sustainability

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Impact of a Carbon Tax on Energy Transition in a Deregulated Market: A Game-Based Experimental Approach

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Abstract: Energy companies in a competitive market face a dilemma between the short-term revenue benefits of using fossil fuels and the long-term market benefits of investing in renewables. This dilemma is caused by uncertainties in price competition, return on investment in renewables, and the price of fossil fuels. This study experimentally investigated whether a carbon tax contributes to overcoming this conflict using an online multi-player game. The participants played the role of energy companies that produce energy from either fossil fuels or renewables. The game was played seven times each, with and without taxation on fossil fuels. In the with-tax condition, the rate and timing of taxation were informed at the beginning of the game, and the tax was imposed late in the game. The gameplay results showed that the investment in renewables was increased by the actual taxation but not by the information of taxation in advance. The answers to in- and post-game questionnaires indicated that information on taxation did not reduce player anxiety about future uncertainties. These results suggest the importance of considering the effects of policies on the perceptions and future behaviors of market players.

Keywords: energy transition; greenhouse gas emission; carbon tax; sustainability; gaming; social psychology; online experiment; oTree

Citation: Suzuki, K.; Ishiwata, R. Impact of a Carbon Tax on Energy Transition in a Deregulated Market: A Game-Based Experimental Approach. *Sustainability* **2022**, *14*, 12785. https://doi.org/10.3390/su141912785

Academic Editor: Vincenzo Bianco

Received: 12 August 2022
Accepted: 30 September 2022
Published: 7 October 2022

1. Introduction

The consumption of fossil fuels has been consistently increasing over the last three decades [1,2] despite reports of serious threats associated with anthropogenic climate change [3,4]. Therefore, the energy transition from fossil fuels to renewable energy has been regarded as one of the most important policies to mitigate global warming. Numerous studies investigated the technological feasibility of 100% renewable electricity systems in terms of renewable resources potential, required capacity of dispatchable power sources to absorb the variation of wind and solar power output, and additional transmission lines [5–13]. These studies have formed a consensus that the energy transition is at least technologically feasible, despite a few counter-arguments [14–16].

Apart from this optimism on the technical aspects, the social aspects of energy transition have been recognized as the main obstacles to the energy transition. The conflict between global and local benefits is one of these obstacles. The welfare of the entire world is maximized by mitigating climate change, whereas each nation, company, and person can typically save costs by avoiding efforts to reduce greenhouse gases [17]. This conflict is a type of social dilemma, defined as a situation in which the optimal strategy for individual players leads to a suboptimal collective outcome [18]. The deregulation of the energy market manifests these social conflicts by significantly increasing the number and type of actors involved in the energy transition [19]. The diversification of stakeholders complicates the mechanism of energy technology selection by market participants [20] and reveals conflicting opinions among diverse stakeholders, including businesses, consumers, civil society organizations, media, local residents, municipal authorities, political parties, advisory bodies, and government ministries [21]. Therefore, the energy transition is hindered primarily by social factors rather than technological factors, and the effectiveness of climate change policies should be evaluated in terms of their ability to mitigate these social factors.

The effects of climate change policies are often assessed using models based on economic theory, such as general or partial equilibrium models [22–29]. These normative analyses are useful for identifying policies with relatively high performance by comparing the solutions of the models for several policy scenarios. For example, Dong et al. identified Chinese provinces where carbon taxes should be preferentially implemented regarding economic losses and CO_2 reductions [26]. Li et al. showed that taxation on only coal and oil can achieve energy savings and CO_2 emission reductions with lesser gross domestic product (GDP) loss than that occurring following taxation on every type of fossil fuel [27]. Takeda and Arimura showed that income from carbon tax should be used to offset corporate tax rather than income or consumption taxes in terms of GDP and national income growth [29]. However, these normative analyses are not suitable for considering the stagnation or delay in decarbonation caused by social factors, as these studies considered an ideal path in which society-wide benefits are considered and maximized. To assess the impact of influential social factors, the dynamic relationships between multiple stakeholders with individual purposes and values need to be modeled.

Some environmental economics studies have adopted game theory: a mathematical approach to analyze situations in which two or more rational individuals make decisions that will influence one another's welfare [30]. These theoretical approaches can be roughly divided into non-cooperative and cooperative game approaches [31]. The non-cooperative game approach investigates the mechanism through which interactions among non-cooperative actors prevent measures against climate change [32–35] and verifies the effects of climate change policies on game solutions [36–38]. Conversely, the cooperative game approach investigates the theoretical possibility that all actors can increase their benefits by forming a coalition [39–41]. However, game theory solutions may not be suitable for capturing the reality of decision-making in social dilemmas because actors in the real world might be affected by factors other than rational thinking, such as communication, trust, learning, and norms [42–45].

Such theoretical limitations have been implemented in experimental studies in which human participants play multi-player games representing social dilemmas. One of the most significant concerns in these studies is the effects of sanctions, which refer to incentives, such as punishments or rewards [46]. In the context of climate change policies, punishments correspond to negative incentives, such as carbon pricing, whereas rewards correspond to positive incentives, such as feed-in tariffs or subsidies to green technologies. Several studies have shown that sanctions promote cooperative behavior in social dilemma situations [47–52]. Conversely, some studies have indicated the limits and side effects of sanctions [46,53–58]. For instance, Tenbrunsel and Messic showed that punishment may reduce voluntary cooperation because participants recognize cooperate/defect selection as a business rather than an ethical problem after experiencing a negative incentive [53]. Ostrom argued that punishment promotes cooperation as long as it is introduced by players, while it reduces cooperation when introduced exogenously [54]. Mulder et al. showed that punishment might reduce voluntary cooperation by undermining trust and cooperation among participants [55]. Kitakaji and Ohnuma suggested that not only punishment but also reward may reduce cooperation; the concern of the participants moving from cooperating to earning rewards [56]. These results suggest that experimental studies with human participants are useful for identifying hidden limitations or side effects of rules that are theoretically expected to work well.

Several of these experimental studies focused on social conflicts between private and public benefits. However, regarding environmental issues, studies on social dilemmas need to focus not only on social conflicts but also on temporal conflicts between short- and long-term benefits [59–61]. Some experimental studies have suggested that pro-environmental actions for long-term benefits are prevented by various uncertainties regarding the future, such as uncertainties associated with the probability and magnitude of hazards caused by environmental destruction or benefits of pro-environmental actions to mitigate these hazards. For example, Stern showed that incomplete information on the relationship between resource depletion and future economic loss reduces the rate of cooperative action [62]. Milinski showed that the rate of cooperative action decreases as the probability of environmental hazards decreases [63]. Zhang showed that people might exploit more resources when their recovery rate is unpredictable [64].

Employing this time-series perspective is expected to be critical in verifying the effectiveness of climate-change policies. For instance, the Japanese Ministry of Environment plans to gradually raise the level of taxation on greenhouse gas emissions (namely, carbon tax). According to their plan, tax rates in the distant future will be announced in advance to increase the predictability of returns on green investment [65]. The phasing-in of carbon tax was also discussed in other countries to address socioeconomic uncertainties and increase the social acceptability of taxation [66–68]. To examine the impact of such future policy plans on the current behavior of economic agents, it is necessary to address both social and temporal conflicts, namely conflicts between public and private benefits and between short- and long-term benefits.

This study investigates the impacts of carbon tax on the energy transition from fossil fuels to renewables. The energy transition suffers from social conflict and price competition among energy companies. In a deregulated market, each company can expand its market share by reducing the selling price, while price competition among companies decreases their overall benefit. The decrease in benefits induces a lack of long-term investment in renewables, resulting in the loss of social welfare. Energy transition also suffers from temporal conflicts such as the selection between fossil fuels and renewables. Fossil fuels are the best choice for reducing short-term energy supply costs, whereas renewables are more favorable considering long-term sustainability. Furthermore, these two types of conflicts are interrelated. Utilizing fossil fuels is preferable for both private and short-term benefits, whereas renewable energy investment is beneficial for both societal and long-term benefits. To consider these social aspects of energy transition, this study employed an experimental approach using a multi-player game with the theme of energy transition in a deregulated market. This game was designed such that participants can simultaneously experience social and temporal conflicts by addressing three types of uncertainties: pricing by other participants, return on investment in renewables, and prices of fossil fuels. Participants played the game under one of two conditions. The first condition was characterized by no taxation on fossil fuels, whereas the second condition included taxation on fossil fuels, which was imposed late in the game. These conditions were explained to participants before the game started. By analyzing records of gameplay and answers to follow-up questionnaires, the effects of carbon tax on the perception and behavior of energy companies in a competitive market were reported. This study is novel in that it verifies the effect of the carbon tax on energy transition considering the multiple uncertainties faced by energy companies.

2. Game Model Design

"Energy Transition" is a multi-player game focusing on the dynamics of energy transition from fossil fuels to renewable energy in a deregulated market [69,70]. The participants play the role of energy companies that produce energy from either fossil fuels or renewable energy resources. The players aim to maximize profits by selling energy to consumers. The latest version of "Energy Transition" used in this study is explained in terms of structural conditions, formal model, and experimental conditions in the following sections.

2.1. Structural Conditions

During game design, the first step was to postulate the structural conditions necessary to represent the social and temporal conflicts faced by participants. These structural conditions include the role of participants, price competition, energy prices, incomplete information, social dilemma structures, and carbon tax. A conceptual scheme of "Energy Transition" is shown in Figure 1.

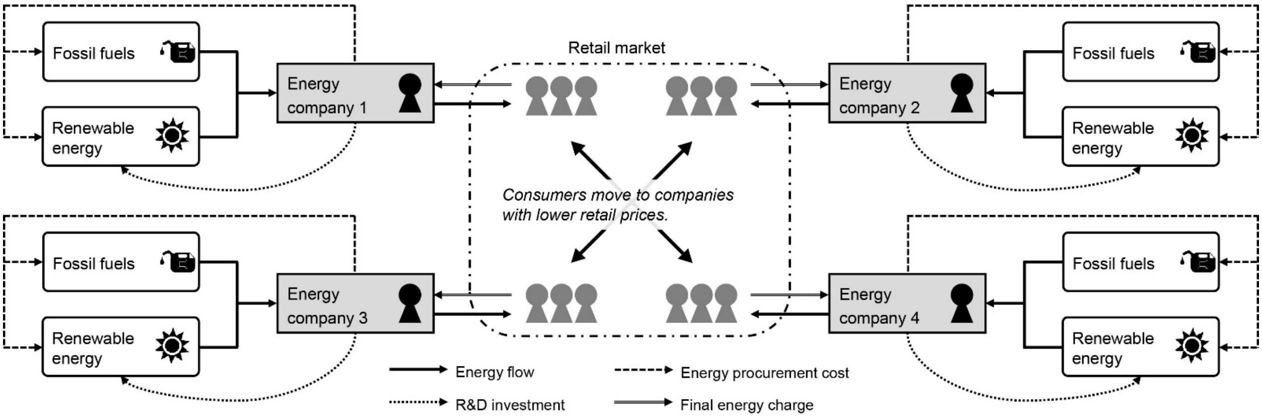

Figure 1. Schematic representation of "Energy Transition" in the case of four players.

2.1.1. Participant Role

The game consists of a virtual energy market with multiple energy companies. A participant plays as an energy company. There are no energy companies that are not controlled by players, and there are no new entrants or withdrawals from the market. The goal of players is to maximize their own profits at the end of the game. Players obtain profits by selling the final energy to consumers. One unit of final energy is produced from one unit of fossil fuels or renewable energy. There is only one type of fossil fuel as well as renewable and final energy. The game proceeds by repeating time units titled "rounds." In each round, players decide the amount of fossil fuels and renewable energy to be procured, the selling price of the produced final energy, and the amount of investment in research and development (R&D) of renewable energy. There is no limitation on energy supply; players can procure fossil fuels and renewable energy as much as they want. At the beginning of the game, all companies start in the same state with the same amount of funds, consumers, and technology levels.

2.1.2. Price Competition

The overall energy demand in the market is constant throughout the game, while the market share of each player changes because of price competition. All consumers contract with one player. The players are obligated to satisfy the demands of all contracted consumers. In each round, some consumers move from companies with relatively high prices to those with relatively low prices.

2.1.3. Energy Prices

At the beginning of the gameplay, the price of renewable energy was much higher than that of fossil fuels. However, the price of renewable energy can be reduced by investing in R&D or by producing energy using renewable energy sources. Conversely, the price of fossil fuels increases over time independent of players' actions. Therefore, the price of renewable energy could be lower than that of fossil fuels if players actively invest in renewable energy.

2.1.4. Incomplete Information

During gameplay, players can refer to the history of the market status, such as the energy mix, market share, and average selling price of the final energy. However, they cannot know the actions of others in advance because their actions in each round are decided simultaneously. Further, the rules of price competition and energy prices are informed only qualitatively; players are not given quantitative information such as an increased rate of fossil fuel prices per round or the effect of one-unit investment in R&D on the price of renewable energy. This incompleteness of information exposes players to three types of uncertainty: pricing by other participants, return on investment in renewables, and prices of fossil fuels.

2.1.5. Social Dilemma

Players choose whether to focus on short- or long-term profits through decisions regarding energy sources, selling prices, and R&D investment. The overall market profit is maximized when all players achieve energy transition until the end of the game. To achieve energy transition as a whole market, players should not reduce their selling prices from the default level to obtain funds for renewable energy investments. Players can increase their funds by reducing their selling price and using fossil fuels in the short term, especially in the early stages of gameplay. Therefore, the energy transition suffers from social conflict—the selection between cooperation to maintain market price vs. competition to obtain market share—and temporal conflict—the selection between fossil fuels and renewables.

2.1.6. Carbon Tax

There is an optional rule representing the carbon tax. The game is played under two conditions: with and without this carbon tax rule. Under the condition with this rule, taxation on fossil fuels is introduced in the second half of the game. The taxation timing and amount are explained to all players before the game begins. The tax rule is not introduced at the beginning of the game because we aimed to investigate the effect of taxation before and after implementation. In particular, we considered whether information on future taxation changes player perception and behavior.

2.2. Formal Model

Next, a formal model of the game was developed to represent the structures postulated in Section 2.1. We assumed a competitive energy market consists of some energy companies. The status of each is expressed by four values; fund $V_{i,t}$, demand for final energy to be satisfied $D_{i,t}$, cumulative production of renewable energy $R_{i,t}$, and knowledge stock $N_{i,t}$. The i and t are company and round indices. Knowledge stock indicates a technology level; a company with a higher knowledge stock can procure renewable energy at a lower cost. The fund $V_{i,t}$ increases by selling the final energy and decreases by procuring fossil fuels, renewable energy, and R&D investment.

$$V_{i,t} = V_{i,t-1} + D_{i,t-1}\, ps_{i,t} - Er_{i,t}\, pr_{\,i,t-1} - (D_{i,t-1} - Er_{i,t})\, pf_{\,i,t-1} - I_{i,t} \quad (1)$$

The first term represents the transfer from the previous round whereas the second term represents the income from selling the final energy, where ps is the selling price of the final energy. The third term is the procurement costs of renewable energy, and the fourth term is that of fossil fuels. Er and pr are the procured amounts and unit procurement costs of renewable energy, whereas $(D - Er)$ and pf are these of fossil fuels. The fifth term, $I_{i,t}$, is the R&D investment in renewable technologies.

At the end of each round, companies with relatively higher prices lose a part of their demand; the consumers move to companies with relatively lower prices. Note that the total energy demand, $\Sigma_i D_{i,t}$, is constant.

$$D_{i,t} = D_{i,t-1} + \alpha(\mu_t - ps_{i,t}) \quad (2)$$

where μ_t is the average selling price of entire market, and α is a coefficient determining the intensity of price competition. The larger the difference between each company's selling price and the market average, the larger the move of demand. However, because the rapid changes in the selling price are not realistic, the selling price cannot be changed more than m per round.

$$ps_{\ i,t-1} - m \leqq ps_{\ i,t} \leqq ps_{\ i,t-1} + m \tag{3}$$

The R&D investment and cumulative usage of renewable energy decrease the price of renewable energy.

$$pr_{\ i,t} = pr_0\{N_{\ i,t}/N_0\}^{-\beta}\{R_{\ i,t}/R_0\}^{-\gamma} \tag{4}$$

Knowledge stock $N_{i,t}$ increases by the ε root ($0 \leq \varepsilon \leq 1$) of R&D investment $I_{i,t}$. This rule represents the superiority of long-term continuous investment against short-term concentrated investment [71].

$$N_{i,t} = N_{\ i,t-1} + {I_{i,t}}^{\varepsilon} \tag{5}$$

The total usage of renewable energy $R_{i,t}$ is also defined.

$$R_{i,t} = R_{\ i,t-1} + Er_{i,t} \tag{6}$$

The price of fossil fuels, $pf_{i,t}$, is exogenously given and is not affected by players' actions. In this study, carbon taxes were included in the price of fossil fuels. Therefore, the difference between the without and with tax conditions is represented as the difference in the time-series changes in $pf_{i,t}$. The quantitative settings of these prices and taxes are explained in Section 2.3.

Equations (1), (5), and (6) are based on the Hoteling-type two-resource model often used in the field of resource economics [72–75]. Equation (4) is a common two-factor learning function [76]. Equations (2) and (3) were originally designed. To promote the understanding of players, fictitious units of energy [E], funds [G], knowledge [K], and prices [G/E] were designated. The actions of players in each round are to decide the amount of renewable energy and fossil fuels to be procured, selling price of final energy, and R&D investment in renewable energy correspond to Er, $(D - Er)$, ps, and I, respectively. The relationships between players' actions and market status are summarized in Figure 2.

2.3. Experimental Conditions

2.3.1. Numbers of Players and Rounds

The number of players was set to four. A larger number of players better represents price competition because small groups can cooperate more easily. However, the overall efforts of the experimenters exponentially increased as the number of players increased. We confirmed that four players were sufficient to design a competitive environment through test sessions.

As explained in Section 3.2, the experimental sessions were conducted online, which requires more time to communicate with participants compared to face-to-face sessions. Prior to determining the number of game rounds, we decided to set the maximum length of experimental sessions to three hours considering the burden on participants. Further, we estimated the time available for gameplay to be one hour (=60 min) considering the time for explanations before the gameplay and debriefings after the gameplay. In the test sessions, we observed that players needed approximately 2 min per round to make decisions. Based on these considerations and observations, the number of game rounds was set to 30. The results of the test session also showed that players increased their selling price for short-term profit in the last few rounds of the game. Therefore, we used the records of the game until the 25th round for analysis; records after the 26th round were omitted.

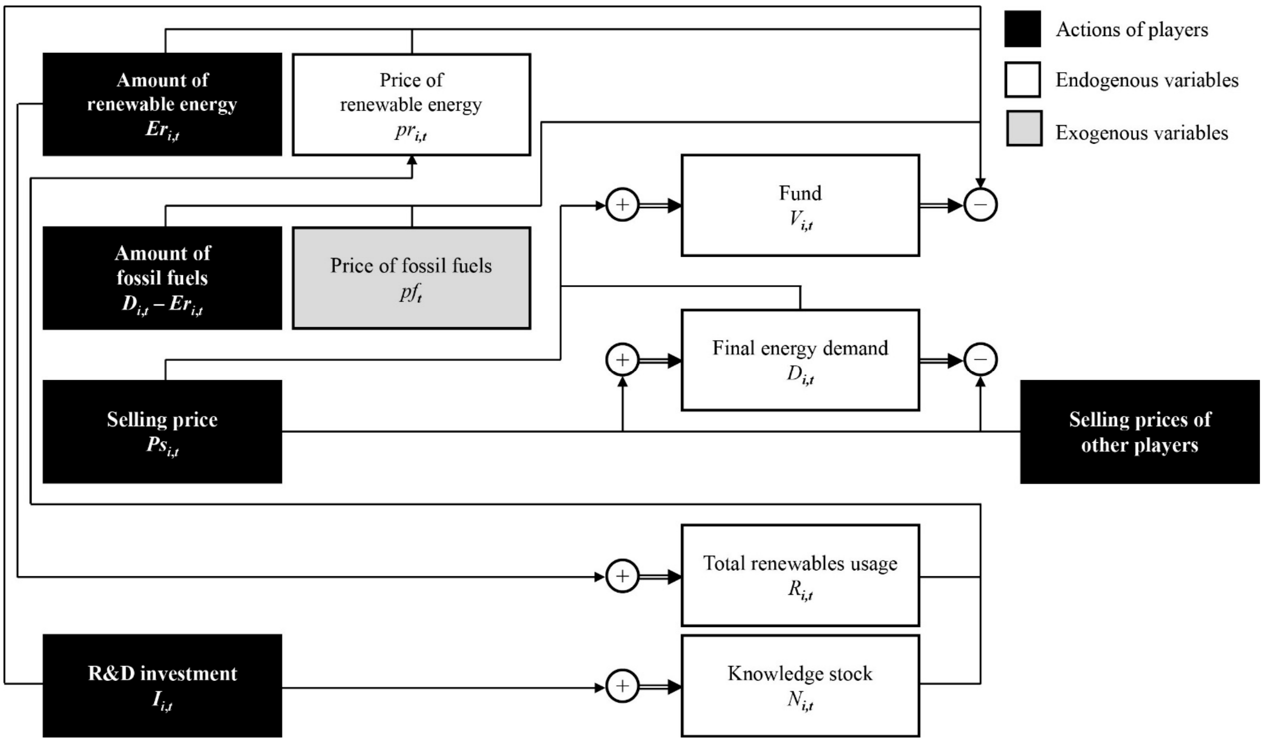

Figure 2. Relationship between players' actions and the market status in the formal Energy Transition model.

2.3.2. Parameter Settings

The structural conditions presented in Section 2.1 were represented by adjusting the following model parameters: fossil fuel prices ($pf_{i,t}$), formation coefficients (β, γ, ε), and initial player status (V_0, D_0, pr_0, ps_0, R_0, and N_0). To adjust these parameters, we constructed a nonlinear programming model that estimated players' actions to maximize the overall market fund in the final round. The objective function of the model was determined as follows:

$$\text{Max } \Sigma_i V_{i,T} \tag{7}$$

The constraints are given by Equations (1), (4), (5), and (6). Because this model cannot represent price competition among players, the selling price ($ps_{i,t}$) was set equal to V_0 throughout the game; only $Er_{i,t}$ and $I_{i,t}$ were optimized. Therefore, a solution to this model represents the optimal patterns of energy choice and R&D investment to maximize profit when a certain level of income is guaranteed.

Using this nonlinear programming model, a combination of parameters satisfying the settings outlined below was heuristically determined. First, the overall market fund is maximized by switching all energy sources from fossil fuels to renewables until the end of the game. Second, when the optimal $Er_{i,t}$ and $I_{i,t}$ are chosen, the overall market fund at the end of the game must be larger than that at the beginning ($\Sigma_i V_{i,0} < \Sigma_i V_{i,T}$). This setting reflects the real-world expectation that green investment will boost economic growth. Third, the procurement costs of renewable energy were never lower than those of fossil fuels in the first half of the game. This setting is essential to represent a temporal conflict as short- and long-term profits will coincide if the energy transition can be easily achieved. Fourth, the energy transition is completed faster in the with-tax condition than in the without-tax condition. This setting ensures the theoretical effectiveness of the taxation rule in terms of energy transition.

Finally, the parameters related to price competition (α and m), which cannot be determined by the optimization model, were adjusted through test plays. In this process, we aimed to ensure that the impact of price competition on the gameplay results is neither too large nor too small. The reduction in selling price must allow surplus loss to promote renewable energy investment, whereas demand loss in one or two rounds must not determine the results of the game.

2.3.3. Parameters and Optimal Actions

Figure 3 shows changes in the price of fossil fuels in the conditions with and without carbon tax. Under both conditions, fossil fuel prices exponentially increase over time. Under the carbon tax condition, a tax of 1[G] is introduced from round 16. Table 1 shows the values of other parameters commonly used in the two conditions. Note that this set of parameters is not the only one to satisfy the structural conditions. We focused on identifying a set of parameters that can represent conflicts to be investigated rather than verifying the effect of parameters on optimal solutions. Figure 4a,b show the pattern of renewable energy usage and R&D investments to maximize overall market funds. In both conditions, the optimal actions are to invest in R&D in the first half of the game and raise the use of renewable energy in the second half of the game. In the condition with carbon tax, the larger amount of funds are invested in R&D in the first half of the game and the transition to renewable energy occurs a few rounds earlier. The authors confirmed that these patterns do not change unless the players lower the selling price from the initial value V_0.

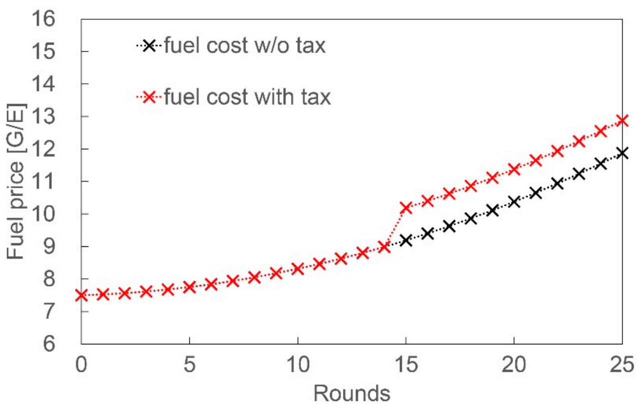

Figure 3. Time-series changes fossil fuel prices with and without carbon tax.

Table 1. Game parameters used in this study.

	m	α	β	γ	ε	V_0	D_0	p_{r0}	P_{s0}	R_0	N_0
Unit	[G/E]					[G]	[E]	[G/E]	[G/E]	[E]	[K]
Value	1	0.5	0.07	0.13	0.79	20	5	16	10	4	4

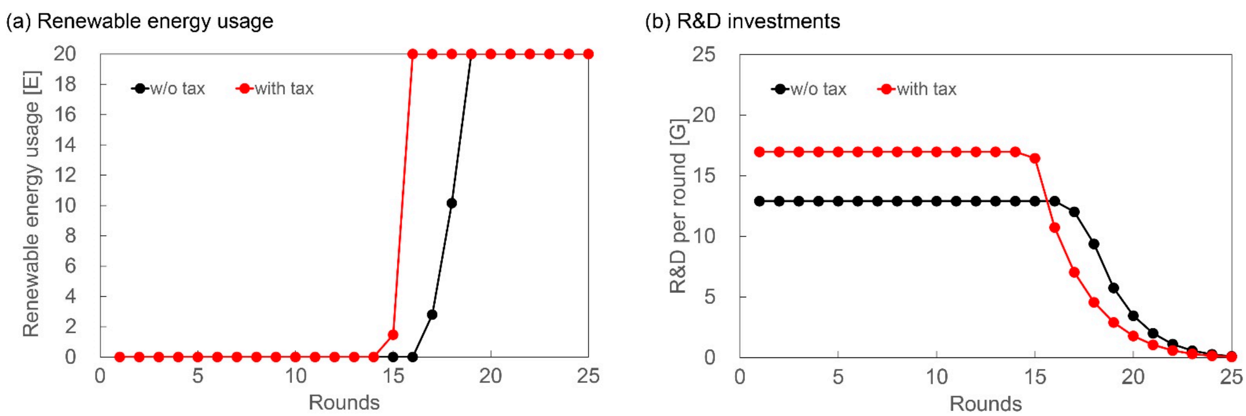

Figure 4. Time-series patterns of (**a**) renewable energy usage ($Er_{i,t}$) and (**b**) R&D investments ($I_{i,t}$) to maximize the overall market fund estimated by a nonlinear programming model.

3. Experimental Design

3.1. Experimental Environment and Procedures

To overcome the behavioral limitations caused by COVID-19, this study developed an environment for remote experiments, thus avoiding physical contact between experimenters and participants. Figure 5 shows the remote experimental environment. The web application of Energy Transition was developed using oTree, a Python-based platform for developing social experiments and surveys [77]. The application was deployed on a web application server, which could be accessed by experimenters and participants via the Internet from any PC with a web browser installed. The experimenters and participants communicated via Zoom.

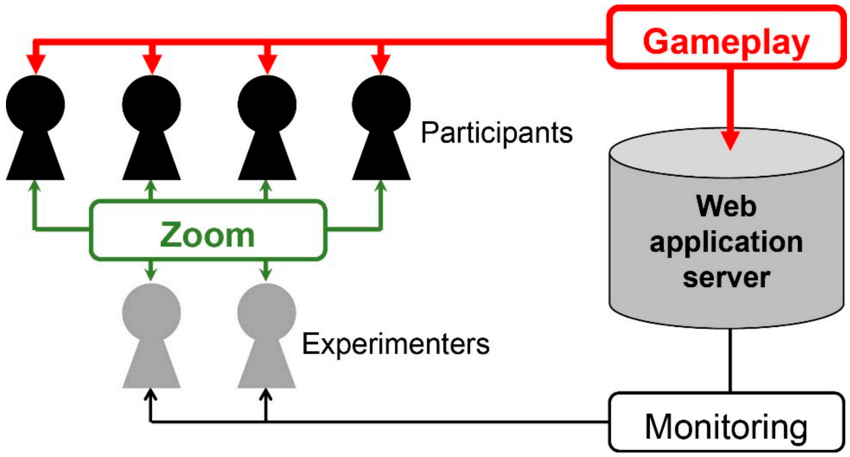

Figure 5. Environment of remote experiments using web application and Zoom.

A total of 56 students from the University of Tsukuba participated in the experiments; 44 were students of engineering, 4 of biology, 3 of medicine, 2 of psychology, 2 of literature, and 1 of mathematics. They participated in 14 experimental sessions, 7 sessions with and 7 without tax conditions. Each session consisted of instruction, experiments, and debriefings. In the instruction phase, participants played a demonstration version of the game, evaluated their understanding of rules by answering questionnaires, and addressed doubts in conversation with experimenters. In the experimental phase, participants played the game and answered the questionnaires as explained in Section 3.2. The time limit per round was set to two minutes, and a pop-up message appeared in the browser when the time was up. Although there was no penalty for exceeding the time limit, players entered their actions on time in most sessions. In the debriefing phase, experimenters explained the whole aspect of the study, informed the amount of personal prize, and answered questions from the participants. The amount of personal prize was determined based on the funds earned by each player until the end of game. The prize range was JPY 2000–4000, approximately USD 15–30. Each session required two and a half hours on average.

3.2. Questionnaire Survey

The in-game and post-game surveys were incorporated into the web application to investigate the subjective experiences of the participants. The in-game survey investigated the dynamic changes in anxiety associated with three types of built-in uncertainty: pricing by other participants, return on investment in renewables, and fossil fuel prices. These questions were asked at the beginning of game and at the end of every five rounds using a seven-point Likert scale. In these rounds, players were given an extra two minutes to answer the questions. The post-game survey investigated the comprehensive understanding of the game such as the perceptions of effective strategies, factors hindering energy conversion, and overall impressions. Table 2 lists the items in these questionnaire surveys.

Table 2. List of in-game and post-game questionnaires.

In-game	Anxiety about uncertainties	q1	How anxious are you about whether you can survive in price competition?
		q2	How anxious are you about whether investing in renewables will yield profits at the end of game?
		q3	How anxious are you about future fuel prices?
Post-game	Effective strategy	Q1	I should have continued using only fossil fuels.
		Q2	I should have completely transitioned to renewables.
		Q3	I should have utilized fossil fuels and renewables together throughout the game.
	Obstacles to energy transition	Q4	The whole market was competitive.
		Q5	Certain players were competitive.
		Q6	The effect of R&D investment on the unit price of renewable energy was not quantitatively shown.
		Q7	The increase rate of fossil fuel prices was not shown in advance.
	Overall impressions	Q8	Do you feel this game was fun?
		Q9	Do you feel this game was easy to understand?

4. Results

4.1. Gameplay Records

Table 3 shows the average values of the three variables corresponding to players' actions for the seven games played under each condition. The total renewable usage was the total amount of renewable energy consumed by the four players in a given game (Σ_t Σ_i $Er_{i,t}$). The total R&D investment was the sum of the four players' R&D investments through a game (Σ_t Σ_i $I_{i,t}$). The average market price was the simple average of the market prices in each round through a game (Σ_t $\mu_t/25$). Total profit was the amount of funds earned by four players during the game (Σ_i $(V_{i,T} - V_0)$).

Table 3. Summary of gameplay results in the 25th round (* indicates 10% significance level).

	Average		**M. W. U Test**	
	w/o Tax	**with Tax**	**U-Value**	***p*-Value**
Total renewables usage [E]	147.7	186.7	11	* 0.097
Total R&D investment [G]	273.1	259.9	24	1.000
Average market price [G/E]	9.7	9.9	18	0.443
Total profit [G]	31.0	53.1	18	0.443

The total renewables usage was greater under the with-tax condition, the Mann–Whitney test revealing a significant difference at the 10% level (p-value = 0.097). The total R&D investment seldom differed among the conditions (p-value = 1.000). The average selling price and total profit were higher under the with-tax condition; however, the difference between the conditions was not significant (p-value = 0.443). These results indicate that the tax rule promotes renewable energy use. Nevertheless, the tax rule did not affect investment in renewable energy or the market price at the aggregated level.

Figure 6a–d show the changes in the usages of renewable energy, R&D investments, energy price, and profit with and without the carbon tax rule (red and black plots, respectively). The results in figures represent the averages of the seven games in each condition.

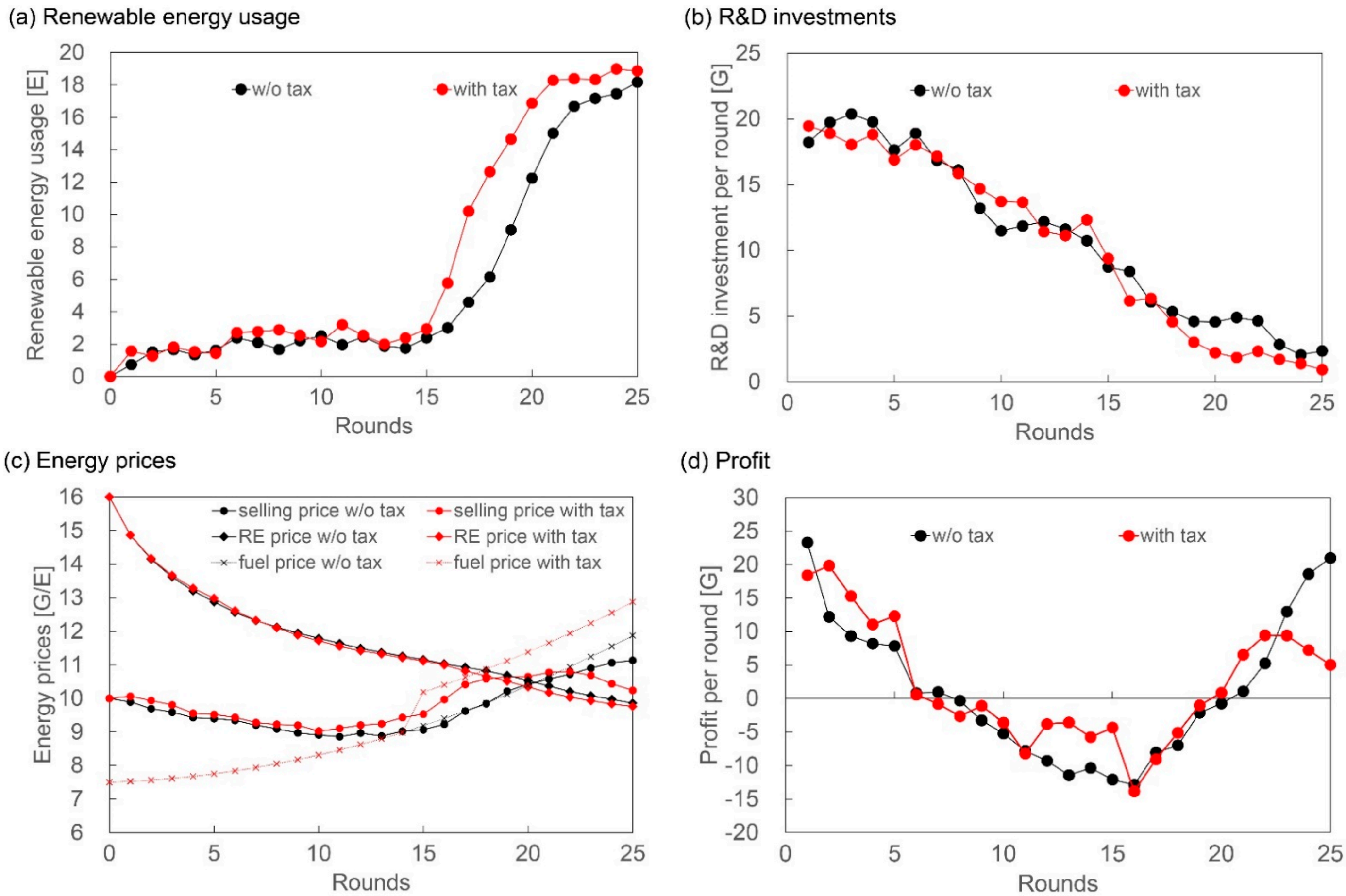

Figure 6. Time-series changes in (**a**) renewable energy usage, (**b**) R&D investments, (**c**) energy prices, and (**d**) profit under with- and without-tax conditions. These values are the averages of seven games under each condition.

Figure 6a shows that almost all energy demand is covered with renewable energy at the end of the 25th round, regardless of whether the carbon tax rule is introduced; the total energy demand in the market is fixed at 20 [E] in this study. The energy transition occurred in the latter half of the game under both conditions, while the rate of transition was higher under the carbon tax rule. This difference in the rate of transition leads to a difference in the total renewable usage, observed in Table 3.

Figure 6b shows that the amount of R&D investment follows a similar trend between the conditions: relatively high at the beginning of the game, linearly decreasing throughout the game, and reaching almost zero at the end of the game. The decreasing trend in R&D investment is natural because the effect of investments on the price of renewable energy diminishes, as defined in Equation (4), while the pattern of diminishing differed from that of the optimal solutions shown in Figure 4.

Figure 6c illustrates the three types of time-series data: the prices of fossil fuels, renewable energy, and final energy. The prices of fossil fuels, as shown in Figure 2, are presented to directly compare the prices of other energies. The price of renewable energy decreases because of R&D investments and the usage of renewables. The decreasing trend for the price of renewable energy is similar between the two conditions. In the no-tax condition, the price of renewable energy was lower than that of fossil fuels in the 21st round. In the with-tax condition, this reversal of prices between the two types of energy occurred in the 18th round. The market price of the final energy linearly decreases until the 10th round and then increases in both conditions. The increase rate was higher in the with-tax condition. Furthermore, in the with-tax condition, the market price decreased again in the last few rounds of the game. A decrease in market price indicates price competition between players because the only advantage of lowering the selling price is to exploit the demand of other players.

As shown in Figure 6d, the total profit of all players has similar trends between conditions: a decrease in the first half and an increase in the second half on the game. In the first half, the settings inherently make it difficult to obtain high profits. Players should invest in R&D for renewable energy as the price of fossil fuels gradually increases and price competition may further decrease profitability. In the second half of the game, profitability improves because the price of renewables gradually decreases as players continue investing in renewables. In the last few rounds of the game, the profit is lower under the with-tax condition because of the price competition observed in Figure 6c.

Table 4 is the summary of Mann–Whitney U test for the time-series differences between two conditions. The renewable energy usage, R&D investment, market price, and profit were averaged every five rounds. For renewable energy usage, there were significant differences from the 16th to 20th rounds (p-value < 0.05) as well as from the 21th to 25th rounds (p-value < 0.10). For the selling price, there was a significant difference in the 16–20 rounds (p-value < 0.10). For, the R&D investment and profit, no significant difference was observed throughout the games.

Table 4. Summary of the Mann–Whitney U test for time differences in two conditions (* and ** indicates p-values < 0.10 and 0.05, respectively).

		Rounds				
		1–5	**6−10**	**11−15**	**16–20**	**21–25**
Renewable energy usage [E]	U-val.	22.5	22	20	6	10.5
	p-val.	0.848	0.798	0.609	** 0.021	* 0.084
R&D investment [G]	U-val.	23	20	23	17	14
	p-val.	0.898	0.609	0.898	0.371	0.201
Market price [G/E]	U-val.	21	24	22	11	15
	p-val.	0.701	1.000	0.798	* 0.097	0.250
Profit [G]	U-val.	21	17	19	22	17
	p-val.	0.701	0.371	0.523	0.798	0.523

Overall, the carbon tax rule encouraged reliance on the renewable energy in the second half of the gameplay, where players are actually taxed. However, the carbon tax rule promoted neither usage of renewable energy nor investment in R&D of renewable energy in the first half of gameplay when players have not yet been taxed. These results suggest that the actual taxation directly affects the behavior of market players, whereas information on taxation at the beginning of the game may not change their behavior.

4.2. Questionnaire Responses

Figure 7a–c illustrates the results of in-game questionnaires regarding anxieties associated with price competition, investment in renewables, and fossil fuel prices (q1–3 in Table 2). The plots in these figures represent the average values for all players in all games. For the first three questions, there were few differences in overall trends between conditions. The anxiety associated with price competition (q1) ranged from 4 to 5 throughout the gameplay. The values for the with-tax condition were slightly higher than those for the without-tax condition. The anxiety associated with renewable energy investment (q2) ranged from 4 to 5 until round 15 while decreasing in rounds 20 and 25. The values in the with-tax condition were slightly higher than those in the without-tax condition. The anxiety associated with fossil fuel price (q3) showed a decreasing trend, with values of 5 at the beginning of the gameplay and under 3 at the end of gameplay. The decrease in anxiety associated with investments in renewables and fossil fuel prices appears to be caused by the reversal in the prices of the two types of energy. As the price of renewable energy became lower than that of fossil fuels, players recognize that R&D investment in renewables in the past rounds yielded results and are no longer bothered by rising fossil fuel prices. For all three questions, no significant differences (p-values > 0.10) were observed through gameplay. Therefore, players' perception of these uncertainties does not appear to be affected by the carbon tax rule during the game.

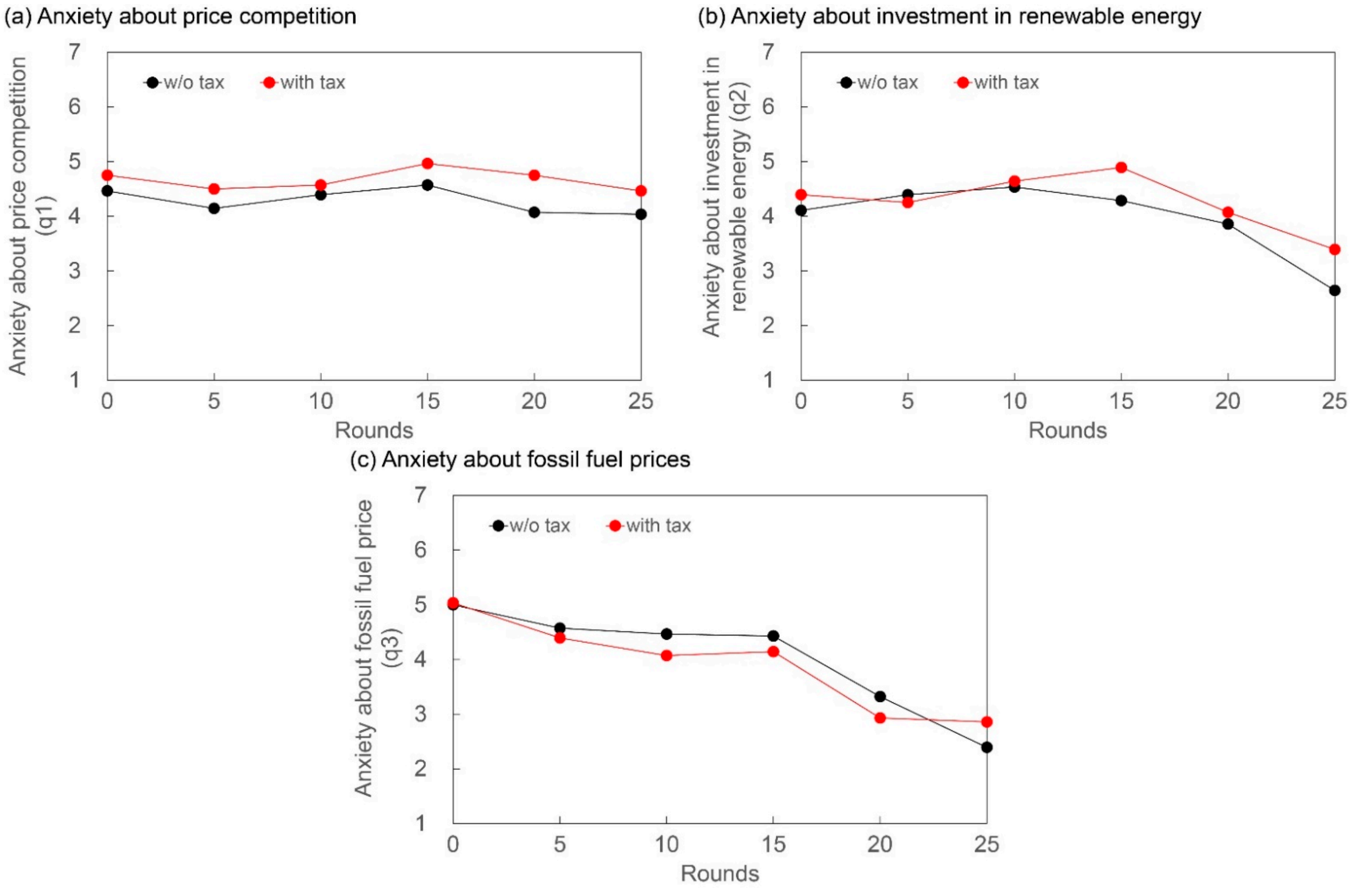

Figure 7. Time-series changes in answers to in-game questionnaire under with- and without-tax conditions. Responses to anxieties about (**a**) price competition, (**b**) investment in renewable energy, and (**c**) fossil fuel prices.

Table 5 shows the answers to post-game questionnaires (Q1–9 in Table 2) assessing the understanding of effective strategies, barriers to energy transition, and impressions of the game. The first and second columns show the average values for all players participating in each condition. The summary of the Mann–Whitney U test between conditions are shown in the third and fourth columns.

Among the questions regarding effective strategies, the answers to Q2 were clearly higher than those to Q1 and Q3 in both conditions. This indicates that most players recognized the optimal solution to the game, which is, completing the energy transition by the end of the game. This result also ensures that most players considered the barrier to transition, as determined by Q4 to Q7, based on this premise.

Under the without-tax condition, the responses to Q4 and Q6 were higher than those to Q5 and Q7. In other words, the players under this condition felt that price competition and uncertainty associated with the effect of R&D prevented them from actively investing in renewable energy. The answers to Q4 were significantly lower (p-value < 0.01) under the with-tax condition. The answers to Q6 under the without-tax condition were similar to those in the without-tax condition. This indicates that under the tax condition, players felt that the uncertainty associated with the effect of R&D for renewable energy was the largest barrier to energy transition. Under the with-tax condition, players faced stronger pressure to introduce a larger amount of renewable energy and raise the selling price in the second half of the game, as shown in Figure 6a,c. Under such circumstances, players appear to feel that the carbon tax rule prevented them from reducing the selling price to remain competitive and contributed to promoting the renewable energy transition.

Table 5. Summary of post-game questionnaire results (*** p-values < 0.01).

		Average		M. W. U Test	
		w/o Tax	with Tax	U-Val.	p-Val.
Effective strategy	Fossil fuel only (Q1)	2	2.1	24.5	0.948
	Complete transition (Q2)	6.1	5.5	15.5	0.274
	Hybrid approach (Q3)	2	2.4	20.5	0.653
Obstacles to transition	Competitive market (Q4)	5.5	3.9	0	*** 0.002
	Competitive player (Q5)	3.4	3.9	17	0.367
	R&D uncertainty (Q6)	5.4	5.6	20	0.605
	Fuel price uncertainty (Q7)	3.8	4.1	21.5	0.748
Overallimpressions	Game was fun (Q8)	6.3	6.1	18	0.438
	Easy to understand (Q9)	5.8	4.9	12.5	0.139

The answers to questions assessing impressions of the game indicate that most participants enjoyed the game (Q8) and had little difficulty understanding the rules of the game (Q9) under both conditions. These results indirectly ensured that the players concentrated on the experiment with a clear understanding of their roles in the game. However, the relatively low responses to Q9 under the with-tax condition should be noted. Although there was no significant difference in responses under these conditions (p-value > 0.10), this result suggests that even a simple rule such as the carbon tax in this study can decrease the understanding of players to some extent.

5. Discussion

Our result show that the carbon tax rule accelerated the energy transition in the second half of the gameplay, with players under the with-tax condition using a significantly larger amount of renewable energy than those in the without-tax condition just after taxation. Simultaneously, taxation raised the selling price of final energy. Figure 6c shows that players under the with-tax condition gradually raised their selling price from the 10th round, while a statistically significant difference was observed only after the 15th round. These results suggest that the carbon tax caused players to focus their attention on investment in renewables rather than on price competition. In this sense, a carbon tax is expected to contribute to the energy transition in a competitive market.

However, the carbon tax rule did not encourage investment in renewable energy in the first half of the game. The results of the in-game survey indicate that the carbon tax did not mitigate player anxieties regarding uncertainties associated with price competition, investment in renewables, and fossil fuel prices. Further, our post-game survey results show that most players regarded the uncertainty associated with the effect of R&D as the largest barrier to energy transition. From the players' viewpoint, the carbon tax certainly reduced the absolute benefit of using fossil fuels but did not guarantee the relative advantage of renewable energy in the future. Even if the carbon tax rule exists, the fossil-fuel-intensive strategy may be more profitable than the energy transition strategy as long as the cost reduction in renewable energy by R&D investment is relatively small. In conclusion, the future plan of taxation may not promote investment in renewable energy as such a plan cannot form an expectation in market players that energy transition is the best strategy to maximize their profit.

These findings support those of previous studies that uncertainties associated with the future direction of the market may hinder pro-environmental actions aimed at providing long-term benefits [62–64]. Furthermore, these findings are consistent with the criticisms of fix-rate carbon taxes as carbon tax rates should be adjusted to create incentives for investing in low-carbon technologies [68]. Even though the adjustment of the carbon tax rates has been discussed in terms of its linkage to the macroeconomy [66] and social acceptability [67], the results of this study suggest the importance of this perspective in reducing the level of uncertainty perceived by individual economic entities.

Thus, policymakers need to ensure over time that the cost of supplying fossil fuels exceeds that of supplying renewable energy by adjusting the carbon tax rates. Such adjustments can accelerate upfront investment in renewable energy by convincing economic entities of the relative disadvantage of a strategy continuously using fossil fuels. Although this study assumes the monotonical rise of fossil fuel prices, the owners of fossil fuels reserves may reduce the selling prices to sell out their assets before the energy transition completes [78]. Under such circumstances, a carbon tax with a fixed rate does not guarantee the relative advantage of renewable energy unless it is set extremely high in advance. Therefore, policy makers should begin to consider mechanisms to adjust carbon tax rates according to fossil fuel prices.

Finally, some limitations of this study are noted to provide directions for future research. First, future studies should investigate scenarios in which carbon tax rates vary over time, as this study employed a scenario with fixed tax rates. Second, the carbon tax rule adopted in this study represents a simple punishment that does not consider the feedback of the tax revenue to the market. Carbon tax has been regarded as having a double dividend: protection of the environment through taxation and economic benefits through tax revenue [79]. Future experiments should consider the feedback of tax revenues to the market, as such feedback may induce more incentives to invest in renewables. Third, this study examined only a limited number of conditions, because we gathered university students as participants using a procedure similar to that associated with traditional laboratory experiments. In future studies, the gameplay results under more diverse conditions should be compared by adopting emergent methods, such as large-scale experiments with crowdsourcing [80] or agent-based simulations in which autonomous machine agents play games [20].

6. Conclusions

This study examined the impact of carbon tax on energy transition in a deregulated market using a multi-player game. The gameplay records suggest that an actual taxation on fossil fuels can promote the usage of renewable energy, whereas information on taxation in advance cannot promote investments. The answers to the questionnaire survey suggested that information on taxation did not reduce the level of uncertainty associated with the return on investments in renewable energy perceived by economic entities. To encourage green investment, policymakers should raise carbon tax rates when the price of fossil fuels are dropped, thus alerting economic entities of the relative disadvantage of relying on fossil fuels.

These conclusions are difficult to generalize to any social dilemma situation because in this study, we assumed a social dilemma in a specific context, that is, energy transition in a deregulated market. The energy transition is hindered not only by competition between energy companies but also by conflicts of interests and values between various actors including local citizens, workers, municipalities, and governments [21,81–83]. To overcome such more local and complex social conflicts, multi-player games aimed at communication among stakeholders may be more useful than the experimental games used in this study. Earlier studies in the fields of water resources management [84–86] and farm systems management [87–89] may prove helpful sources of inspiration for the field of energy transition. In addition, the participants' responses to a tax on fossil fuels may have depended on the structural assumptions of this study such as monotonically rising fossil fuel prices and having a fixed market size. Furthermore, the difficulty of increasing capital investment in a shrinking market is not considered. For instance, the energy demand in developed countries, including Japan, is expected to remain flat or decline in the future. Therefore, the experimental approach adopted in this study is more a heuristic illustration of the effect of a carbon tax in a specific context than a rigorous examination of the comprehensive effect of a carbon tax.

Despite such a limitation, the results of this study demonstrate the advantages of game-based policy evaluation by experimentally examining the effects of policies on the perceptions and behaviors of economic entities. In the game design field of studies, the purpose of game designers is to indirectly design the experiences of players by directly designing the rules of the game [90]. Similarly, the goal of policy makers is to indirectly design the perceptions and behaviors of economic entities by designing the rules of taxation. The game-based policy evaluation is useful to test whether the rules designed by policy makers work as intended by considering the subjective interpretations of uncertainty by economic entities. Further methodological development and exploration will be carried out to complement conventional normative analyses based on economic theory.

Author Contributions: Conceptualization, K.S.; methodology, K.S. and R.I.; software, R.I.; validation, K.S. and R.I.; formal analysis, K.S. and R.I.; data curation, K.S. and R.I.; writing—original draft preparation, K.S.; writing—review and editing, K.S.; supervision, K.S.; project administration, K.S.; funding acquisition, K.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Foundation for the Fusion of Science and Technology (FOST) (grant number 2018-01 and 2020-01) and JSPS Kakenhi (grant number 22H03807).

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Faculty of Engineering, Information and Systems, University of Tsukuba (protocol code 20-193).

Informed Consent Statement: Informed consent was obtained from all participants involved in the study.

Data Availability Statement: The corresponding author will provide the data and materials upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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