ System integration and control technology ➢ Design and system integration of FCEV ➢ Cost reductions	➢ Novel key fuel cell materials ➢ Key auxiliary system components ➢ High performance fuel cell electric drive system ➢ Hydrogen infrastructure in production, transport, storage and refueling

Source: Tu (2020)

In 2020, to promote hydrogen industry, the central government promulgated the "*Notice on launching demonstration applications of fuel cell electric vehicles*", the expected hydrogen demonstration program. Specifically, China's central government has selected several cities or provinces (Beijing, Shanghai and Guangdong) for hydrogen demonstration application. These places will be designated as FCEV demonstration pilot areas and they will form respective hydrogen energy development alliances. They need to meet the requirements for HRS construction set by the central government, such as building at least 15 HRS within a 4-year period. They will earn financial rewards provided by the central government with successful implementation of hydrogen demonstration. Local governments will be responsible for the hydrogen development. The reward is provided to local governments, not directly to hydrogen industry or companies.

4. Methodology

4.1. Main actors in the game

The first step is to identify actors in the game. Based on China's recent hydrogen policy and key barriers to the HRS (Xu et al., 2020), there are three main stakeholders as follows.

(i) Public sectors

In this paper public sectors refers to local government and state-owned enterprises (SOEs) in the selected cities for the program. Local government is in charge of local affairs. Governmental intervention in HRS diffusion is necessary, given that the hydrogen vehicle industry is in infancy (Ren et al., 2020). For local governments, encouraging HRS diffusion is beneficial for environmental improvement and attracting policy support from central government (Kendall et al., 2017). The local governments from selected areas can decide whether to provide subsidies for private investors and consumers (Hwang et al., 2021; Li et al., 2021). For instance, Guangdong provincial government will subsidize HRS with refueling capacity of over 500 kg/day[2]. Even in the same city, different district governments have different subsidy policies: only Nanhai District in Foshan City of Guangdong province has subsidies for hydrogen refueling. As the hydrogen industry is not mature, the provision of subsidies is an incentive for promoting the HRS diffusion (Bae and Cho, 2010).

If the HRS project does not attract private investors, public sectors will build the HRS through SOEs[3]. The participation of SOEs not only meets the quantity requirements set by central government[4], but also seizes the strategic opportunities to deploy the entire hydrogen industry chain. Public sectors in China encourage private sectors to participate in the development of HRS[5], which can mitigate the fiscal burden of public sectors and accelerate the layout of the hydrogen industry. It is also beneficial to promote the public-private partnerships (PPP) in HRS investment and operation. For the demand side, the increasing consumers participation in the hydrogen market will play a dominant role in reducing the cost of FCEV and HRS and help the local government achieve the hydrogen development goal.

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[2] https://www.chinadaily.com.cn/a/202101/06/WS5ff51a99a31024ad0baa0c53.html.

[3] A SOE is a legal entity responsible for commercial activities on behalf of government. For instance, after Shandong government showed strong interest in hydrogen, two provincial SOEs, Shandong Heavy Industry Group and Shandong Port Group, recently cooperated on HRS building in seven ports in Shandong.

[4] Price of hydrogen at HRS ≤ RMB 35/kg; Promote at least 1000 FCEV and 15 HRS.

[5] http://www.cqcs.gov.cn/zwgk_164/jytabl/zxtabl/202009/t20200903_7843666_wap.html.

(ii) Private investors

The development of China's hydrogen industry is bottom-up. Private enterprises take the lead in entering and local governments give strong support. Therefore, private enterprises have been the vanguard of the hydrogen energy industry. The hydrogen transport market is considered a niche business which has not been monopolized by SOEs. The aim is to attract private enterprises to participate in the HRS projects (El-Taweel et al., 2019), especially in demonstration and commercialization stages, as in the Chinese solar market (Tu, 2020). Private investors need to explore local policies for selecting the appropriate projects. Considering sunk cost, uncertainties in governmental policies, consumer preferences and other risks, private investors need to appraise the investment opportunities in the HRS (Ball and Weeda, 2015).

The retrofit and expansion of HRS on existing gas stations has proved important for accelerating the network layout of HRS (Wu et al., 2021). The large number of gas stations in China offers the opportunity to retrofit them with hydrogenation equipment. If private gas station companies are willing to transform the existing stations into hybrid stations for both gas and hydrogen refueling, there is no need to reapply to the government for land requisition or to employ new staff. The retrofit model thus reduces the marginal cost of diffusion. At the same time, the existing stations meet the needs of consumers and can promote hydrogen stations on a large scale. Participation of private companies can weaken the monopoly of SOEs in the HRS to create a market-oriented hydrogen industry less restrained by government intervention, resulting in lower hydrogen retail price and adoption by more consumers (Trencher, 2020). Accordingly, subsidy and expected consumers will be the propellant for private sectors' participation in the hydrogen market.

(iii) Consumers

The entry of consumers into the hydrogen market is the key to reducing the cost of HRS, increasing investor profit, and completing the government demonstration and application goals. Consumers will buy FCEV and use the HRS to refuel their cars. FCEV has shorter refuel time, less noise and pollution than other vehicles. Therefore, without considering other factors, consumers prefer FCEV and HRS. However, China just officially planned to regard hydrogen as an energy source in 2020. Despite the enthusiasm of public sectors for FCEV and HRS, for many consumers, the fear of hydrogen given its explosive nature may not be dispelled in the short term. Besides, retail price for hydrogen and FCEV in China are higher than in other countries (Bruce et al., 2018). Against this backdrop, in the near-term, the main consumers of HRS and FCEV in China are the logistics and transportation firms. Consumers will hesitate over whether or not to purchase FCEV and use HRS because of high usage cost. Therefore, hydrogen usage standards and subsidy incentives from governments, and participation of private investors to prevent high hydrogen prices are critical to consumer adoption of HRS.

4.2. Hypotheses in the game

The hypotheses of the model are shown as follows:

H1: Public sectors, private investors and consumers have bounded rationality.

H2: The agents can learn from each other to dynamically alter their own strategies.

H3: Public sectors have two strategies: "provide subsidies" and "not provide subsidies", with the probabilities being x ($0 \leqslant x \leqslant 1$) and 1-x respectively.

H4: Private investors have two strategies: "invest in HRS" and "not invest in HRS", with the probabilities being y ($0 \leqslant y \leqslant 1$) and 1-y respectively.

H5: Consumers have two strategies: "consume hydrogen in the HRS" and "not consume hydrogen in the HRS", with the probabilities being z ($0 \leqslant z \leqslant 1$) and 1-z respectively.

4.3. Replicator equations

The interaction between public sectors, private investors and consumers is evident in HRS diffusion. Using evolutionary game we can describe the decision-making process and learning behavior of multiple participants, reveal the dynamic evolution process of the system, and analyze and predict the group behavior of actors (Tang et al., 2021). The evolutionary game theory relaxes the hypotheses of perfect rationality and complete information in the static game, and has been applied in different fields (Chen et al., 2021; Fan and Dong, 2018; Fang et al., 2019; F. Li et al., 2021; Li et al., 2019; Wang et al., 2021; Xu et al., 2019; Zhu et al., 2020).

The basis of evolutionary game is replicator dynamics which is a dynamic differential equation describing the frequency of a particular strategy being adopted in a population. According to the principle of evolution, if the payoff of a strategy is higher than the average payoff of the population, this strategy will dominate in the population (i.e., survival of the fittest), which is reflected in the growth rate (replicator equation) of this strategy is greater than 0. The replicator equation can be given by the following differential equation (Friedman, 1991):

$$\frac{dx_k}{dt} = x_k[u(k,s) - u(s,s)],\ k=1, 2, 3, \dots, K \quad (1)$$

where x_k is the proportion of the population using strategy k, $u(k,s)$ is the payoff using strategy k, $u(s,s)$ is the average payoff, k is different strategies, and K is the overall strategies. If $\frac{dx_k}{dt}$ reaches a stable state in iteration, then strategy k is the so-called ESS.

The evolutionary game model reveals the complicated interactions among the public sectors, private investors, and consumers regarding the diffusion of HRS. The overall structure of the methodology is shown in Fig. 1.

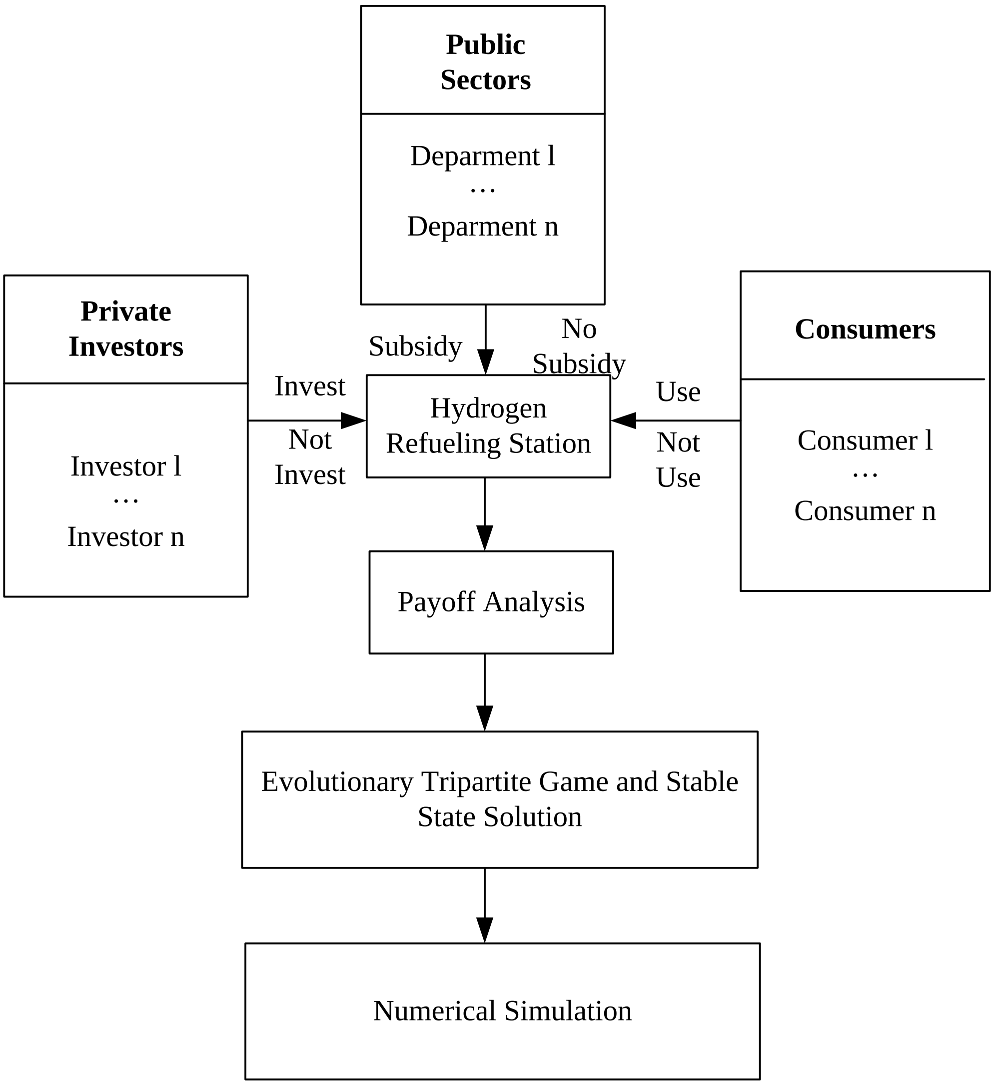

Fig. 1. The structure of the methodology in this paper.

5. Results

5.1. Payoff matrix

When consumers purchase hydrogen in the HRS, G_{s1} and G_{s2} respectively means political performance and fiscal rewards of the public sectors from the central government with and without providing subsidies to private investors and consumers. If there is no consumer, G_{s0} denotes political performance and fiscal rewards of the public sectors in the demonstration areas.

When public sector decides to provide subsidies to private investors and private enterprises decide to invest in HRS, S_{c1} and S_{c0} respectively means subsidies for the costs of construction and operations with and without consumers. S_{i0} is the bailout from public sector to private investors if no consumers are attracted. If there are no private sectors willing to participate in the HRS project, public sectors enter to fill the investment gap. Public sectors invest in hydrogen infrastructure to stimulate demand and participation in the hydrogen industry. Consumers need to purchase FCEV and use the HRS. Currently, they denote the logistics and transportation companies. P_h is payment for hydrogen consumption in the HRS. R_u is the additional environmental benefits when consumers adopt the HRS, such as favorable industrial support because they use zero-carbon transportation, and carbon mitigation benefits of CO_2 reduction by using hydrogen. S_u is the subsidy that consumers receive from the public sector. C_h represents the construction cost. C_{i1} and C_{i0} denote cost of operations and maintenance (O&M) when there are consumers and no consumers respectively. C_{g0} is the cost of O&M for public sectors when choosing to subsidize while private enterprises do not invest and consumers do not utilize HRS.

The payoff matrix of three stakeholders in the game is shown in Table 2. The core objective of this model is to address the social dilemma encoded in Table 2, to promote the game system to the optimal strategy state (P, P, P) with a superior environmental performance (Encarnação et al., 2018).

Table 2

Payoff matrix.

Type	Strategies	Payoffs
	(Public, Private, Consumers)	(Public, Private, Consumers)
(x, y, z)	(P, P, P)	$(G_{s1}-S_{c1}-S_u, P_h+S_{c1}-C_h-C_{i1}, R_u+S_u-P_h)$
$(x, y, 1-z)$	(P, P, D)	$(G_{s0}-S_{c0}-S_{i0}, S_{i0}+S_{c0}-C_h-C_{i0}, 0)$
$(x, 1-y, z)$	(P, D, P)	$(G_{s1}-C_h-C_{i1}+P_h-S_u, 0, R_u-P_h+S_u)$
$(x, 1-y, 1-z)$	(P, D, D)	$(G_{s0}-C_h-C_{g0}, 0, 0)$
$(1-x, y, z)$	(D, P, P)	$(G_{s2}, P_h-C_h-C_{i1}, R_u-P_h)$
$(1-x, y, 1-z)$	(D, P, D)	$(G_{s0}-S_{i0}, S_{i0}-C_h-C_{i0}, 0)$
$(1-x, 1-y, z)$	(D, D, P)	$(G_{s2}-C_h-C_{i1}+P_h, 0, R_u-P_h)$

(1-x, 1-y, 1-z)	(D, D, D)	(G_{s0}-C_h-C_{i0}, 0, 0)

Note: P and D respectively means actor participation and not participation in the HRS project.

5.2. Evolutionary strategy analysis

As shown in Table 2, we can calculate expected payoff of public sectors selecting "providing subsidies" (π_{11}) and "not providing subsidies" (π_{12}), and the average expected payoff of public sectors ($\overline{\pi_1}$), respectively:

$$\pi_{11} = y[z(G_{s1} - S_{c1} - S_u) + (1-z)(G_{s0} - S_{c0} - S_{i0})] + (1-y)[z(G_{s1} - C_h - C_{i1} + R_u - S_u) + (1-z)(G_{s0} - C_h - C_{g0})] \quad (2)$$

$$\pi_{12} = y[zG_{s2} + (1-z)(G_{s0} - S_{i0})] + (1-y)[z(G_{s0} - C_h - C_{i1} + P_h) + (1-z)(G_{s0} - C_h - C_{i0})] \quad (3)$$

$$\overline{\pi_1} = x\pi_{11} + (1-x)\pi_{12} \quad (4)$$

Likewise, the expected payoff of private investors selecting "investing" (π_{21}) and "not investing" (π_{22}), and the average expected payoff of private investors ($\overline{\pi_2}$) are shown as follows:

$$\pi_{21} = z[x(S_{c1} + P_h - C_h - C_{i1}) + (1-x)(P_h - C_h - C_{i1})] + (1-z)[x(S_{c0} + S_{i0} - C_h - C_{i0}) + (1-x)(S_{i0} - C_h - C_{i0})] \quad (5)$$

$$\pi_{22} = 0 \quad (6)$$

$$\overline{\pi_2} = y\pi_{21} + (1-y)\pi_{22} \quad (7)$$

Finally, the expected payoff of consumers selecting "using HRS" (π_{31}) and "not using HRS" (π_{32}), and the average expected payoff of private investors ($\overline{\pi_3}$) are obtained by:

$$\pi_{31} = x[y(R_u - P_h + S_u) + (1-y)(R_u - P_h + S_u)] + (1-x)[y(R_u - P_h) + (1-y)(R_u - P_h)] \quad (8)$$

$$\pi_{32} = 0 \quad (9)$$

$$\overline{\pi_3} = z\pi_{31} + (1-z)\pi_{32} \quad (10)$$

Accordingly, the replicator dynamic system including three actors is shown as follows:

$$F(x) = \frac{dx}{dt} = x(\pi_{11} - \overline{\pi_1}) = x(1-x)\big[yz\big(-S_{c1} - G_{s2} + S_{c0} - R_u + G_{s0} + P_h + C_{i0} - C_{g0}\big) - y\big(S_{c0} + C_{i0} - C_{g0}\big) + z(G_{s1} + R_u - S_u - G_{s0} - P_h - C_{i0} + C_{g0}) + C_{i0} - C_{g0}\big] \quad (11)$$

$$F(y) = \frac{dy}{dt} = y(\pi_{21} - \overline{\pi_2}) = y(1-y)[xz(S_{c1} - S_{c0}) + z(P_h - C_{i1} - S_{i0} + C_{i0}) + xS_{c0} + S_{i0} - C_h - C_{i0}] \quad (12)$$

$$F(z) = \frac{dz}{dt} = z(\pi_{31} - \overline{\pi_3}) = z(1-z)(xS_u + R_u - P_h) \quad (13)$$

When the system of replicator equations, including Eq. (11)-(13), equals 0, we can get eight equilibrium points, that is, E_1 (0, 0, 0), E_2 (1, 0, 0), E_3 (0, 1, 0), E_4 (0, 0, 1), E_5 (1, 1, 0), E_6 (1, 0, 1), E_7 (0, 1, 1) and E_8 (1, 1, 1). Further, the Jacobian matrix J is shown in Eq. (14). Of the eight equilibrium points, only E_8 (1,1,1) is the ideal outcome because it indicates the state of cooperation that government provide subsidy, private investors invest in HRS and consumers use hydrogen. The necessary and sufficient condition of the ESS is that all three eigenvalues of one Jacobian matrix are negative (Shan and Yang, 2019). Through substituting E_8 into Eq. (14), the Jacobian matrix consistent with equilibrium point E_8 are shown in Eq. (15).

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(y)}{\partial z} \end{bmatrix} \quad (14)$$

$$J_8 = \begin{bmatrix} G_{s2} + S_{c1} + S_u - G_{s1} & 0 & 0 \\ 0 & C_h + C_{i1} - S_{c1} - P_h & 0 \\ 0 & 0 & P_h - R_u - S_u \end{bmatrix} \quad (15)$$

Therefore, in order to obtain a policy design that make the system evolve to E_8 (1,1,1), the conditions that the parameters need to meet are shown in Eq. (16).

$$\begin{cases} G_{s2} + S_{c1} + S_u - G_{s1} < 0 \\ C_h + C_{i1} - S_{c1} - P_h < 0 \\ P_h - R_u - S_u < 0 \end{cases} \quad (16)$$

Specifically, from Eq. (16), the financial reward that public sectors receive when they provide subsidies minus the financial expenditures caused by the subsidies, need to be larger than the financial reward they receive when they do not provide subsidies. When HRS is in operation, the sum of the hydrogen sales income received by private investors plus the subsidies provided by the public sectors is greater than the construction and O&M costs of HRS. Consumer subsidies plus additional environmental benefits should be greater than fuel purchase expenditures. If these three conditions are met, the entire game system will stabilize at E_8 (1,1,1). This setting of parameter values is the policy design mechanism that promotes the active participation of the three actors in the development of the HRS industry.

6. Numerical Simulations

In order to make the analysis visualization, we use the numerical simulation to examine the dynamic trajectory of each actor from the initial state to the ESS. Specifically, the impacts of initial willingness of actors and changes of key parameters on the game system are analyzed. This paper takes the Foshan city, Guangdong province in China as an example. Because it is one of the first cities in China to start promoting FCEV, and it has relatively good financial incentives[6].

6.1. Parameter assignment

According to the China's HRS development target, in the 4-year demonstration period, the selected city should build at least 15 HRS. We assume that Foshan City will build 15 new HRS with the filling capacity of 350 kg/day. Currently, the FCEV in China are mainly logistics vehicles. We assume that logistics vehicle travels 150 km/day, and the number of driving days of each vehicle is 300 days/year. Therefore, the HRS is assumed to be used in 300 days/year as a result. Assuming that the HRS operate at full capacity daily, the total usage of hydrogen is 6300000 kg. A logistics FCEV with a load of 3.5t consumes approximately 2.5kg of hydrogen per 100 kilometers, so these 15 HRS can supply 1400 FCEV in this 4-year demonstration period. The construction cost of each HRS is 15.5 million yuan, and the annual operating cost of each HRS is 2 million yuan. Therefore, the total construction and operating cost of the HRS are 0.2325 billion yuan and 0.12 billion yuan, respectively.

When the HRS is not in use, the operating cost is 0. According to the local government's policy, each new HRS will be subsidized 3 million yuan, and retailed hydrogen/kg will be subsidized 18 yuan[7]. As a result, when HRS is in use and not in use, the total subsidy is 0.1584 billion yuan and 0.045 billion yuan respectively. Based on the current policy[8], each logistics FCEV will receive a subsidy of 300000 yuan, so the total subsidy received by logistics company is 0.42 billion yuan. If there are no consumers, private investors receive subsidies totaling 0.12 billion yuan based on annual HRS operating expenses. According to the current policy[9], the

[6] https://nanhaitoday.com/nhxww/articles/2019/09/06/5f7c902bfbdd484693b97936bef42196.html.

[7] http://www.china-hydrogen.org/?newslist-bzjqz/12390.html.

[8] https://www.miit.gov.cn/n1146295/n1652858/n1652930/n3757018/c5449722/part/5449738.pdf.

[9] http://www.gov.cn/zhengce/zhengceku/2020-10/22/content_5553246.htm.

retail price of hydrogen needs to be set at 35 yuan/kg, so the refueling cost for consumers is 0.2205 billion yuan.

Considering that the transportation industry has not yet been included in carbon market, the "dual-credit policy" measures for new energy vehicles are also aimed at automakers (Ma et al., 2021), so consumers' additional benefits from using hydrogen are set to 0. We assume that if public sectors complete the demonstration target because of the subsidy provided, they will receive fiscal reward of 1.87 billion yuan, and if without providing subsidies, they will be rewarded 0.76 billion yuan[10]. If the HRS has been built but no consumers, the reward for public sectors is set to 0. Accordingly, the values of parameters are shown in Table 3.

Table 3: Values of parameters.

Symbols	**Actors**	**Descriptions**	**Values (billion yuan)**
G_{s1}	Public sectors	Rewards when offering subsidies and HRS used	1.87
G_{s2}		Rewards when no subsidies and HRS used	0.756
G_{s0}		Rewards when HRS not being used	0
S_{c1}		Subsidy for private investors when there are consumers	0.1584
S_{c0}		Subsidy for private investors when no consumers	0.045
S_u		Subsidy for consumers	0.42
C_{g0}		O&M cost of HRS when choosing to subsidize and there no private investors and consumers	0
S_{i0}		Bailout from the public sector to private investors when no users	0.12
C_h	Private investors	Construction cost of HRS	0.2325
C_{i1}		O&M cost of HRS when there are consumers	0.12
C_{i0}		O&M cost of HRS when there are no consumers	0
R_u	Consumers	Additional environmental benefits of using HRS	0
P_h		Payment for use of the HRS	0.2205

[10] For specific calculation standards see http://www.gov.cn/zhengce/zhengceku/2020-09/21/content_5545221.htm.

As a result, the evolutionary process of public sectors, private investors, and consumers is shown in Fig. 2. This means that regardless of the initial probabilities of three actors, the definitive evolutionary result is E_8 (1, 1, 1). The parameters in Table 3 exactly meet the requirements of Eq. (16) through calculation. Therefore, this simulation verifies the solution obtained from the model.

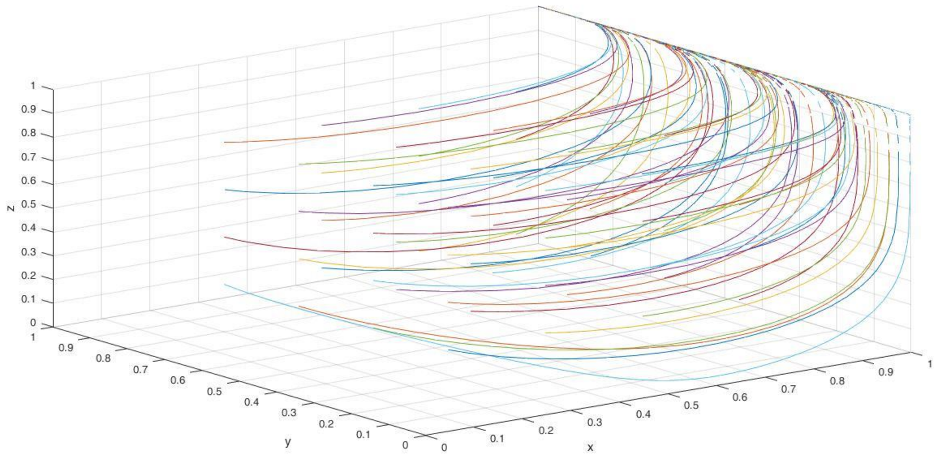

Fig. 2. The dynamic trajectory of the game system.

6.2. Sensitivity analyses of initial probabilities

First, we set x_0, y_0 and z_0 as the initial probabilities of public sectors, private investor and consumers respectively. We explore whether the initial probability affects the ESS. In addition to setting the initial probability of each actor choosing to cooperate at a middle level of 0.5 to reflect strategic neutrality, we also set the initial probabilities at 0.3, 0.7 and 0.9 respectively. The evolution path of the system is shown in Fig. 3.

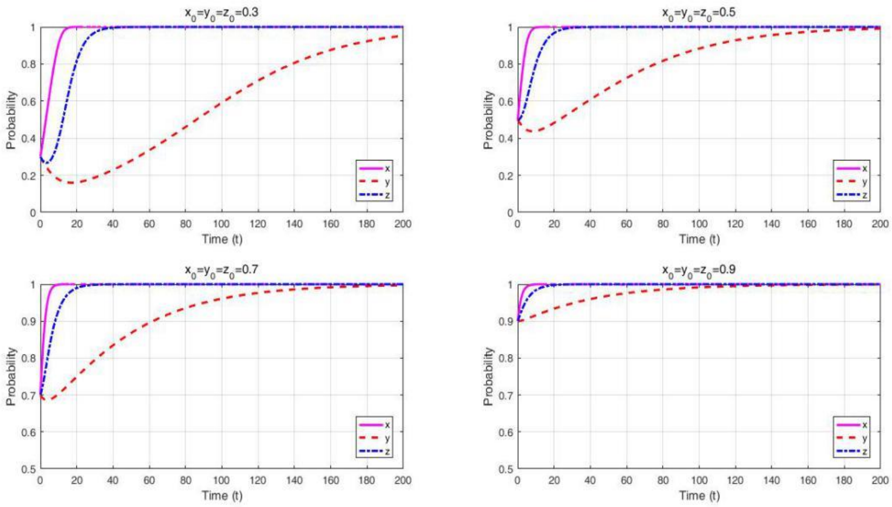

Fig. 3. The evolutionary process under different initial probabilities.

From Fig. 3, the ESS all stabilize at (1, 1, 1), meaning that public sectors choose positive subsidy policies, private investors choose investment and consumers choose adoption. All actors will choose to cooperate. The larger initial probabilities, the more likely the system is to evolve into (1, 1, 1). This illustrates that the initial willingness can affect final behaviors. Further, in all four scenarios, the public sector is the fastest to stabilize, followed by consumers, and private investors. This is mainly because that under current policies, public sectors are eager to complete the HRS construction goals in order to obtain rewards from the central government and seize the development opportunities in other regions. Existing incentives are also very attractive to users. For private investors, although their status will eventually converge to 1, the slowest rate shows that they are the least active actors now. This is why most of HRS are built by SOEs represented by Sinopec at present.

The above analysis is a situation where the initial probabilities of the three actors change at the same time. Next, we discuss how trajectories alter when the initial probability of an actor changes from 0.1 to 0.9 while other actors remain strategy neutral (0.5). The impact of one on the others is shown in Fig. 4-6. From Fig. 4 we see that, as x rises, consumers and private investors are increasingly willing to evolve to 1. This shows that the clearer the subsidy policy, the greater is the enthusiasm from private investors and consumers to participate. Besides, consumers respond more quickly to subsidies than private investors. This shows that the existing subsidies are more attractive to consumers. For private investors, due to low hydrogen prices and high costs, the existing subsidy makes investors to consider a longer time to decide whether to accept the high risks.

Fig. 5 shows that the greater the y, the shorter the time it takes for private investors to reach the ESS. On the other hand, as the y rises, the evolution rate of consumers remains basically unchanged, but the x is slightly reduced. This is because when the government notices that private investors are more willing to invest, it will become less willing to provide subsidies. Fig. 6 shows that when z increases, the enthusiasm of the government choosing subsidy provision and private investors choosing investment will increase significantly. This proves that increasing user demand is important.

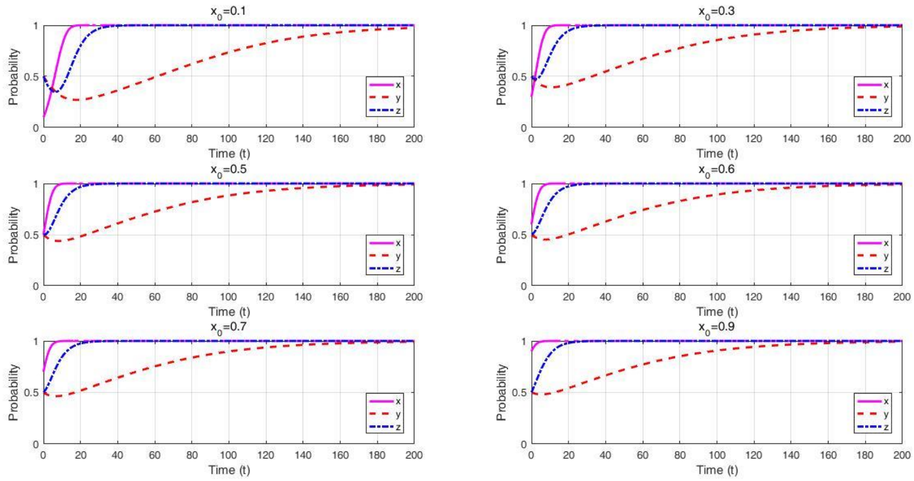

Fig. 4. The impact of changes of x on y and z.

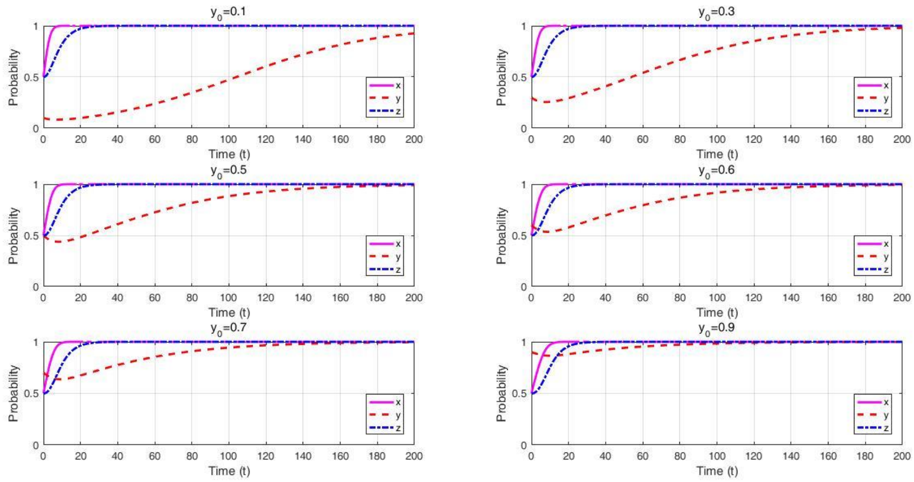

Fig. 5. The impact of changes of y on x and z.

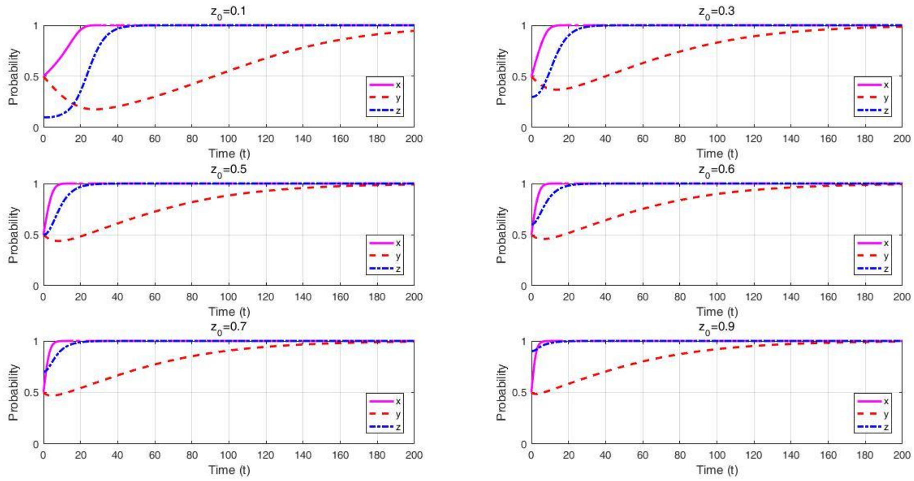

Fig. 6. The impact of changes of *z* on *x* and *y*.

6.3. Sensitivity analyses of key parameters

In order to perform sensitivity analyses of some key parameters in Table 3, corresponding parameters are set to three values with a 10% gradient. From Fig. 7 (a), we see that when *x* is 0.2, the public sector's sensitivity to rewards is much greater than the case when *x* is 0.8. This is because when public sectors refuse to provide subsidy, the greater the reward from the superior, the more it can stimulate the initiative of the public sector. Fig. 7 (b) and (c) show that when *y* and *z* are 0.8, changes in G_{s1} have no impact on private investors and consumers. When *y* and *z* are 0.2, private investors and consumers will become more cooperative when they find the favorable reward policies by the central government. However, changes in rewards will not change their speed to reach the ESS.

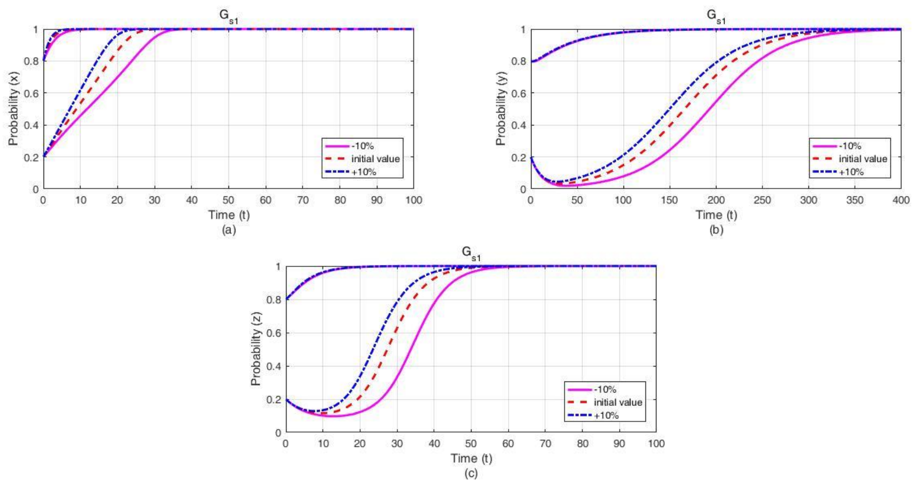

Fig. 7. The impact of G_{s1} on the game.

From Fig. 8 we see that when consumers use HRS, the increase in subsidies for private investors will shorten the time it takes for investors to reach the stable strategy, but have no impact on the evolution speed of public sectors and consumers. Fig. 8 (b) shows that when y is 0.2 and the subsidy to the private investor is reduced by 10% from the initial value, the time required for the system to reach the stable strategy greatly increases. When the subsidy increases by 10% from the initial value, the time for the system to reach the stable strategy only slightly decreases. This reflects the significance of subsidies when private investors are not very willing to participate. Similarly, from Fig. 9-10, changes in costs only affect the trajectory of private investors. And when y is 0.2, the increase in cost will greatly inhibit the system from becoming stable.

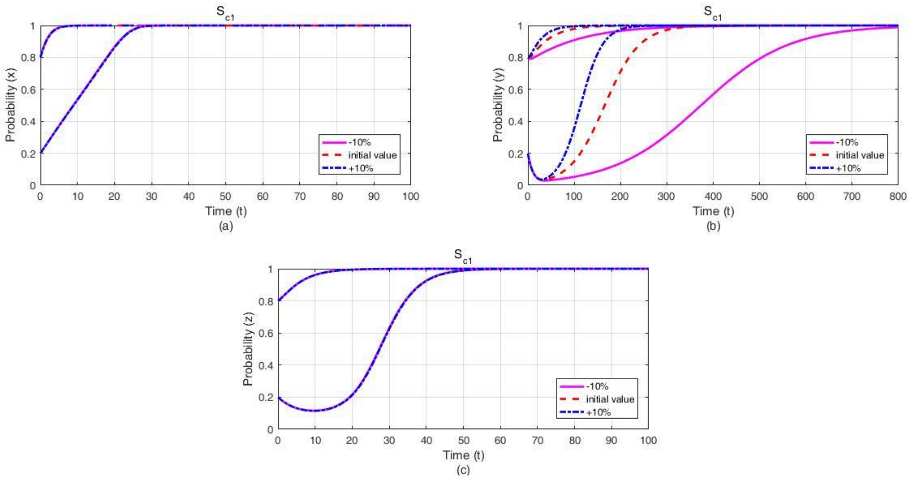

Fig. 8. The impact of S_{c1} on the game.

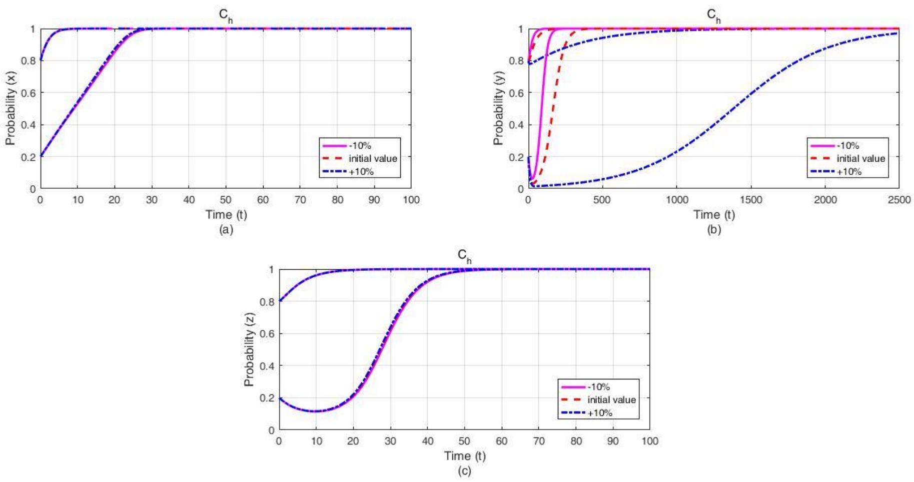

Fig. 9. The impact of C_h on the game.

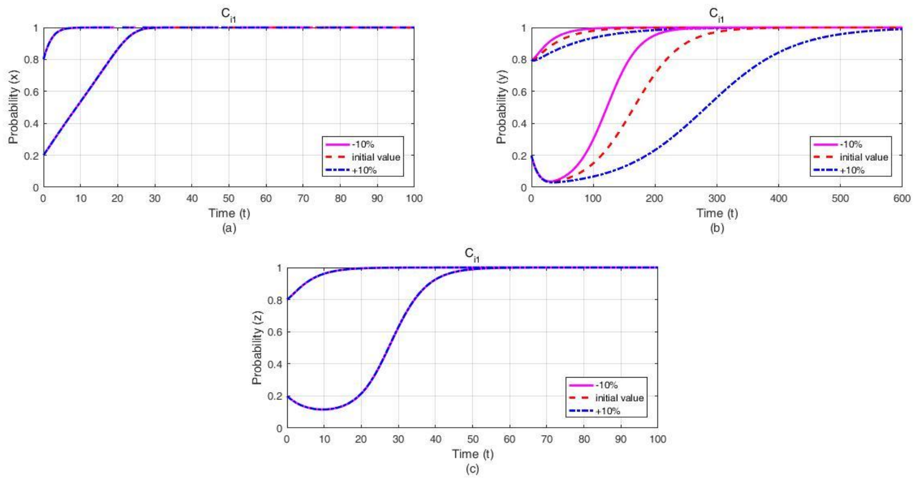

Fig. 10. The impact of C_{i1} on the game.

Fig. 11 shows that consumers are more likely to use hydrogen when they receive more subsidies, with this being more obvious at a lower z. Public sectors and private investors at low levels of x and y will be more active at first considering that consumer demand is high due to more subsidies. However, the government realizes that subsidies have a financial burden, and private investors believe that the increase in consumers does not offset the potential investment risks, and the time for them to reach stable strategy has not shortened. When initial probabilities increase to 0.8, the change of S_u has almost no effect on the evolution speed of actors.

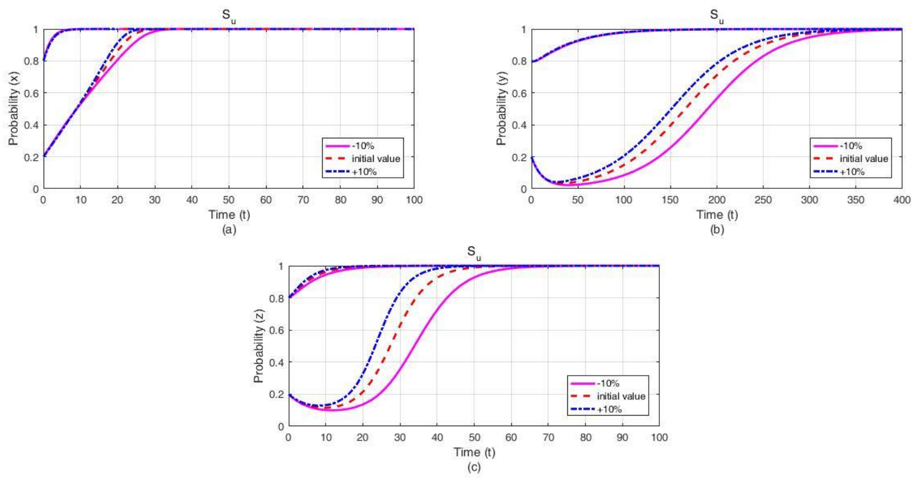

Fig. 11. The impact of S_u on the game.

From Fig. 12 (a) and (c) we see when x and z are 0.2 or 0.8, reducing the P_h by 10% will not significantly increase the speed of public sectors and consumers evolving to ESS. However, Fig. 12 (b) shows this has a negative impact on the investment confidence of private investors. In order to attract private investors, the hydrogen price can be kept at the initial value of 35 yuan/kg which is the target price set by China for the demonstration period. With the reduction of HRS costs and the gradual improvement of government incentives, the hydrogen price can be gradually being reduced.

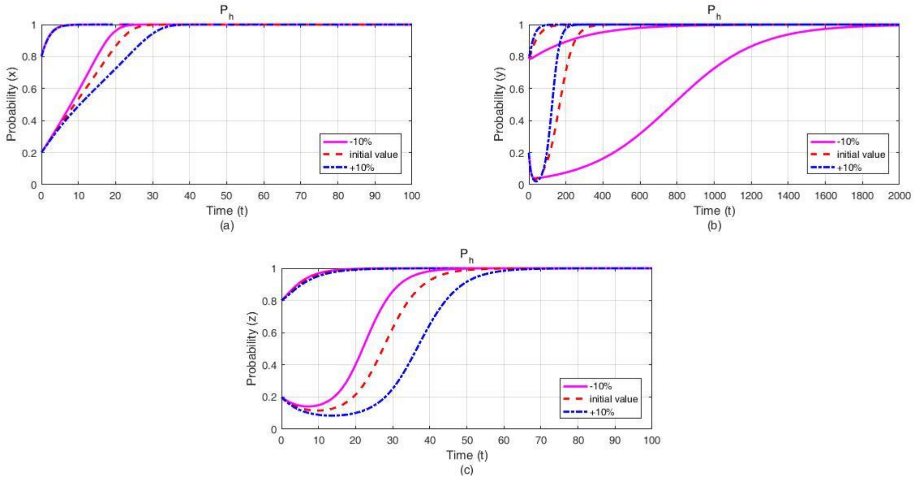

Fig. 12. The impact of P_h on the game.

Changes of other parameters have no effect on the trajectory of the entire system. Therefore, those factors play little part in increasing the speed of the system to reach the ESS. Decision-makers do not need to formulate policy measures based on those factors.

7. Conclusion and Policy Implications

This paper analyses China's policy for the development of a hydrogen industry and diffusion of HRS. The key stakeholders in the policy are the public sectors, private investors, and consumers. We explore their conflicts of interest and simulate their interaction using a novel tripartite evolutionary game model given their financial incentives and willingness to participate. In order to study the interplay among the actors, we devise a policy mechanism based on public sectors subsidies, private investment in HRS, and consumers using the HRS.

We find that increasing the initial willingness of actors to choose active hydrogen strategies, is important to lead the game to the ideal diffusion of HRS. Besides, sensitivity analyses of key parameters from high and low initial probabilities respectively show that stronger financial incentives and reduction in the cost of construction, O&M, and use of HRS are significant for the ideal ESS. Based on the results, we propose some recommendations to promote the development of hydrogen infrastructure. This paper also provide insight for other cases of the development of hydrogen infrastructure.

First, it is important to assess the initial cooperation willingness of the key actors. Although having promoted the development of the hydrogen by issuing various policy documents, China lacks relevant standards for the approval and construction of HRS. At present, the main bottleneck is the lack of relevant laws, regulations, and technical norms. This prevents hydrogen from being more widely used. Moreover, under China's current system, the approval process for the construction of HRS is more complicated than that of gas refueling stations. Therefore, speeding up the formulation of standards for HRS and clarifying the role of hydrogen in the transportation industry are crucial for the participation of the actors. Relevant departments should enhance the publicity of hydrogen, such as regarding HRS as a science popularization site, organizing institutions to visit and study, and media coverage. The provision of public subsidy is necessary to provide leadership in the initial phases and to reassure the private investors and consumers. Further, the transport industry should be integrated into the carbon market, to increase carbon benefits due to emission reduction from FCEV and HRS.

Further, changes in key parameters are critical to promote HRS. As for public sectors, the central government should provide financial incentives to local governments that implement subsidy policies and achieve good HRS diffusion. FCEV procurement and HRS construction by public sectors in large quantities for publicity is key for the reduction of hydrogen price through economies of scale. A scoring and penalty system to review HRS demonstration results can be used to measure local development of hydrogen infrastructure and distribute reward.

For private investors, due to the need to reduce the retail price of hydrogen to develop demand, we focus on reducing the cost of HRS. Apart from public sector subsidies, companies can cooperate with research institutions. The objective is to support breakthrough of HRS technologies and reduction in expensive imported equipment to reduce the investment cost. Meanwhile, the daily management and operation of HRS can improve by increasing the number of continuous trouble-free hydrogenation, to prolong equipment life and reduce operating wastage of hydrogen. Private investors can innovate the operation mode of HRS, such as retrofitting the existing gas station with hydrogen refueling equipment to reduce investment and O&M cost.

For consumers, the main driver to enhance their enthusiasm for HRS is the reduction of hydrogen price. Subsidies from government and car manufacturers are important and should be maintained or increased. Moreover, hydrogen is still defined as a hazardous chemical and not clearly given the energy attributes as a transportation fuel. Hazardous chemicals must be produced in chemical parks, away from HRS, therefore increasing unnecessary transportation cost, which in turn increase the price of hydrogen. Finally, miniaturized hydrogen production equipment can be used to realize the integration of hydrogen production and refueling in one HRS, thus reducing the length of the industrial chain and transportation costs.

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