Evaluating Impacts of Carbon Tax on Energy Selection Focusing on Perception of Risk by Consumers

by

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Abstract

A carbon tax for energy transition has been considered as a measure against climate change. A large number of studies on carbon tax have adopted a theoretical analysis that assumes that economic agents behave reasonably under perfect information. However, in a liberalized energy market, economic agents change their behavior according to market conditions and the behaviors of others. We developed a multiplayer game simulating the real energy market and conducted an experiment in which human participants played a game to evaluate the impact of carbon tax. We subsequently analyzed the gameplay and questionnaire answers. The results showed that when the tax rule was implemented, anxiety regarding energy price was higher during the early stage of the game, and a larger amount of backstop energy was introduced during the middle stage. This can be interpreted to mean that the introduction of the tax could have caused some players to adopt backstop energy. However, as the tax was low when introduced in the early stages, anxiety increased. This conflict and deviation could have undermined the intention to promote the energy transition. In conclusion, a carbon tax may undermine the introduction of backstop energy when the tax rate is relatively low and thus postpone energy transition.

1. Introduction

The Japanese government pledged to reduce carbon dioxide emission by 46% by 2030 compared to 2013 (MOFA, 2022) to the international community. However, 84.8% of primary energy in Japan was derived from fossil fuels in 2020. This ratio has seldom changed over the past 30 years, despite the transition from fossil fuels to non-fossil energy being an important goal (ANRE, 2022).

A major barrier to decarbonization is the social dilemma inherent to the current energy supply system. Platkowski (2017) defined social dilemma as a strategy game that satisfies the following four conditions. First, multiple players have the option of cooperation or defection. Second, all players benefit when they choose cooperation over defection. Third, the larger the number of players who choose cooperation, the greater the payoffs they obtain. Fourth, the optimal strategy of one player is affected by the strategies of other players. In the context of energy transition, cooperation and defection correspond to introducing backstop energy and continuing to consume fossil fuel, respectively. The welfare of society is expected to be maximized when all energy consumers introduce backstop energy for mitigating climate change. However, they can benefit from the efforts of others for investing in backstop energy by continuously consuming fossil fuels. Thus, a large number of consumers continue to use fossil fuels. This phenomenon is known as the Nash equilibrium in the field of game theory.

Conventional social psychological studies have demonstrated that sanctions increase the cooperation rate in social dilemma situations (Tenbrunsel & Messick, 1999). In the context of energy transition, carbon pricing policies, including carbon tax or emissions trading schemes, correspond to sanctions against defection; taxation on carbon dioxide emissions is expected to promote the transition to backstop energy. The positive effects of carbon tax have been inferred by ex-ante theoretical analyses (Dong et al., 2017; Descateaux et al., 2016) and ex-post policy observations (Murray et al., 2015; Hites, 2018); uncertainty in the effects of taxation has also been established (O'Mahony, 2020).

However, the negative effect of sanctioning in social dilemmas has also been suggested. Sanctions may decrease the cooperation rate despite the intention of policymakers; for example, Tenbrunsel and Messick (1999) demonstrated that sanctions make people recognize their selection in a social dilemma as an economic problem rather than an ethical problem. Mulder et al. (2006a) showed that cooperation through a sanction system was broken by another defecting choice overlooked by the sanction system. Mulder et al. (2006b) showed that sanctions can undermine trust among members of society and decrease cooperation rates after removing sanctions.

These social psychological studies adopted an experimental method in which participants played games representing a social dilemma situation in the real world. This approach may supplement theoretical analyses and policy observations by inferring the potential side effects of policies considering the subjective perceptions of decision makers and strategic interactions. However, a large number of experimental studies have adopted games that are highly abstracted, such as the N-person prisoner's dilemma or public goods game. These cannot consider the unique mechanism of the energy supply system, such as the complex relationship between the energy mix and payoff of players and cost reduction of backstop energy by learning.

This study investigates the impact of carbon tax on energy transition in a liberalized market using a multiplayer game designed based on the Hotelling model in resource economics. The multiplayer game was played under two conditions: with and without tax. The optimal solution of the game is to continuously consume fossil fuels under the without tax condition and switching to backstop energy under the with tax condition. Through an integrative analysis of the records of gameplays and questionnaires to participants, we inferred the mechanism by which the carbon tax impacts consumers' perception and behavior and the energy mix of the entire market.

2. Design of the multiplayer game

The multiplayer game was designed in three stages: defining structural conditions, constructing a formal model, and setting parameters. First, we elucidated the structural conditions: a set of conditions must be satisfied by the game, considering the objective of this study. Subsequently, we constructed a formal model representing the interactions between the factors included in the model. Then, we set the parameters of the formal model to represent the dilemma that we would like to focus on. Figure 1 is a conceptual figure of the designed game, and Figure 2 presents the game flow. The game proceeds by repeating a time unit termed "round".

The six structural conditions were elucidated as follows: First, players in the game are energy consumers, and obtain benefits by consuming fossil fuels and/or backstop energy; the benefit from unit energy is the same between both types of energy. The objective of players is to maximize their own benefit at the end of the game. Second, the unit price of backstop energy is higher than that of fossil fuels at the start of the game. Third, the unit price of backstop energy decreases in correlation with its accumulative consumption, while that of fossil fuels increases over time. These settings represent a decrease in the backstop energy cost due to the learning effect and an increase in the cost of mining fossil fuels owing to the shortage of high-quality fuels. Fourth, the benefit of each player is maximized by continuously using fossil fuels under the without tax condition and by switching to backstop energy under the with tax condition. We assumed that the social cost of fossil fuels is not internalized under the without tax condition. Fifth, environmental damage accelerates as the cumulative consumption of fossil fuels increases. This assumption expresses irreversible damage due to climate change, such as glacier melting or species extinction. Sixth, players cannot know the future behavior of others and energy costs in advance. This setting simulates imperfections in the information that real energy consumers often face. These structural conditions represent a situation in which players must sequentially decide the mixed composition based on imperfect information and provide a framework for investigating the impact of a carbon tax on their selections.

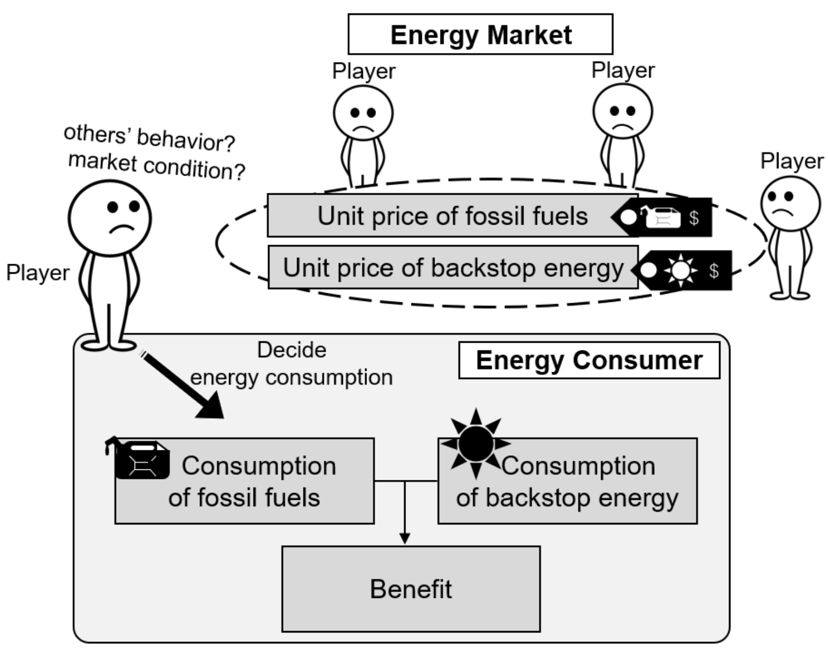


Figure 1: Conceptual figure of multiplayer game

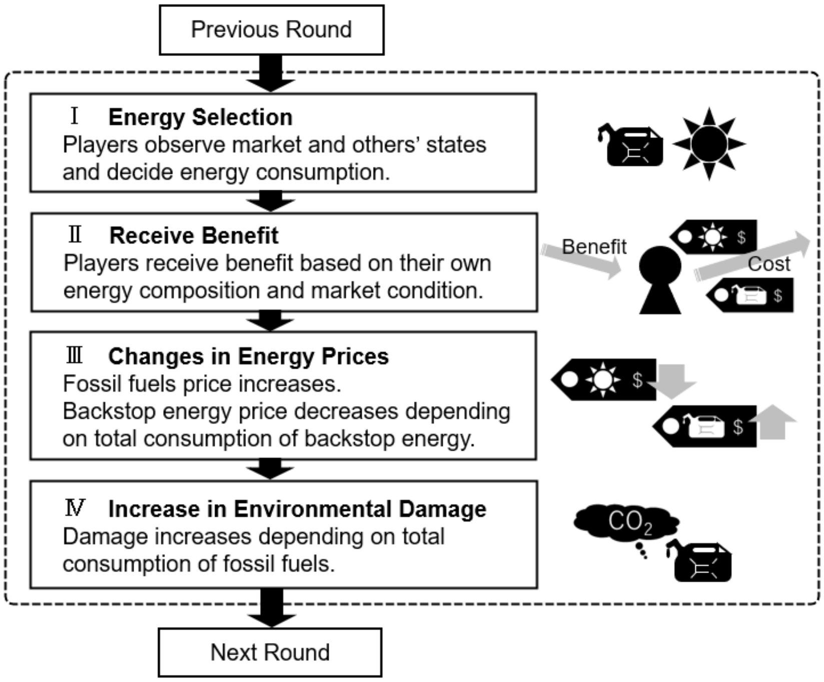


Figure 2: Flow of game progression

Figure 3 illustrates the structure of the formal model. The duration of the game was set to 50 rounds. The number of players, N, was set to four, which is the standard number in social-psychological experiments. The market prices of fossil fuels and backstop energy are shared by all players. The rules of the game are expressed by the following five formulas: First, the net benefit of player i in round t, $V_{i,t}$, is defined as the difference between the benefits of energy consumption and the cost of energy purchases. This setting has generally been adopted by Hotelling models in the field of resource economics (Tsur & Zemel, 2003; Ploeg & Withagen, 2012).

$$V_{i,t} = U_{i,t}\,(e_{i,t}) - eb_{i,t}\,pb_{t-1} - ef_{i,t}\,pf_{t-1} \tag{1}$$

$$e_{i,t} = eb_{i,t} + ef_{i,t} \tag{2}$$

$U_{i,t}$, the benefit from energy consumption, is defined as a quadratic function of total energy consumption, $e_{i,t}$ (α<0). This function represents a decrease in the marginal benefit in correlation with energy consumption.

$$U_{i,t}\,(e_{i,t}) = \alpha e_{i,t}^{\;2} + \beta e_{i,t} \tag{3}$$

The unit price of fossil fuels, pf_t, was set to increase with time, irrespective of the players' behavior.

$$pf_t = pf_0\, e^{\sigma t} \tag{4}$$

The unit price of backstop energy, pb_t, was set to decrease according to the cumulative consumption of backstop energy in the entire market.

$$pb_t = pb_0\,(1+\delta b_t)^{-\varepsilon} \tag{5}$$
$$b_t = \Sigma_{k=1\sim t}\,\Sigma_i\, eb_{i,k}\,/\,N \tag{6}$$

Environmental damage was set as a quadratic function of the cumulative consumption of fossil fuels in the whole market (μ>0).

$$D_t \;= \mu f_t^2 + \nu f_t \tag{7}$$
$$f_t = \Sigma_{k=1\sim t}\,\Sigma_i\, ef_{i,k}\,/\,N \tag{8}$$

All players simultaneously decide the consumption of fossil fuels $ef_{i,t}$ and that of backstop energy $eb_{i,t}$ in each round. After the players decide, the states of each player ($\Sigma_t\, V_{i,t}$, $ef_{i,t}$, $eb_{i,t}$, $\Sigma_i\, eb_{i,t}$, $\Sigma_i\, ef_{i,t}$) and energy prices in the market (pf_t, pb_t) are updated. We introduced an imaginary unit of energy [E] and benefit [G] for the game.

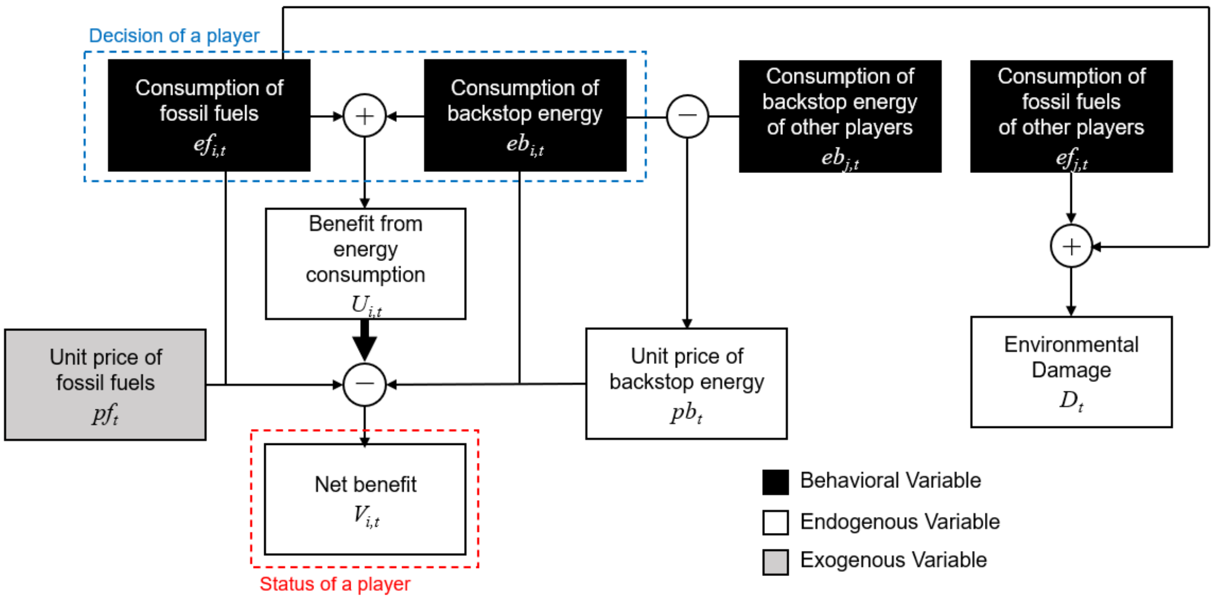


Figure 3: Structure of formal model

Finally, we set the parameters of the formal model so that the structural conditions were satisfied using the dynamic optimization model. The dynamic optimization model finds the set of independent variables, the combination of $eb_{i,t}$ and $ef_{i,t}$ for all i and t, and maximizes the benefit of players at the end of the game using mathematical programming. The objective function of this model is expressed by equation (9) when the environmental damage is not considered and by equation (10) when it is considered. Equations (1)–(8) act as model constraints.

$$max \ \Sigma_t \Sigma_i V_{i,t} / N \quad (9)$$

$$max \ \Sigma_t \Sigma_i V_{i,t} / N - D_{50} \quad (10)$$

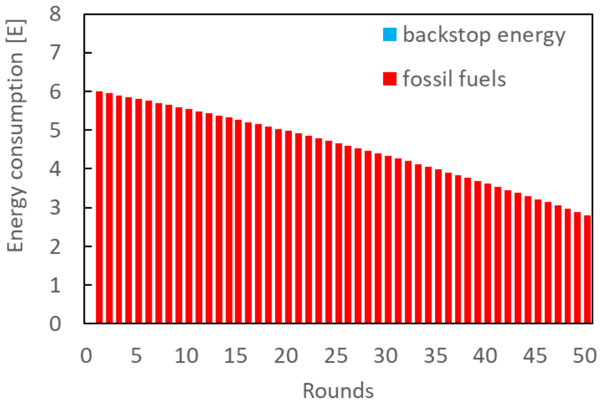
To satisfy the structural conditions, the optimal solution to (9) must be $eb_{i,t} = 0$ and $ef_{i,t} > 0$, whereas that to (10) must be $eb_{i,50} > 0$ and $ef_{i,50} = 0$. This is because we built a situation in which it is best to continuously consume fossil fuels, without considering environmental damage, to promote energy transition considering environmental damage. Table 1 lists the parameters that satisfy these conditions.

Figures 4(a) and (b) show the optimal solution against (9): the time-series changes in the energy mix and unit prices of the two types of energy. Backstop energy is not consumed, and the price of backstop energy is higher than that of fossil fuels, even at the end of the game. Figure 5 (a) and (b) show the optimal solutions against equation (10). The transition from fossil fuels to backstop energy occurred during the 20^{th} round, and the price of backstop energy was lower than that of fossil fuels at the end of the game.

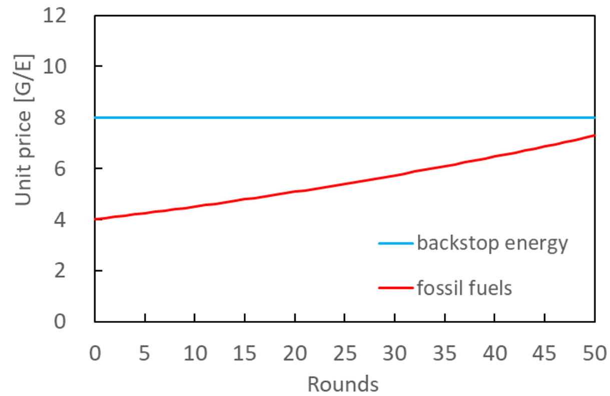
This study models the carbon tax as an extra cost for fossil fuels. As the rate of carbon tax is gradually raised in the real world, this study sets a stepwise carbon tax rate, as shown in Figure 6. The cost for fossil fuels increases by 1[G] every 10 rounds. This tax rate is set such that the optimal solution against equation (9) with tax is close to that against equation (10) without tax. Figure 7 shows the optimal energy selection and the resulting energy prices against equation (9) with tax. As intended, the energy transition occurred during the 20^{th} round, and the price of backstop energy was lower than that of fossil fuels, as shown in Figure 5.

Table 1: Parameter settings

Symbol	α	β	δ	ε	σ	μ	ν	pb_0	pf_0
Unit								[G/E]	[G/E]
Value	-0.5	10	0.007	0.3	0.012	0.012	0.2	8	4

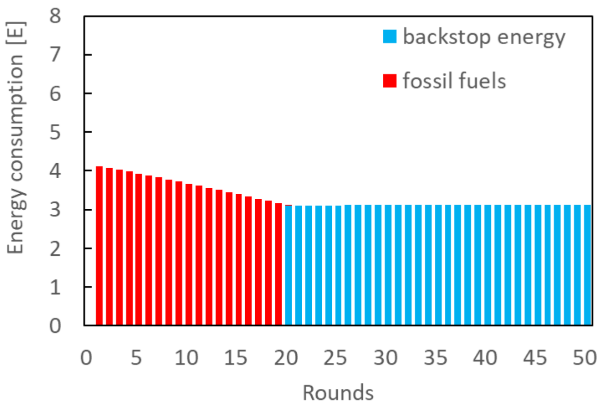


(a) Energy consumption

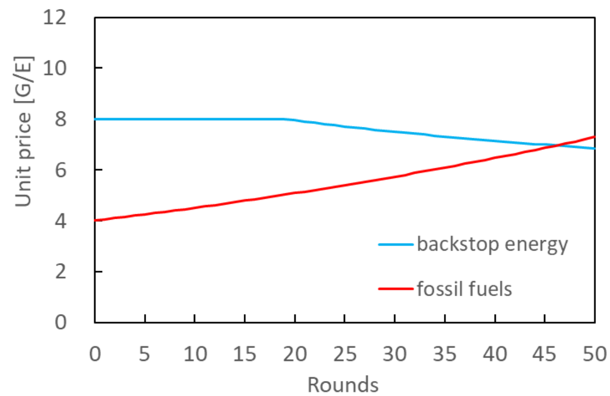


(b) Energy price

Figure 4: The optimal solution NOT considering environmental damage

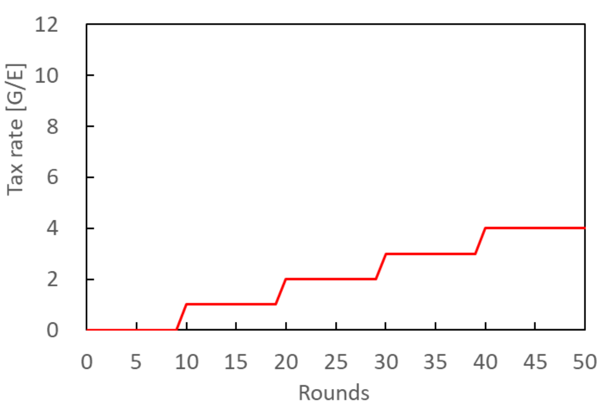


(a) Energy consumption

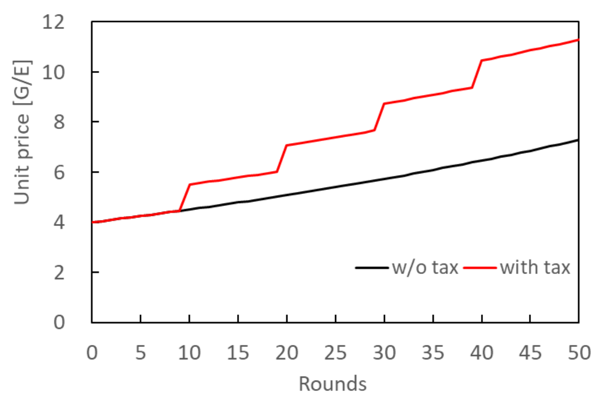


(b) Energy price

Figure 5: The optimal solution considering environmental damage

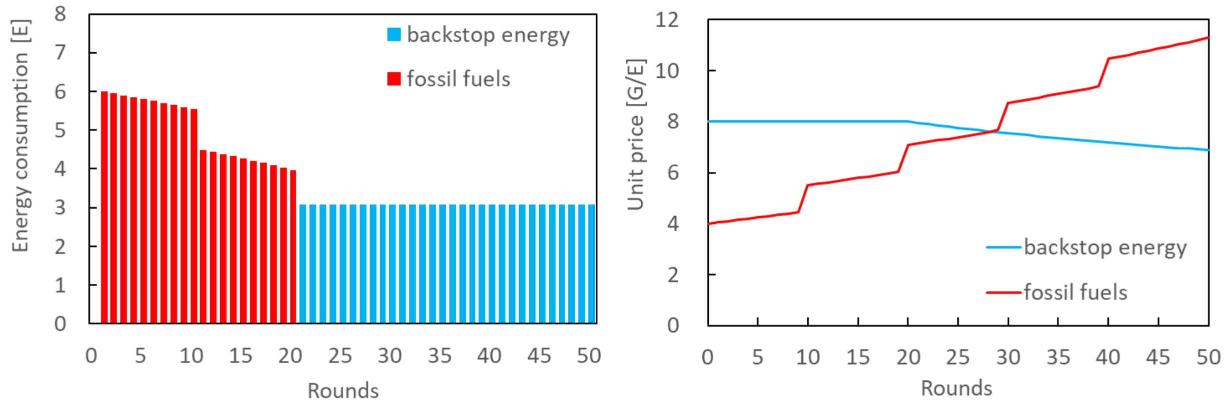


(a) Tax rate



(b) Fossil fuel price per condition

Figure 6: Time-series changes in carbon tax rate and fossil fuels price



(a) Energy consumption

(b) Energy price

Figure 7: The optimal solution not considering environmental damage in the with tax condition

3. Experiments

Forty students from the University of Tsukuba participated in this experiment. The games were played five times for each condition: without and with tax. These experiments were conducted online as a measure against the COVID-19 epidemic. A web application for gameplay and a questionnaire survey were developed using oTree (Chen, 2016). The participants and experimenters communicated through Zoom.

The questionnaire was administered in and after the game for identifying the factors affecting player selection. Table 2 lists the questions used in this experiment. Q1 and Q2 were in-game questions to inquire about time-series changes in anxiety about uncertainty in energy prices. These questions were displayed at the beginning of the game and every five rounds. Participants answered these questions on a scale of 1 to 7, with a larger number corresponding to stronger anxiety. Q3‑8 were postgame questions. Participants also answered these questions on a scale of 1 to 7, with a larger number corresponding to stronger affirmation. The objectives of Q3‑5, Q6‑7, and Q8‑9 were to survey the understanding of the optimal strategy, perception of factors hindering energy transition, and degree of commitment to the game, respectively. These questions were embedded in a web application within the game.

Before the gameplay, the abstract of the experiment and the rules of the game were explained to the participants. Their objective was to maximize their own benefit: the larger the benefit they obtained until the end of the game, the more rewards they would gain. During the game, all players provided the consumption of fossil fuels and backstop energy in every round simultaneously, and they could not observe the inputs of others in that round. The inputs by players were sent to the web application server online, and feedback against their selection was returned. The participants could freely refer to the record of energy selection by all players and past energy prices. Furthermore, they could use a calculator embedded in the web application, which enabled participants to estimate the results of their inputs. Players could communicate with each other through public chats and talk during the game. After the experiments, participants received Amazon gift cards worth 2,000–4,000 JPY (16–32 USD), depending on their final benefit.

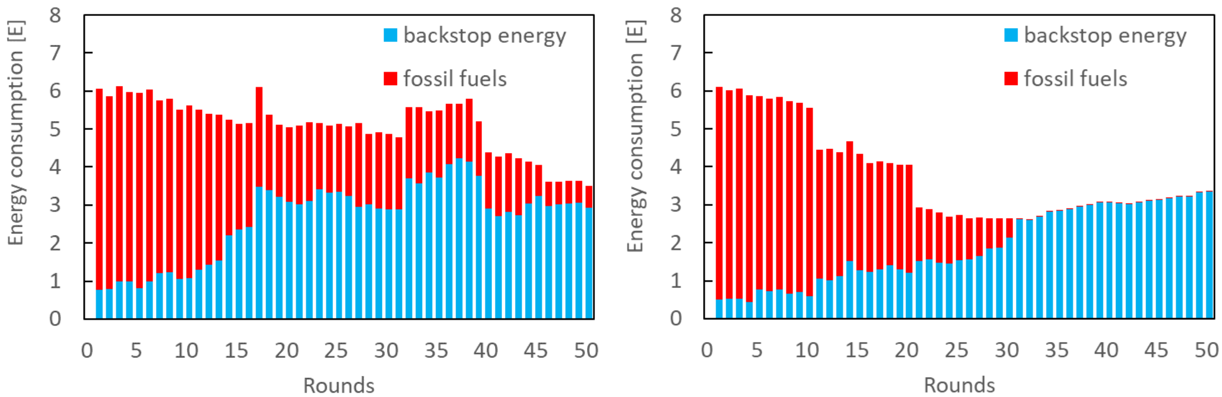
Table 2: Questionnaire during and after the gameplay

In-game	Anxiety about uncertainty	Q1	How anxious are you about not knowing the future fossil fuels price?
		Q2	How anxious are you about not knowing the future backstop energy price?
Post-game	Effective strategy	Q3	I should have adopted only fossil fuels.
		Q4	I should have completed transition to backstop energy.
		Q5	I should have used both fossil fuels and backstop energy until the end of game.
	Obstacles to energy transition	Q6	The rate of increase in fossil fuels price was not assessed quantitatively.
		Q7	I do not know how aggressively other players would use backstop energy.
	Commitment to game	Q8	Did you enjoy this game?
		Q9	Did you understand this game with ease?

4. Results

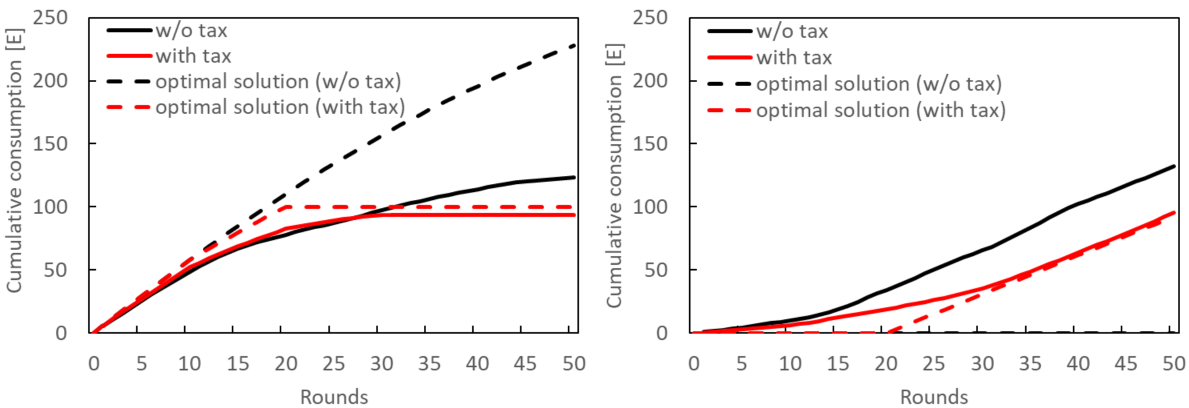
Figures 8 (a) and (b) show the time series changes in the consumption of fossil fuel and backstop energy per round without and with tax conditions, respectively. These values are the total consumption of four players averaged over five games for each condition.

Figures 9 (a) and (b) show the cumulative consumption of fossil fuels and the backstop energy per round for each condition. The solid lines show the results of experiments calculated from Figure 8, the dashed lines show the optimal solutions maximizing the objective function (9), and the black and red lines correspond to the without and with tax conditions, respectively.



(a) Without tax (b) With tax

Figure 8: Time-series changes in the energy consumptions in (a) without tax and (b) with tax experiments



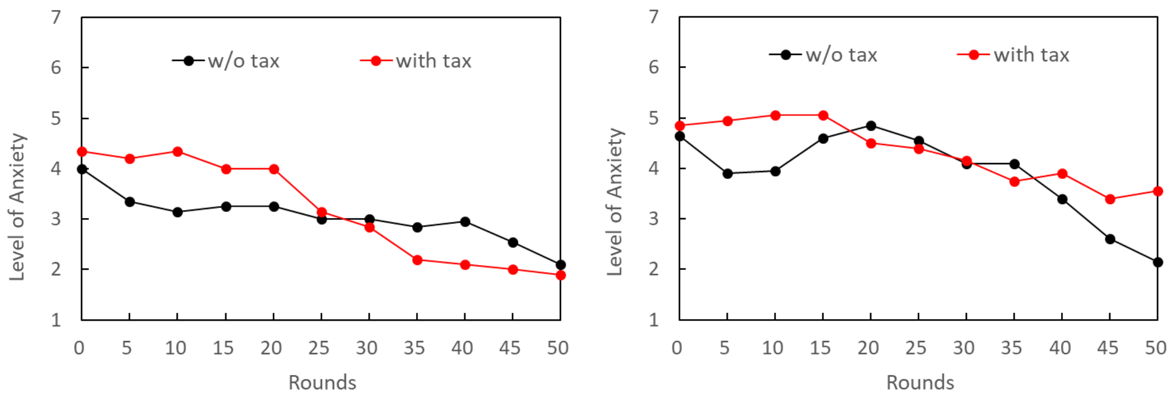
(a) fossil fuel (b) backstop energy

Figure 9: Time-series changes in the cumulative energy consumptions, experimental results, and optimal solutions for (a) fossil fuel and (b) backstop energy

By comparing the black lines in Figures 9(a) and (b), we found that the participants of the experiments consumed a smaller amount of fossil fuels and a larger amount of backstop energy compared with the optimal solutions until the end of the game under the without tax conditions. Conversely, by comparing the red lines in these figures, we found that the participants consumed similar amounts of both types of energy under the with tax conditions. These results indicate that the carbon tax rule makes players choose a rational energy mix for the entire society. However, the total consumption of backstop energy is lower under the with tax condition than under the without tax condition.

Focusing on the energy consumption per round in Figure 8, the players under the without tax condition consistently consumed backstop energy from the start to the end of the games; during the 15th to 30th rounds, they consumed a larger amount of backstop energy compared with those under the with tax condition. In addition, players under the without tax condition consumed fossil fuels in every round throughout the game, while players under the with tax condition stopped consuming fossil fuels after the 30th round. Based on these trends, the entire game was divided into three stages: rounds 1 to 15 were defined as the early stage, rounds 16 to 30 were defined as the middle stage, and rounds 31 to 50 were defined as the late stage. In the early stage, there were few differences in the energy consumption patterns between the two conditions. In the middle stage, a larger amount of backstop energy was consumed under without tax conditions. In the late stage, a larger amount of fossil fuels was consumed under without tax conditions.

Figures 10 (a) and (b) show the level of anxiety regarding uncertainty in the prices of fossil fuels and backstop energy: the time-series changes in the answers to Q1 and Q2 in Table 2. The black and red lines correspond to the answers in the without tax and with tax conditions, respectively. These values are the means of the answers of all the participants in each condition. All lines show a decreasing trend throughout the game. This trend appears to reflect a decrease in uncertainty for players as the game approaches the end.



(a) Fossil fuel (b) Backstop energy

Figure 10: Time-series changes in anxiety about uncertainty of energy price for (a) fossil fuel and (b) backstop energy

During the early stage (1st to 15th rounds), the anxiety level regarding the prices of both backstop energy and fossil fuels was higher under the with tax condition than under the without tax condition. However, this difference in the anxiety level did not lead to a large difference to the energy mix, as shown in Figure 8. During the middle stage (15th to 30th rounds), the anxiety level about the price of fossil fuels was relatively high under the with-tax condition, while the anxiety level regarding the price of backstop energy was similar between the two conditions. During the late stage (30th to 50th rounds), the anxiety level regarding the price of backstop energy was relatively high under the with tax condition, and the anxiety level regarding the prices of fossil fuels was relatively high under the without tax condition.

Figure 11 shows the answers to the post-game questionnaire and the answers to Q3–Q9 are presented in Table 2. The black and red dots in Figure 11 represent the answers by players who participated in the without tax and with tax conditions, respectively.

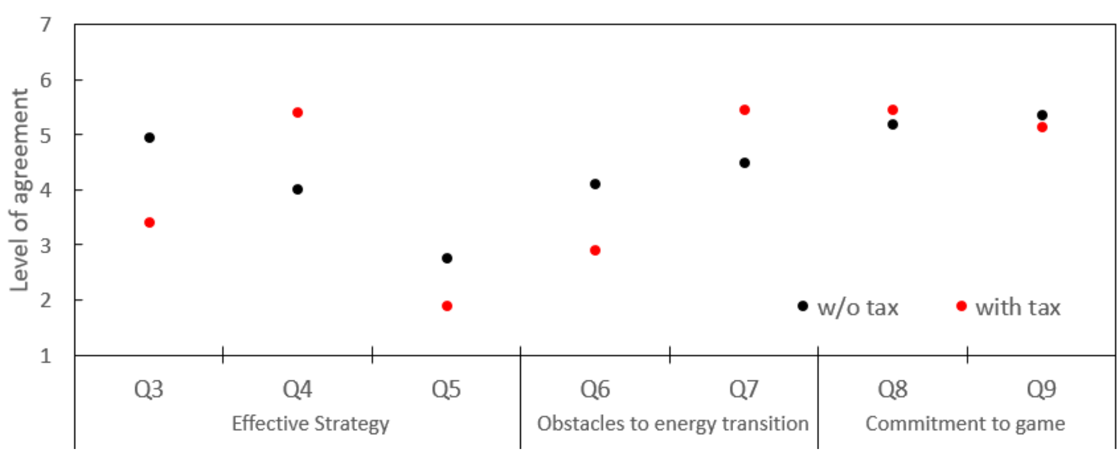


Figure 11: Answers to post-game questionnaire under the without tax and with tax conditions

Comparing the level of agreement with the three types of strategies, dependence on fossil fuels, complete transition to backstop energy, and hybrid use of two types of energies (Q3, Q4, and Q5), the agreement with the first strategy was highest under the with tax conditions and the agreement with the second strategy was the highest under the with tax conditions. These results suggest that players recognized the optimal strategy in these conditions at the end of the game.

Under the with tax condition, the uncertainty in the price of fossil fuels is less recognized as an obstacle to energy transition compared to the without tax condition (Q6). Conversely, the uncertainty in the behaviors of others is recognized as an obstacle to energy transition under the with tax condition (Q7). These results suggest that the tax can increase anxiety about the behavior of others while lowering anxiety about the future prices of fossil fuels.

Judging from the answers to Q8, participants appear to face few difficulties in understanding the rules of the game under both conditions, as there appear to be few differences in the understanding of rules between the conditions. Judging from the answers to Q9, the interest of participants in the game appears to be high under both conditions, as they are expected to concentrate on playing the role of energy consumers during the game.

5. Discussion

Under the with tax condition, anxiety regarding energy price was relatively high during the early stage, and the consumption of backstop energy was relatively low during the middle stage. These results can be explained by the phenomenon reported by Pillutla and Chen (1999). They conducted experiments using social dilemma games under competitive and non-competitive storylines; the players of the game decided how much they invested in their property for public purposes. After the first game, players were informed of the behavior of others. The contents of the feedback were pre-determined, and players were informed that others were cooperative or competitive, regardless of their actual behaviors. After the feedback, the same game was played again. In the non-competitive situation, players obtained the “competitive” feedback and became competitive in the next game. Pillutla and Chen (1999) discussed that players largely change their perception of social status from cooperative to competitive when they recognize the behavior of others as being competitive despite a non-competitive storyline. Therefore, players’ behavior is strongly affected by the gap between positive and negative expectations. Mulder et al. (2006b) suggested that a sanction rule under the social dilemma situation forms this gap and undermines the trust of cooperative players in others.

In this study, we explained the tax rule to players at the beginning of the game only under the with tax condition. This explanation appeared to form the expectation of players that others aggressively introduce backstop energy. However, contrary to this expectation, players seldom installed relatively expensive backstop energy during the early stages of games. The relatively high anxiety regarding energy prices during the early and middle stages under the with tax condition can be interpreted as a conflict between intention for energy transition and economic thinking that prefers cheap fossil fuels. This gap between expectation and observation appeared to decrease the introduction of backstop energy during the middle stage. The results of the questionnaire survey about the obstacle to energy transition (Q6 and Q7) support this interpretation; the uncertainty in the aggressiveness of other players to energy transition was recognized as an obstacle under the with tax condition.

In conclusion, the results of this study suggest that a stepwise carbon tax can contribute to achieving energy transition; the switch from fossil fuels to backstop energy was completed only under the with tax condition. However, during the earlier stage of the game, the spontaneous investment in backstop energy may be postponed because the relatively lower tax rate is insufficient to force the players to invest in backstop energy, while it is sufficient to form expectations for the transition.

6. Conclusions

This study evaluated whether a carbon tax can promote energy transition by using a multiplayer game modelling energy selection in a liberalized market. By comparing the experimental results with and without tax, we found that a carbon tax appears to be helpful in achieving the emission reduction goal. However, it was also suggested that the tax may undermine the spontaneous intention to transition to backstop energy and postpone the spread of backstop energy. This negative effect appears to be caused by the gap between the expectations and observations formed by the carbon tax. In future research, we intend to further investigate this and verify other problems of carbon tax, such as regressivity, which can impose different burdens on large and small consumers.

7. Acknowledgement

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