Game Theory Approach of Stakeholder Decisions in Natural Hydrogen Exploration

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Game theory approach of stakeholder decisions in natural hydrogen exploration

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Summary

This study presents a game theory-based model to analyze the decision-making processes of key stakeholders in the exploration of natural hydrogen. The model incorporates uncertain parameters such as revenue from hydrogen businesses, government subsidies, and technological risks to provide a comprehensive framework for understanding the stakeholder decisions between governments and energy firms. Numerical experiments reveal that the probability of different Nash equilibria is significantly influenced by the levels of risk compensation and subsidies. Higher subsidies increase the likelihood of passive supervision and market entry by energy firms, while lower subsidies favor active supervision and market entry. These findings highlight key economic and regulatory considerations.

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Introduction

Natural hydrogen, occasionally referred to as natural, golden, or geologic hydrogen, is a naturally occurring form of hydrogen gas generated through geological processes within the Earth's crust (Blay-Roger et al., 2022). One of major attractions of natural hydrogen is its huge potential of reserves. Hand (2023) speculates it to be around five million tons trapped under expansive horizontal sills of ancient volcanic rock, making it an attractive option in the global transition towards cleaner energy systems. The exploration and commercialization of natural hydrogen, however, present several challenges that require careful consideration.

The primary challenge in natural hydrogen exploration lies in the uncertainty associated with its distribution and the economic feasibility of its extraction. This makes it difficult to evaluate its techno-economic analysis, although there are some models available for hydrogen produced by renewable electricity (Paneru et al. 2024). Unlike hydrocarbon in the subsurface, the occurrence of natural hydrogen is less well understood, necessitating advanced subsurface surveys and production technologies (Zgonnik, 2020). Additionally, the economic viability of natural hydrogen depends on various factors, including the amount of the potential reserves, the cost of extraction, government policies, and the price of hydrogen in the energy market.

To address these challenges, this study proposes a game theory-based model to analyse the decision-making processes of key stakeholders involved in the hydrogen exploration. By incorporating uncertain parameters such as revenue of subsurface businesses of hydrogen, government subsidies, and technological risks, the model aims to provide a comprehensive framework for understanding the strategic interactions among stakeholders. This approach not only helps in identifying optimal strategies for stakeholders but also offers insights into the potential economic and environmental benefits of natural hydrogen.

Method

We employ a game theory-based model to analyse the decision-making processes of key stakeholders involved in the subsurface hydrogen exploration by modifying the CCS and CCUS frameworks in Zhao and Liu (2019) and Masaya and Nishitsuji (2024), respectively. The model here is designed to capture the strategic interactions between government and energy firms, considering various uncertain parameters that influence their decisions.

The model includes two primary stakeholders: the government and energy firms. The government supervises the exploration and utilization of natural hydrogen, while energy firms decide whether to enter the hydrogen exploration market. Key parameters used in the model and a concept of the strategic interactions among stakeholders are respectively shown in Table 1 and Figure 1.

Table 1 *Key parameters used in the game model in this study. These variables are identical to ones used in Fig. 1. Note that all variables have non-negative values unless being specified.*

Variables	Stakeholders	Descriptions
C_s	Government	Supervision cost
S		Risk compensation for natural hydrogen technology
W		Subsidies for purchasing natural hydrogen technology
B		Political achievement for active supervision
C_e		Cost of mitigating excessive CO2 emissions
C_a	Energy firms	Cost of deploying natural hydrogen technology
R_h		Revenue of natural hydrogen businesses
R_c		Carbon credit revenue

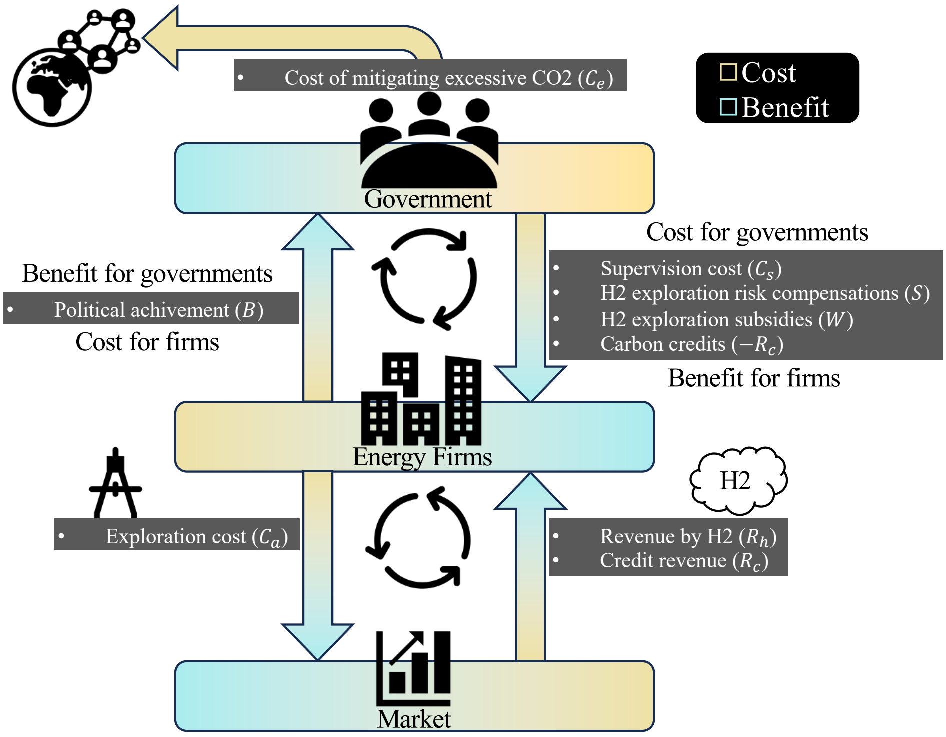

Figure 1 *A concept of strategic interactions among stakeholders. Color in light orange indicates cost, while color in light blue indicates benefit.*

Our approach utilizes a payoff matrix, a table displaying the rewards or penalties for players in a game theory, to model a scenario in which the government issues carbon credits, operating within a compliance market framework. The payoff matrix between government and energy firms is shown in Table 2.

Table 2 *Payoff matrix in this study.*

Government \ Energy firms	Entry	Not entry
Active superision	$(B - C_s - S - W - R_c, R_h + R_c + S + W - C_a)$	$(-C_s - C_e, 0)$
Passive supervision	$(0, R_h - C_a)$	$(-C_e, 0)$

The Nash equilibria of this payoff matrix are derived to identify the optimal strategies for both the government and energy firms. The analysis considers the conditions under which each stakeholder would choose to actively supervise or passively supervise the exploration activities, and whether energy firms would decide to enter or not enter the market.

There are two major assumptions we adopt:

(I) $B > C_s + S + W$ (Zhao and Liu, 2019), which is the long-term political incentive for government to support the subsurface hydrogen;

(II) $C_a > R_c$, which means the cost of deploying technologies of natural hydrogen is greater than the carbon credit revenue.

With these two conditions, three of Nash equilibria in Table 2 can be analytically derived. Figure 2 visualizes the analytical diagram of how the three Nash equilibria ((i) [active supervision, entry]; (ii) [passive supervision, entry]; (iii) [passive supervision, not entry] in the figure) dynamically change in the R_h and $(S + W)$ domains depending on three divided cases ((a)-(c) in the figure). Specifically, the three Nash equilibria of (i) [active supervision, entry] is derived by a case of $C_a - R_c - P - R_a < S + W < B - C_s - R_c$. Likewise, (ii) [passive supervision, entry] is derived by $B - C_s - R_c < S + W \cap R_a > C_a$ and (iii) [passive supervision, not entry] is derived by $R_a < C_a$.

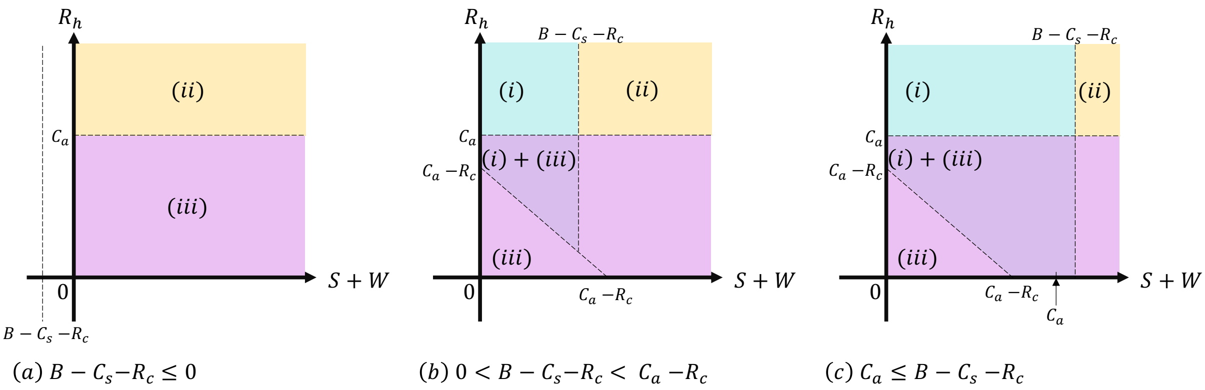

***Figure 2** Analytical diagrams for three Nash equilibria: (i) [active supervision, entry]; (ii) [passive supervision, entry]; (iii) [passive supervision, not entry].*

Numerical experiments

Numerical experiments are conducted to investigate the dependence of the revenue of natural hydrogen businesses, $R_h = 0, 1, \cdots, 18$, and summation of risk compensation and subsidies for purchasing of natural hydrogen technology, $S + W$, on the probability of the three Nash equilibria. The results are plotted in Figure 3. 1000 samples are generated using uniform random numbers for parameters ($B, C_a, R_c, and\ C_s$), and the probability of each Nash equilibrium is calculated.

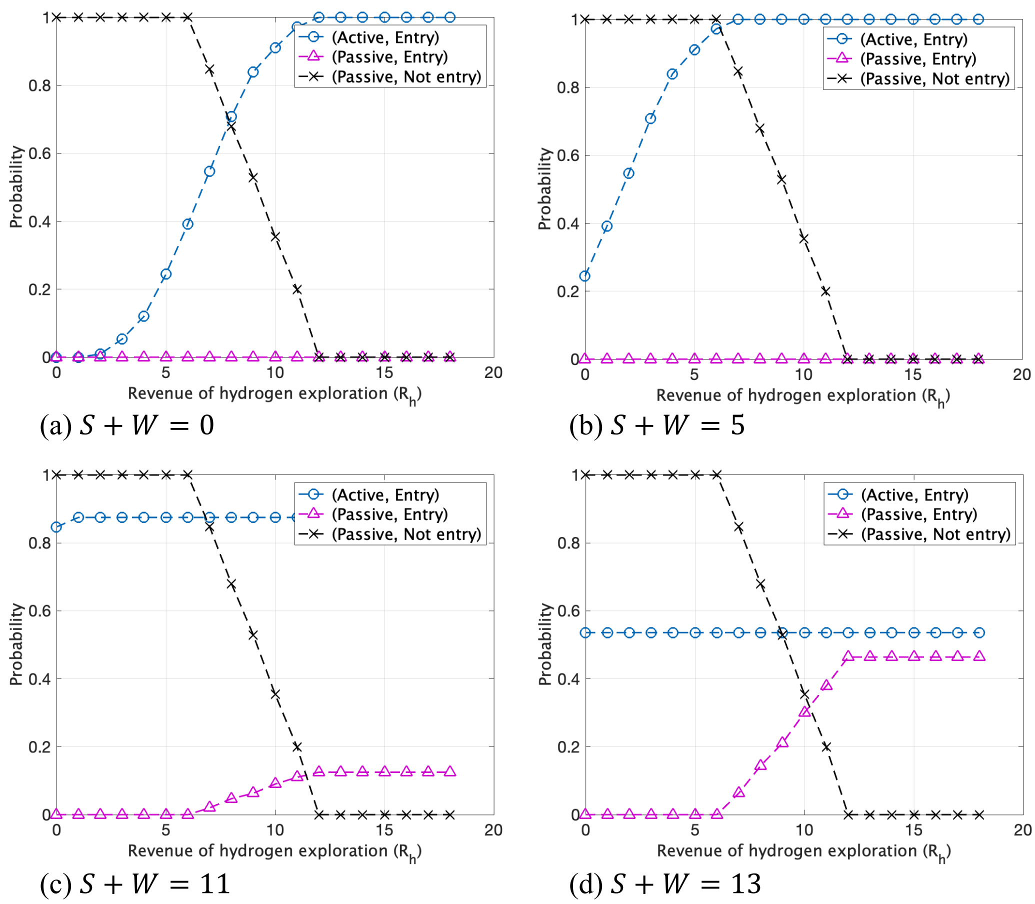

***Figure 3** Probability of the Nash equilibria for revenue of natural hydrogen business in the numerical experiments with $B \sim U[17,19]$, $C_a \sim U[6,12]$, $R_c \sim U[0,5]$, $C_s \sim U[1,4]$, and four values of $(S+W)$: (a) $S+W=0$, (b) $S+W=5$, (c) $S+W=11$, and (d) $S+W=13$. Note that $x \sim U[a,b]$ represents "x is a uniform random number between a and b".*

Discussion

When $S + W$ is small (i.e., $S + W = 0$), the probability of [active supervision, enter] increases and [passive, not entry] decreases as R_h increases, while [passive, entry] shows no probability (Figures 3(a)-3(b)). In cases where $S + W$ is as high as 11 (Figure 3(c)), the probability of [active supervision, enter] increases for $0 \leq R_h \leq 4$ compared to the case of $S + W = 5$; however, it decreases while [passive, entry] increases for $5 \leq R_h \leq 18$. This trend becomes even more evident when $S + W = 13$ as shown in Figure 3(d). This relationship indicates a trade-off for government costs. Excessive spending on $S + W$ diminishes the incentives for the government, especially when energy firms achieve higher R_h.

On the other hand, the analytical diagram in Figure 2 visually demonstrates how dynamically each Nash equilibria takes positions. For instance, giving a constant $S + W$ that is smaller than $B - C_s - R_c$ in Figure 2(b), the probability of [active supervision, entry] ($(i) + (iii)$ in the figure) increases as the revenue from carbon credits increases.

In actual situations, therefore, it is important for government to carefully examine the dynamics of the aforementioned relationship in order to provide optimal support to energy firms. The findings from the model and numerical experiments offer strategic policy guidance. Energy firms can optimize their strategies for entering the natural hydrogen market, potentially leading to more successful business values.

Conclusions

This study employs a game theory-based model to analyze the decision-making processes of key stakeholders in the exploration of natural hydrogen. By incorporating various uncertain parameters such as revenue from hydrogen businesses, the model provides a comprehensive framework for understanding the stakeholder decisions between government and energy firms. The numerical experiments reveal that the probability of different Nash equilibria is significantly influenced by the levels of risk compensation and subsidies. Specifically, higher subsidies tend to increase the likelihood of passive supervision and market entry by energy firms, while lower subsidies favor active supervision and market entry. These findings suggest that government policies and financial incentives play a crucial role in shaping the strategic decisions of stakeholders.

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