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ORIGINAL PAPER

New mechanisms in decentralized electricity trading to stabilize the grid system: a study with human subject experiments and multi-agent simulation

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Abstract The Smart grid concept has lately attracted attention because of the increase in decentralized electricity generators and the development of the information communication technology. In the Smart grid concept, mutual information exchange among suppliers and consumers can be achieved to balance and optimize the supply and demand of electricity, which is generally necessary for a grid system. Taking this background into consideration, the necessity for electricity trade by which small-scale consumers such as households buy and sell electricity is now advocated to realize further stability of the grid system. However, it is noteworthy that consumers are self-interested, which endangers the grid system stability. This study proposes new trading mechanisms applied in the electricity trade and evaluates them in terms of stability and social surplus in the market. We examine their validity using experiments with human subjects and multi-agent simulations.

Keywords Decentralized electricity trading · Trading mechanism · Multi-agent simulation · Human subject experiment

1 Introduction

In consideration of global warming and the steep increase in energy prices, various countries have been promoting the introduction of renewable energy generation modes such as photovoltaic (PV) power generation and wind power generation [1]. Because there is generally difficulty in storing the electricity generated using those means, it is necessary to balance demand and supply of electricity simultaneously to stabilize public electrical grid systems. Considering such characteristics of electricity, introduction of renewable energy generations into the current grid system makes it more difficult to stabilize the supply of electricity because some renewable energy generation modes involve output-power fluctuation. Using the Smart grid concept, mutual information exchange among medium-scale electricity suppliers, small decentralized suppliers, and consumers can be realized using information communication technology, which can balance and optimize the supply and demand related to electricity. Moreover, expansion of residential PV systems might enable electricity trade among even small-scale consumers such as households and might play a role in the further stabilization of the grids through household participation in the electricity trade market. Information communication technology helps consumers to give real-time information related to the balance of demand and supply, which is expected to achieve balanced trades by market principals and thereby increase in social surplus. In addition, a technology exists to enable electricity trade among small-scale consumers. Digital grid, which was advocated by Abe et al. [2], enables identification of who generates how much electricity by attaching information such as an address to units of generated electrical power.

To realize electricity trading, however, we must take several points into consideration. First, as described above, the amount of electricity supply and that of electricity demand must be balanced at any given time. Second, members of the grid are self-interested, meaning that their only purpose of trading electricity is to maximize their profit, which might endanger the grid system stability.

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Third, electricity is one of the most vital daily necessities which people almost always use incessantly. Therefore, trading mechanisms that compel consumers to follow a complicated process are not desirable.

Recently, the number of studies related to electricity trade is increasing as the introduction of renewable energy for electricity is promoted worldwide. For example, Rudkevich et al. [3] estimated electricity pricing under a market mechanism called Poolco, in which electric power companies bid to maximize their profit; Tanaka [4] simulated the Japanese wholesale electricity market as a transmission-constrained Cournot market. Above all, Vitelingum et al. [5] propose a mechanism based on a continuous double auction for electricity trade in which small-scale consumers can participate. However, few reports describe that kind of electricity trade. Moreover, even the mechanism proposed by Vitelingum et al. is not sufficiently simple for households when considering the features of electricity such as incessant daily use.

In this study, we define "decentralized electricity trading" as "electricity trading in which small-scale consumers who possess their own generator participate not only as consumers but also as producers."

In these circumstances, we propose two new electricity trading mechanisms which entail simple procedures and which can stabilize a system even when grid participants are self-interested. To evaluate the mechanisms, we conduct human subject experiments and multi-agent simulations. A model of decision making by human beings is constructed through subject experiments. We use it for multi-agent simulation as input data.

2 Modeling decentralized electricity trading and proposed trading mechanisms

2.1 Model of decentralized electricity trading

We construct a model of decentralized electricity trading. As Fig. 1 shows, decentralized electricity trading consists of a market, one electric power company, and n consumers who have their own generator and who can generate electricity independently.

2.1.1 Decentralized electricity trading market

As Fig. 1 shows, in decentralized electricity trading, the electric power company and all consumers trade the generated electricity in this market. This market has a trading mechanism that determines what kind of information consumers must send as an input to trade electricity and how much electricity is traded in the market. The market then determines how to distribute electricity to consumers and the electricity price based on its mechanism.

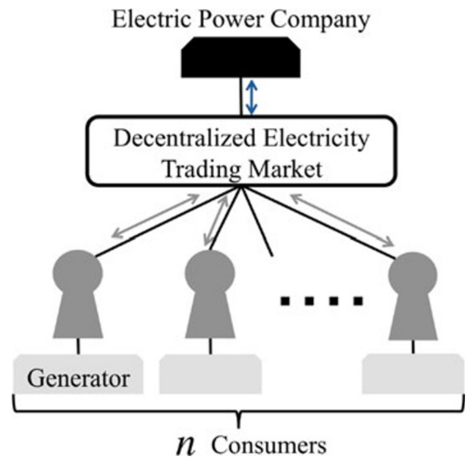


Fig. 1 Model of decentralized electricity trading

2.1.2 Electric power company

An electric power company exists in the model. Compared with consumers, this electricity trading company has much greater capacity to generate electricity. It takes responsibility for stabilizing the electrical grid system. This company executes actions of two types in decentralized electricity trading.

- In case too much amount of electricity is generated by consumers, the company purchases the excess electricity for constant price $p^{\min}$.
- In case too little electricity is generated by consumers, the company sells an amount to alleviate the shortage for constant price $p^{\max}$.

Consumers in the market have no incentive to sell their electricity to other consumers for less than $p^{\min}$, for which they can surely sell their electricity to the electric power company, and also have no incentive to buy other consumers' electricity for more than $p^{\max}$. In this study, we assume $p^{\min} = 0$ for simplicity. We designate $p^{\max}$ as the "electric power company's electricity sales price."

2.1.3 Consumers

Consumers send necessary information and electricity they generate to the market. Each of the consumers gains profits through the trade, which is determined by their own demand function for electricity and the amount of electricity they consume through the trade. The purpose of consumers is to maximize their profit.

2.1.4 Consumers' reservation price for electricity

Each consumer has its own reservation price for electricity per unit. The reservation price for electricity of consumer

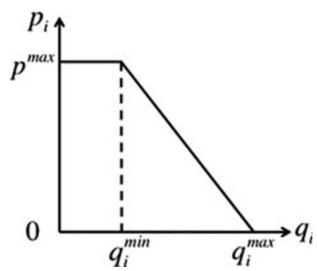


Fig. 2 Reservation price for electricity of consumer i

i $(1 \le i \le n)$ is determined by min-demand $q_i^{\min}$, max-demand $q_i^{\max}$, and the reservation price for min-demand $p_i^{\max}$. The min-demand means the minimum amount of electricity that consumer i consumes irrespective of electricity price. The max-demand means the maximum amount of electricity that consumer i can consume. We assume in this study that all consumers' reservation prices for the min-demand equal the electric power company's electricity sales price. We can write the reservation price as Eq. (1) in decentralized electricity trading. $p_i(q)$ represents the reservation price of consumer i for the amount of electricity q.

$$p_i(q) = \begin{cases} p^{\text{Max}} & (0 \le q < q_i^{\text{Min}}) \\ -\frac{p_i^{\text{Max}}}{q_i^{\text{Max}} - q_i^{\text{Min}}}(q - q_i^{\text{Max}}) & (q_i^{\text{Min}} \le q \le q_i^{\text{Max}}) \end{cases}. \quad (1)$$

This can be represented as Fig. 2.

2.1.5 Consumers' demand function

The demand is easily derived from Eq. (1). The potential maximum amount of electricity that the consumer wants to consume is determined according to Eq. (1) if a certain price is given. Figure 3 portrays consumer i's demand function $q_i(p)$ given price p.

2.1.6 Consumers' profit

Consumers gain profits through electricity trading. The consumers' profit is divisible into three elements as follows:

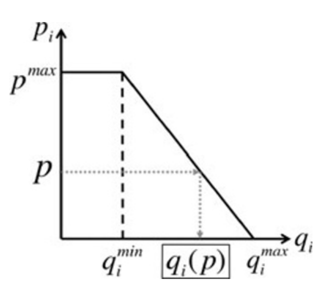


Fig. 3 Demand function for electricity of consumer i

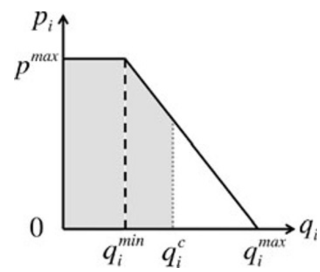


Fig. 4 Profit from consuming electricity of consumer i

- Profit from consuming electricity
- Profit from selling electricity
- Payment for purchasing electricity

Consumer i's total profit π_i can be calculated as equation (2) using these elements.

$$\pi_i = \int_0^{q_i^c} p_i(q_i)dq_i + \sum\nolimits_j pq_{i,j}^s - \sum\nolimits_i pq_{i,j}^c. \quad (2)$$

The first term represents consumer i's profit from consuming electricity. Here, we assume that a consumer consumes all the electricity the consumer has purchased from the market and does not sell it to other consumers or store it. This profit is calculable with their demand function for electricity and the amount of electricity they consume q_i^c. This profit can be depicted as the colored area in Fig. 4.

The second term represents consumer i's profit from selling the electricity the consumer generates, which is calculable with the electricity price in the market and the amount of electricity sold in the market. p represents the electricity market price, and $q_{i,j}^s$ represents the amount of electricity that consumer i sells to another consumer j.

The last term represents consumer i's payment for purchasing electricity, which is calculable with the electricity price in the market, p, and the amount of electricity purchased by consumer i from consumer j, $q_{i,j}^c$.

Consumers' purposes for making their decisions in the decentralized electricity trading are to make this total profit as large as possible.

2.2 Proposed trading mechanisms

We propose two new trading mechanisms applied to the decentralized electricity trading. These trading mechanisms are devised not only to make the social surplus larger, which is calculated as the sum of consumers' profit, but also to stabilize the grid system, which means that electricity trading under mechanisms can balance the demand and supply of electricity. The two mechanisms differ from each other in two points as shown below.

- Kind of input information
- Tradable amount of electricity

2.2.1 *Mechanism 1: Aggregated demand–supply mechanism*

2.2.1.1 Input and the amount of electricity sent to the market Each consumer must input an "offer price" in the market under Mechanism 1. The offer price is the price at which a consumer wants to sell the electricity the consumer generates. All consumers' electricity is traded in the market in this mechanism (Fig. 5).

2.2.1.2 Determining the electricity price The electricity price is determined using an aggregate demand curve and aggregate supply curve. The aggregate demand curve is made from demand curves of all consumers, as shown in Fig. 6. The aggregate supply curve is made from the offer price and electricity sent from all consumers, as shown in Fig. 7. Here, p_k^s and q_k^g, respectively, represent the offer price and generated electricity output of consumer k, who sends the kth cheapest offer price in the market.

The intersection point of the aggregate demand curve and the aggregate supply curve is determined as the electricity price in the market, which we call a "trading price." All the electricity is traded for that price in the market (Fig. 8).

2.2.1.3 Order of selling electricity The order of selling electricity is determined by the consumers' offer price.

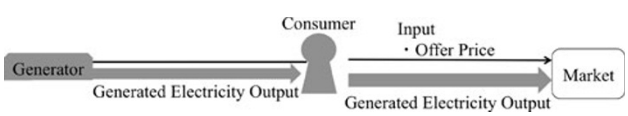


Fig. 5 Input and the amount of electricity sent to the market under Mechanism 1

The cheaper an offer price consumers input, the earlier they can sell their electricity in the market. For example, a consumer who inputs the cheapest offer price can sell electricity first, and a consumer who inputs the second cheapest offer price can sell electricity next. A cheaper offer price gives a lower probability of not selling all their generated electricity.

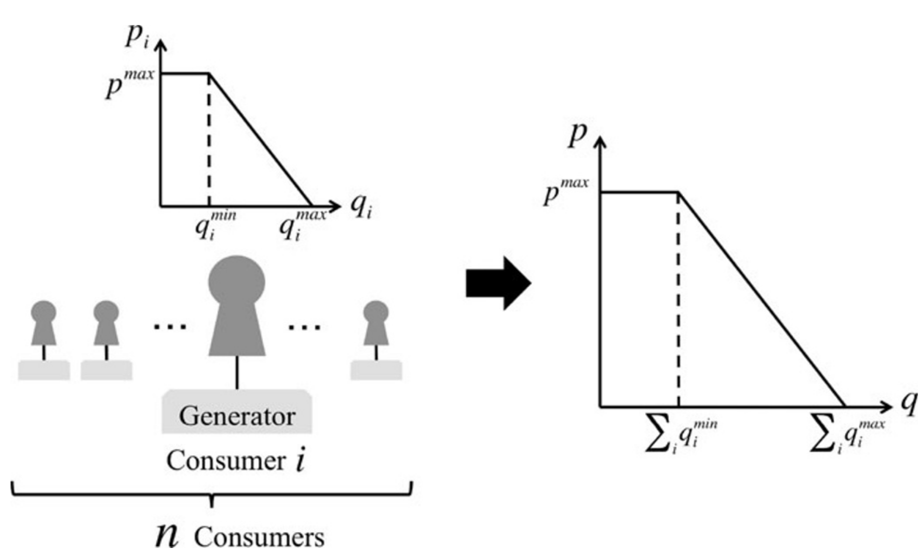
2.2.2 *Mechanism 2: Residual electricity-based mechanism*

2.2.2.1 Input and the amount of electricity sent to the market Consumers must input an "offer price" and a "quantity of electricity to secure" in the market under Mechanism 2. The offer price is the price at which a consumer wants to sell electricity that the consumer generates. The Quantity of Electricity to Secure is the quantity of electricity which a consumer wants to consume from the electricity that is generated. This quantity of electricity is not traded. The rest is traded in the market (Fig. 9).

2.2.2.2 How to determine the electricity price The electricity price is determined by the aggregate demand curve and aggregate supply curve from which secured amounts are removed. The aggregate demand curve is made from the demand curve. The quantity of electricity to secure of all consumers is shown in Fig. 10. The aggregate supply curve is produced from the offer price, Quantity of Electricity to Secure, and electricity sent from all consumers, as shown in Fig. 11.

The intersection point of the aggregate demand curve and the aggregate supply curve determines the trading price in the market. All electricity is traded with that price in the market (Fig. 12).

Fig. 6 How to make an aggregate demand curve under Mechanism 1



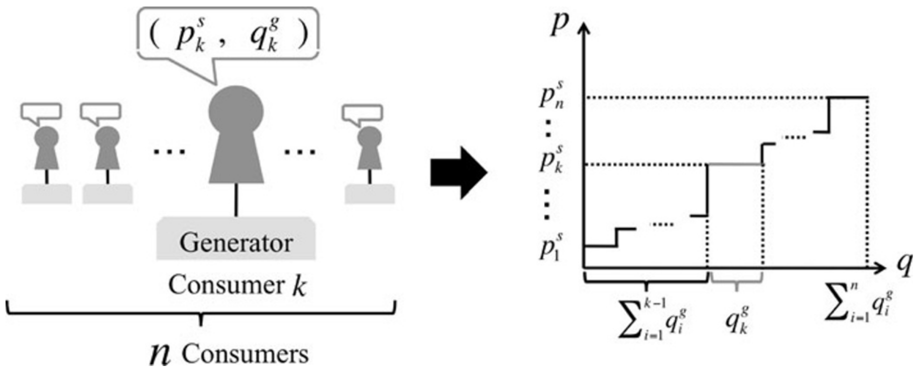


Fig. 7 How to make an aggregate supply curve under Mechanism 1

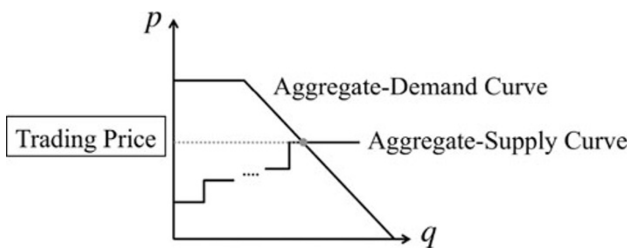


Fig. 8 Determining the trading price under Mechanism 1

2.2.2.3 Order of selling electricity The order of selling electricity is determined by the consumers' offer price, as shown in Mechanism 1. The lower the consumers set their offer price, the earlier they can sell their electricity.

3 Experiments with human subjects

We conducted experiments with human subjects to analyze how human beings make their decisions in the decentralized electricity trading under each of two mechanisms. It is generally assumed in economic theory that human beings do not always make their decisions rationally, which should be considered when we evaluate how stable the mechanisms are. The experiments are based on the experimental economics methodology [6, 7]. Subjects were promised a monetary reward according to the payoff earned in experiments. The experiments were conducted with 54 subjects on December 3 and 14, 2011.

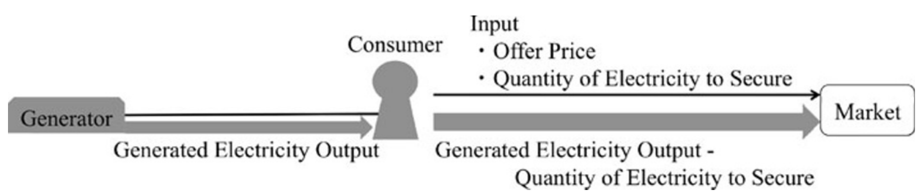


Fig. 9 Input and amount of electricity sent to the market under Mechanism 2

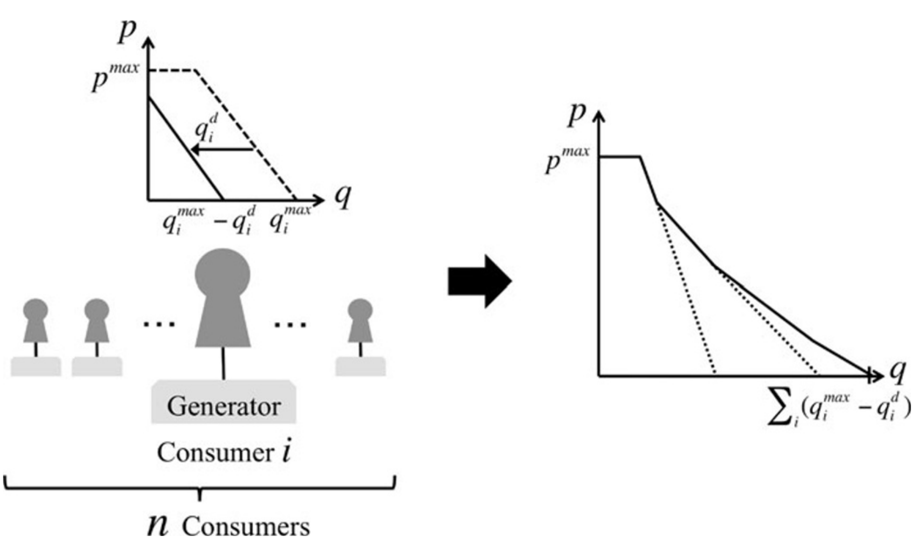


Fig. 10 How to make the aggregate demand curve under Mechanism 2

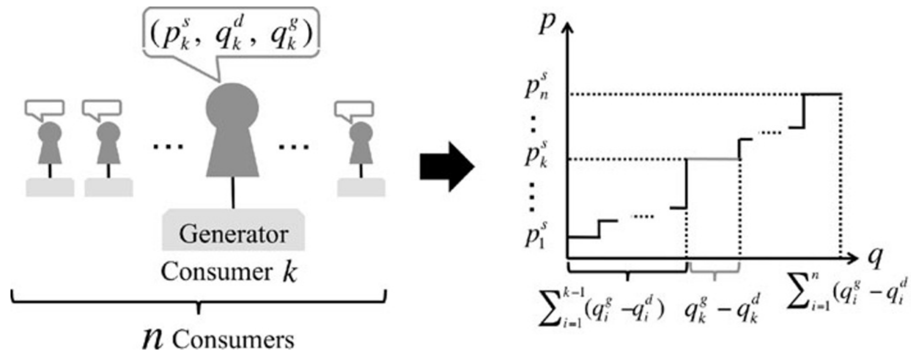


Fig. 11 How to make the aggregate supply curve under Mechanism 2

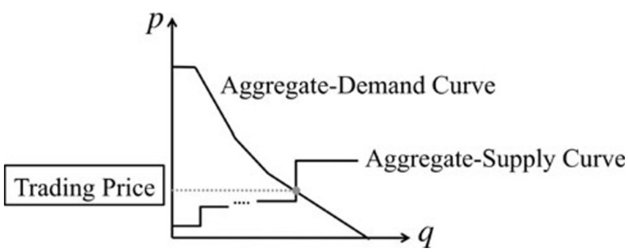


Fig. 12 How to determine the trading price under Mechanism 2

3.1 Experimental settings

We fixed the number of consumers in the market as three. Twenty seven subjects joined each day. Therefore, the subjects are divided into nine groups. Consumers of three types are assumed and are set to each subject, respectively, in a group. Each type has a different min-demand and generated electricity output, as shown in Table 1.

Subjects made their decisions based on their parameters and profits they were able to gain through trading electricity. They knew their own parameters and profits, but they could not know the others'.

3.2 Experimental results

We were able to elicit models of decision making by human subjects from the experiments. The model we elicited is the following.

- Subjects make their decisions based on decision change and profit change from the previous trade. The decision change shows whether consumers make values of input larger or smaller or do not change them; the profit change shows whether the consumers' profit becomes larger or smaller or shows no change.
- Subjects make their decisions for the next trade based on a combination of their decision change and profit change from the previous trade. Whether they make the values of input larger or smaller or do not change them for the next trade is determined stochastically according to a probability derived from the experiments.

Table 1 Consumer parameters

	Type 1	Type 2	Type 3
Min-demand	10	20	30
Max-demand	100	100	100
Generated electricity output	120	80	60

Tables 2 and 3 portray the probability elicited from the result of the experiments. These results are used in the next section as the decision-making model of agents.

4 Multi-agent simulation considering decision making by humans

We conducted a multi-agent simulation in which agents' decisions were based on the model elicited in the experiments with human subjects in the former section. We evaluated the two mechanisms proposed in Sect. 2 in terms of stability of the grid system and social surplus.

4.1 Parameters

We set up the parameters used in the simulations as follows:

- The number of agents, n, is 100.
- Max-demand of each consumer is 100.
- Min-demand of each consumer is between 10 and 50 in intervals of 10.
- The generated electricity output of each consumer is between 10 and 200 at intervals of 10.
- The min-demands and electricity outputs are uniformly distributed, meaning that all consumers have a different set of min-demand and electricity output.

4.2 Simulation results

Table 4 presents the simulation results. We use the variance of each consumers' decisions as an index of how

Table 2 Model of decision making by human beings under Mechanism 1

A change in profit from before last trade to last trade	A change in offer price from the previous trade	Next decision	Probability (%)
Become larger	Raised	Raise	17
		No change	33
		Lower	50
	Did not change	Raise	11
		No change	80
		Lower	9
	Lowered	Raise	25
		No change	54
		Lower	21
Unchanged	Raised	Raise	40
		No change	40
		Lower	20
	Did not change	Raise	5
		No change	72
		Lower	22
	Lowered	Raise	64
		No change	21
		Lower	14
Become smaller	Raised	Raise	8
		No change	8
		Lower	85
	Did not change	Raise	16
		No change	58
		Lower	27
	Lowered	Raise	75
		No change	15
		Lower	10

stable the grid system under each of the mechanisms is. Variances are average values of 100 trials. Values of social surplus are the moving average values of the prior 200 steps in 100 trials. Each trial has 1,000 steps.

As Table 4 shows, Mechanism 2 achieves smaller values of variance in both the offer price and trading price compared with Mechanism 1. The low variance indicates stability in the mechanism because it means consumers in the market do not change their values of input frequently. It can therefore be said that Mechanism 2 makes the electricity trading more stable than Mechanism 1 does. In addition, as Table 4 and Fig. 13 show, social surplus in the market under Mechanism 2 is larger. Moreover, it is apparent in Fig. 13 that the high social surplus is realized in early steps under Mechanism 2. We infer that consumers can obtain profits to some extent without fail because they are sure to consume some amount of electricity as the Quantity of Electricity to Secure under Mechanism 2. We conclude that Mechanism 2 is better than Mechanism 1 not only in terms of grid system stability but also in terms of social surplus.

5 Conclusion

Electricity trade in which small-scale consumers such as households participate, which we call Decentralized Electricity Trading, is regarded as realizable in the near future. This paper proposes new trading mechanisms applied to decentralized electricity trading and is evaluated using an integrated approach with experiments using human subjects and multi-agent simulation. Results show that, when considering irrationality in decision making by human beings, Mechanism 2, by which consumers secure the electricity they use beforehand and by which the rest is traded in the market, achieves a good result in terms of grid system stability and social surplus. Considering the fact that balancing demand and supply with robustness is

Table 3 Model of decision making by human beings under Mechanism 2

	A change in quantity of electricity to secure from the previous trade	Next decision on quality of electricity to secure	A change in offer price from previous trade								
			Raised			Did not change			Lowered		
			Next decision on offer price								
			Raise (%)	No change (%)	Lower (%)	Raise (%)	No change (%)	Lower (%)	Raise (%)	No change (%)	Lower (%)
A change in profit from before last trade to last trade											
Become larger	Raised	Raise	0.0	0.0	14.3	0.0	23.8	0.0	10.5	5.3	0.0
		No change	0.0	14.3	57.1	4.8	47.6	0.0	10.5	36.8	10.5
		Lower	0.0	14.3	0.0	0.0	14.3	9.5	15.8	10.5	0.0
	Did not change	Raise	0.0	0.0	0.0	0.0	4.9	2.4	4.2	0.0	4.2
		No change	50.0	0.0	50.0	2.4	85.4	2.4	8.3	62.5	4.2
		Lower	0.0	0.0	0.0	0.0	2.4	0.0	0.0	12.5	4.2
	Lowered	Raise	0.0	0.0	33.3	0.0	20.0	0.0	6.7	6.7	6.7
		No change	0.0	33.3	0.0	10.0	50.0	0.0	26.7	46.7	6.7
		Lower	33.3	0.0	0.0	0.0	10.0	10.0	0.0	0.0	0.0
Unchanged	Raised	Raise	11.1	11.1	11.1	0.0	33.3	0.0	0.0	0.0	0.0
		No change	11.1	11.1	11.1	0.0	11.1	11.1	0.0	0.0	0.0
		Lower	11.1	11.1	11.1	0.0	33.3	11.1	5.0	50.0	0.0
	Did not change	Raise	11.1	0.0	0.0	0.0	6.7	2.2	0.0	33.3	0.0
		No change	11.1	44.4	33.3	7.8	72.2	3.3	33.3	16.7	0.0
		Lower	0.0	0.0	0.0	0.0	7.8	0.0	16.7	0.0	0.0
	Lowered	Raise	0.0	0.0	0.0	7.7	15.4	15.4	0.0	0.0	0.0
		No change	0.0	50.0	50.0	0.0	30.8	0.0	0.0	100.0	0.0
		Lower	0.0	0.0	0.0	7.7	15.4	7.7	0.0	0.0	0.0
Become smaller	Raised	Raise	8.3	8.3	0.0	8.3	16.7	0.0	0.0	0.0	50.0
		No change	0.0	0.0	8.3	0.0	8.3	0.0	0.0	0.0	0.0
		Lower	8.3	16.7	50.0	8.3	33.3	25.0	50.0	0.0	0.0
	Did not change	Raise	6.7	13.3	13.3	1.9	7.4	3.7	20.0	20.0	0.0
		No change	0.0	13.3	40.0	3.7	68.5	9.3	20.0	20.0	0.0
		Lower	0.0	0.0	13.3	0.0	5.6	0.0	0.0	20.0	0.0
	Lowered	Raise	0.0	11.1	44.4	7.7	53.8	15.4	60.0	0.0	0.0
		No change	0.0	0.0	33.3	0.0	23.1	0.0	0.0	0.0	20.0
		Lower	0.0	11.1	0.0	0.0	0.0	0.0	0.0	0.0	20.0

Table 4 Simulation results

	Mechanism 1	Mechanism 2
Variance of offer price	714.92	658.04
Variance of quantity of electricity to secure	–	280.53
Variance of trading price	30.76	19.88
Social surplus	604,284.6	630,106.3

desired to make large profit, which Makris et al. [8] mention in their research, we think the methods used in this research are also useful in manufacture.

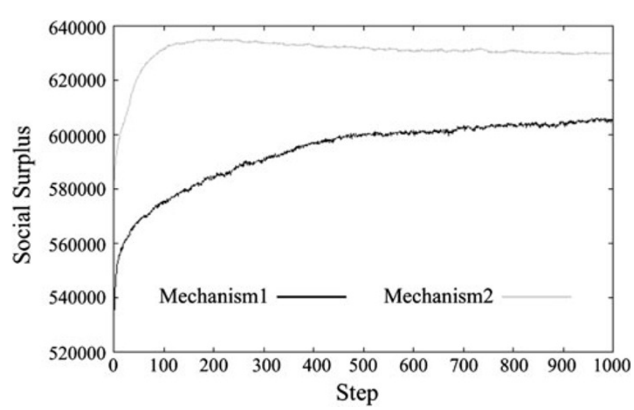


Fig. 13 Social surplus transition of Mechanism 1 and Mechanism 2

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