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A carbon price model with game theory for CCUS

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Abstract

Carbon dioxide capture, utilization, and storage (CCUS) are widely expected to play a significant role in decarbonization efforts. In discussing the commercialization of CCUS, it is essential to consider various factors, including the revenue and cost associated with CO2 utilization, carbon dioxide capture and storage (CCS), governmental subsidies, and carbon pricing. Among these, carbon pricing is particularly crucial for offsetting the costs of CCUS and enabling its commercialization. Carbon prices vary depending on factors such as the method of carbon credit issuance (e.g., forestry, solar, and wind energy), transaction mechanisms (e.g., cap-and-trade systems), carbon markets (e.g., voluntary markets), and country-specific regulations. Previous studies have investigated the impact of carbon pricing on carbon emissions; however, the pricing mechanisms are largely contingent on the method of carbon credit issuance. For instance, carbon credits generated through CCUS differ from those issued via forestry regarding associated costs, technologies, and subsidies. Therefore, carbon price models focusing on CCUS would be useful for the stakeholders, such as governments, firms, and investors. A significant challenge in developing an optimal carbon pricing model for CCUS lies in the complexity arising from uncertain parameters (e.g., carbon prices in voluntary markets, and revenue from CO2 utilization) across these stakeholders. This study presents a game theory-based model to provide an index of carbon credit revenue, i.e., the carbon price, to consider entry into the CCUS business. Our model aims to analytically simplify this complex problem with uncertain multi-parameters among several stakeholders and provide an index of the carbon price for CCUS in the voluntary carbon markets.

Keywords: CCUS; Carbon price; Game theory

1. Introduction

Carbon dioxide capture, utilization, and storage (CCUS) are expected to play a crucial role in greenhouse gas control and sustainable energy transformation (e.g., [1]). In considering the commercialization of CCUS, several components, such as the revenue from CO2 utilization, the cost of CCUS (e.g., [2]), government subsidies, and carbon price, need to be considered. In particular, the carbon price would be a significant factor in compensating the cost of CCUS and thus making it realize commercialized because there are differences in carbon prices depending on each process to issue carbon credit (e.g., forestry, solar, wind), transaction method (e.g., cap-and-trade), carbon market (e.g., voluntary markets) [3], country [4], etc. Several researchers have proposed approaches to forecasting and optimizing carbon prices (e.g., [5-7]). Previous studies have also reported whether carbon pricing influences carbon emissions (e.g., [8-9]). Although carbon pricing has complex mechanisms, actual markets show that carbon pricing largely depends on the process of issuing carbon credits. For example, carbon credits issued by CCUS differ from those issued by forestry in terms of cost, technology, and subsidies. Therefore, carbon price models focused on CCUS would also be valuable for stakeholders, such as governments, firms, and investors.

A major challenge in constructing an optimal carbon price model for CCUS is the complexity of uncertain parameters, such as the carbon price in voluntary carbon markets and the revenue from CO2 utilization, among various stakeholders. The values of these parameters can vary depending on each country and also change in response to future technological advancements. The research by Zhao and Liu (2019) [10] presented an evolutionary game framework to investigate the complexity of interest in carbon dioxide capture, and storage (CCS) adoption between governments and coal-fired power plants in China. Their study includes an analysis of the effects of critical parameters on the evolution trajectories, but it does not cover the discussion related to carbon prices and CCUS. One of the key research questions in this study is, "How will carbon prices for CCUS be determined in voluntary carbon markets?" This study proposes a carbon price model designed for CCUS, based on game theory, to address this research question by considering stakeholder decisions and uncertain parameters.

2. Method

This study extends a two-player game model on CCS between governments and power plants presented by Zhao and Liu (2019) [10] to a two-player game model between governments and energy firms that emit CO2 and consider entry into the CCUS business.

2.1. Review: Zhao and Liu model

We begin by reviewing the Zhao and Liu model [10]. Tables 1 and 2 present the notation definitions used in their model and their proposed payoff matrix, respectively. Their model formalizes the government's level of commitment to CCS (active or passive supervision for CCS) and the decision-making process of CO2-emitting entities (e.g., power plants) regarding the adoption of CCS in power plants. A feature of the model is that when the government engages in active supervision and CO2-emitting entities implement CCS, the government obtains political achievements (B), while CO2-emitting entities receive subsidies (W) for CCS technology and risk compensation (S) from the government. Conversely, when the government maintains active supervision but CO2-emitting entities do not implement CCS, it is important to note that the government imposes a penalty (P) on the CO2-emitting entities and pays the control cost of mitigating excessive CO2 emissions (C_e). These features are reflected in the respective payoffs for the government.

Table 1. Notations and descriptions of parameters in the Zhao and Liu model.

Notations	Stakeholders	Descriptions
C_s	Governments	The supervising expenditure
S		CCS technology risk compensations
W		CCS technology purchase subsidies
P		The punishments on power plants if CCS is not adopted
B		The political achievements from active supervision
C_e		The control cost of mitigating excessive CO2 emissions
R_t	Power plants	Power plants income gained by power plants if CCS is not adopted
C_a		Extra cost for CCS technology deployment
R_a		Additional low-carbon profit

Table 2. Payoff matrix in the Zhao and Liu model.

Governments \ Power plants	Adoption	Not adoption
Active supervision	$(B - C_s - S - W, R_t + R_a + S + W - C_a)$	$(P - C_s - C_e, R_t - P)$
Passive supervision	$(0, R_u + R_a - C_a)$	$(-C_e, R_t)$

Furthermore, the Zhao and Liu model assumes the following:

$$C_a > R_a, \qquad (1)$$

$$B > C_s + S + W, \qquad (2)$$

where equation (1) represents the present fact that the additional costs (C_a) incurred by CO2-emitting entities for implementing CCS exceed the compensation (R_a) for achieving low-carbon emissions (e.g., carbon credits). On the other hand, equation (2) indicates that, from the government's perspective, the current political achievements (B) resulting from CCS implementation outweigh the sum of the associated costs. Note that this assumption described in equation (2) is maintained in our model proposed subsequently.

2.2. Our proposed model

Next, we consider a modified model that transforms the "game between the governments and power plants" in the Zhao and Liu model into a "game between the governments and energy firms considering entry into CCS operations". Our proposed model removes two parameters (R_t and R_a) in the nine parameters on the Zhao and Liu model and newly adds three parameters (R_c, R_u, and C_p) to satisfy the problem setting in this study (see Table 3). Note that all of these parameters in our model have positive values. We newly define R_c as the revenue obtained from carbon credits while removing the broadly defined R_a. Since our model assumes that the carbon credit revenue (R_c) consists of a carbon price in voluntary carbon markets and the amount of CO2 emissions offset by CCUS, we can discuss the carbon price for the certain amount of CO2 offset through R_c in this model. In our model, because we posit that the player paired with the government is not a power plant operator, but rather a CCS operator, we do not incorporate a revenue (R_t) analogous to the income generated from electricity sales by power plants, which is assumed in the Zhao and Liu model. On the other hand, with the anticipated commercialization of CCUS through technological advancements, CO2 will not only be stored underground but also potentially reused as raw material for energy and materials, generating new profits. Hence, we denote this potential profit as R_u. As R_u represents the revenue obtained from CO2 utilization in CCUS, the carbon price model with $R_u \to 0$ corresponds to the case for CCS.

From the perspective of CCS operators, public acceptance, such as obtaining positive public opinions for CCS operations and understanding of CCS from residents near CCS sites, is crucial in implementing CCS (e.g., [11]). We add to represent the cost associated with gaining this public acceptance. This cost is imposed when the government's support is insufficient for the company implementing CCS. When the government's support is adequate, we set $C_p \to 0$, as public acceptance becomes easier to obtain. We retain the government-imposed fine (P) on CO2-emitting entities, as entities considering entry into CCS operations would be CO2-emitting companies, such as oil development firms. The payoff matrix in the proposed model describes the result of the government's choices (active supervision or passive supervision for CCUS) and the energy firm's choices (entry or not entry into the CCUS business) in a game, as shown in Table 4.

Table 3. Notations and descriptions of parameters in the proposed model. Note that all of these parameters have positive values.

Notations	Stakeholders	Descriptions
C_s	Governments	Supervision cost
S		CCUS technology risk compensations
W		CCUS technology purchase subsidies
P		Penalty on CO2 emissions for energy firms (e.g., carbon tax)
B		Political achievement for active supervision
C_e		Cost of mitigating excessive CO2 emissions
C_a	Energy firms	Cost of CCUS technology deployment
R_u		CO2 utilization revenue
R_c		Carbon credit revenue (= the carbon price × the amount of offset CO2 emissions)
C_p		Cost for public acceptance

Table 4. Payoff matrix in the proposed model.

Governments \ Energy firms	Entry	Not entry
Active supervision	$(B - C_s - S - W, R_u + R_c + S + W - C_a)$	$(P - C_s - C_e, -P)$
Passive supervision	$(0, R_u + R_c - C_a - C_p)$	$(-C_e, 0)$

3. Theoretical analysis

Using the same assumption as equation (2) in the Zhao and Liu model, which indicates the long-term political incentive for governments to support CCUS, we can derive analytical conditions for three Nash equilibria of [Active supervision, Entry], [Active supervision, Not entry], and [Passive supervision, Not entry] on this payoff matrix. We then consider three distinct cases:

(i) When $R_u + R_c + S + W - C_a > -P$, (Active supervision, Entry) becomes the Nash equilibrium.

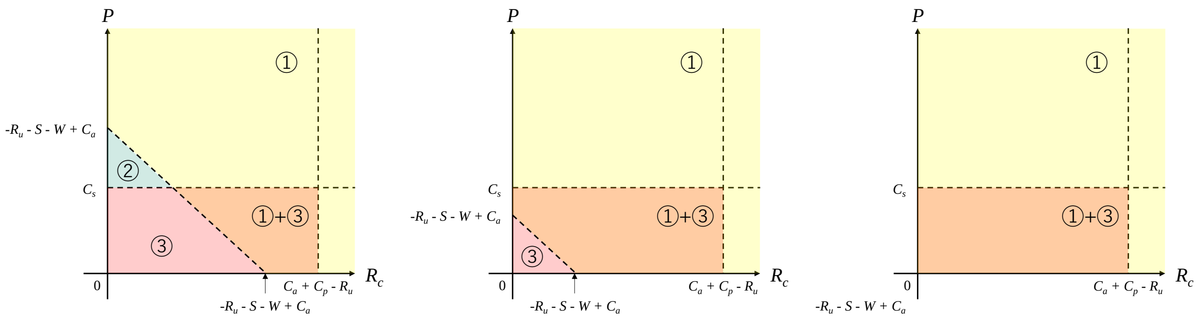
(ii) When $P - C_s - C_e > -C_e$ and $R_u + R_c + S + W - C_a < -P$, i.e. $C_s < P < -R_u - R_c - S - W + C_a$, [Active supervision, Not entry] emerges as the Nash equilibrium. Note that there is no contradiction between C_s and $-R_u - R_c - S - W + C_a$, as $(-R_u - R_c - S - W + C_a) - C_s$ can be positive.

(iii) When $P - C_s - C_e < -C_e$ and $R_u + R_c - C_a - C_p < 0$, [Passive supervision, Not entry] becomes the Nash equilibrium.

This game in our proposed model shows that [Active supervision, Not entry] of the three Nash equilibria represents opposite decisions on CCUS between governments and energy firms, which is not intentional for governments. Figure 1 illustrates the analytical diagrams to show the region of the three Nash equilibria for the proposed model in the R_c and P domains. The analytical diagrams visualize the boundaries of carbon credit revenue among the three combinations of governments' and energy firms' decisions, which represent the minimum carbon credit revenue (~minimum carbon price) to change the stakeholders' decisions. These diagrams provide the following reference index of the minimum carbon price.

$$\hat{R}_c \equiv -R_u - S - W + C_a, \qquad (3)$$

where the index represents the carbon price boundary to change firms' decisions on entry into the CCUS business independently of P. Furthermore, a significant feature of the diagrams is that the three conditions (a)-(c) in Figure 1 analytically characterize the number and region of the Nash equilibria.



(a) $C_s < -R_u - S - W + C_a$ (b) $0 \leq -R_u - S - W + C_a \leq C_s$ (c) $-R_u - S - W + C_a < 0$

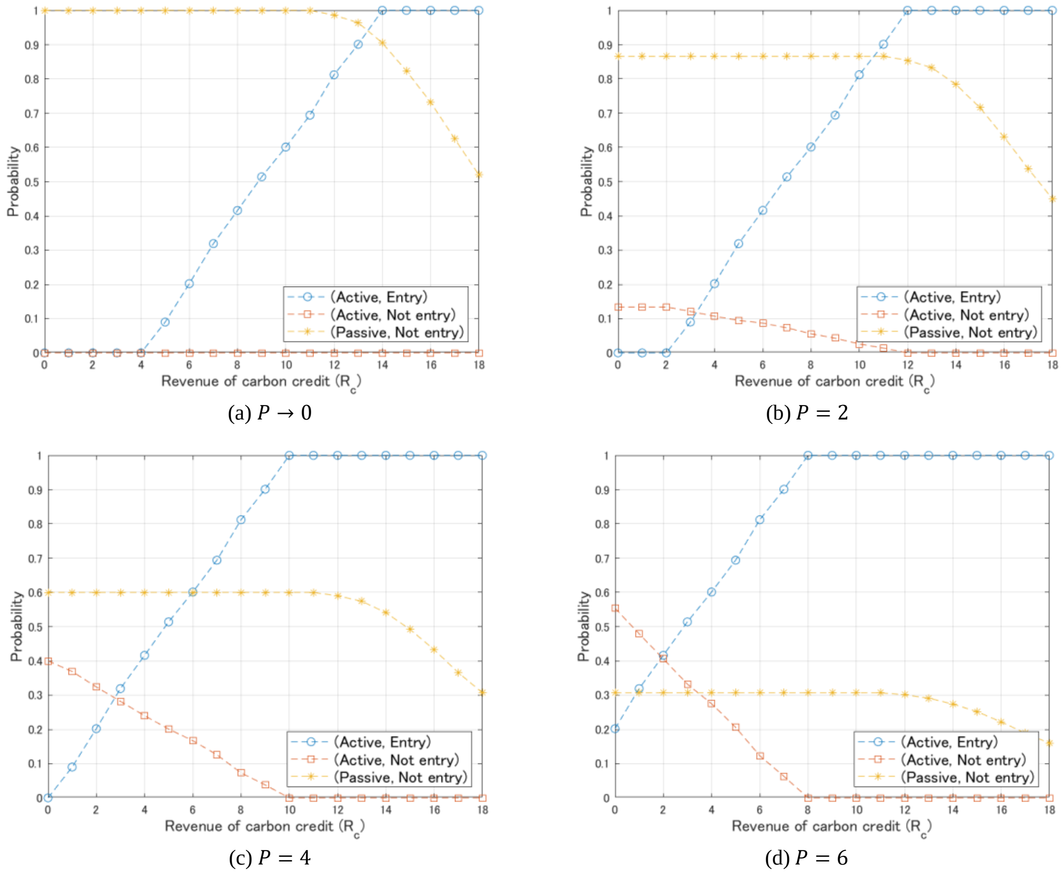
Fig. 1. Analytical diagrams to show region of the three Nash equilibria (①[Active supervision, Entry], ②[Active supervision, Not entry], and ③ [Passive supervision, Not entry]) for the proposed model.

4. Numerical experiments

We conduct numerical experiments to investigate the dependence of carbon credit revenue and CO2 emission penalty on the probability of the three Nash equilibria in the proposed model (see Figure 2). We generate 1000 samples for several parameters using uniform random numbers to calculate the probability of the Nash equilibria for each carbon credit revenue ($R_c = 0, 1, \dots, 18$). It should be noted that strictly speaking R_c is positive, and thus $R_c = 0$ in numerical calculations corresponds to considering the limit as $R_c \to 0$ in the analysis. The result shows that the probability of [Active supervision, Entry] is 1.0 in the range of $R_c \geq 14$ independent of P.On the other hand, the probability of the three Nash equilibria rapidly varies depending on each value of the CO2 emission penalty in the range of $0 < R_c < 14$. We can also calculate the carbon price index of $\hat{R}_c$ for the firm's decisions from the input parameters (see a caption in Figure 2) in the experiments. For example,

1. CCUS with governments' financial support: $\hat{R}_c = -\bar{R}_u - S - W + C_a = -5 - 4 - 2 + 20 = 9$,
2. CCUS without governments' financial support ($S \to 0$, $W \to 0$): $\hat{R}_c = -\bar{R}_u + C_a = 15$,
3. CCS with governments' financial support ($R_u \to 0$): $\hat{R}_c = -S - W + C_a = 14$.

As shown in this example, this carbon price index of $\hat{R}_c$ could be useful for relative comparison of the carbon price among multiple conditions without the effect of P.



(a) $P \to 0$ (b) $P = 2$

(c) $P = 4$ (d) $P = 6$

Fig. 2. Dependence of carbon credit revenue on the probability of the three Nash equilibria for the proposed model in the numerical experiments with $B \sim U[14,18]$, $C_s \sim U[1,8]$, $S = 4$, $W = 2$, $C_a = 20$, $R_u \sim U[0,10]$, $C_p \sim U[1,6]$, $C_e = 2$, and four values of P: (a) $P \to 0$, (b) $P = 2$, (c) $P = 4$, and (d) $P = 6$. Note that $x \sim U[a, b]$ represents "x is a uniform random number between a and b".

5. Discussions

The Nash equilibrium [Active supervision, Not entry], a key theoretical feature of our model, is also indicated to occur with a realistic probability in the numerical experiments (Figure 2). Based on the results of these numerical experiments, it can be observed that the probability of the Nash equilibrium [Active supervision, Not entry] decreases for smaller P.

For the government, one approach to avoiding the unintended Nash equilibrium of [Active supervision, Not entry] would be to reduce P; however, in practice, the relationship with C_e will be crucial in determining the value of P (see (ii) and (iii) in Section 3). The relationship between P and C_e is not independent; reducing P would require the government to pay a larger C_e, creating a trade-off. Thus, from the government's perspective, in theory, it is preferred to set P and C_e such that $P < C_e$ to avoid unintended Nash equilibria. However, in practice, C_e is not necessarily something that can be fully replaced by monetary control. Since C_e reflects the cost of CO2 offsetting alternatives to CCS, there would be limits to increasing C_e in reality. Considering these factors, the theoretical conditions to avoiding [Active supervision, Not entry] can be summarized as follows:

$$P < C_e, \qquad C_e \le C_{e,max}, \qquad s.t.\ P + C_e = \text{const.}, \qquad (4)$$

where $C_{e,max}$ represents the maximum value of C_e.

6. Conclusions

This study proposed a game theory-based model for carbon pricing in voluntary carbon markets for CCUS. The model involves two players: companies deciding whether to enter the CCUS business and the government determining the extent of its supervision. The game theoretical analysis reveals three Nash equilibria, including [Active supervision, Entry], [Passive supervision, Not entry], and [Active supervision, Not entry]. Numerical experiments demonstrate that the [Active supervision, Not entry] equilibrium, which contradicts the government's intentions, can occur with a significant probability under realistic conditions. We also discussed the theoretical conditions on P (Penalty on CO2 emissions for energy firms: e.g., carbon tax) and C_e (cost of mitigating excessive CO2 emissions) for avoiding the Nash equilibrium of [Active supervision, Not entry], which is contrary to the government's intentions. In future work, this model should be applied to read data or more realistic data.

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