Design and Evaluations of Multi-Agent Simulation Model for Electric Power Sharing among Households

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Abstract. Electric power sharing among households based on the bidding method is studied as a future service. In order to verify the feasibility of such a service, a new multi-agent simulation model has been designed. We validated this model through some evaluations. For example, it is confirmed that the market price on this service stably changes according to the supply-demand balance between both sold and purchased bid volumes. In addition to that, the results of the household profit and contract rate of this service showed that the design for bid strategies works as intended in most cases.

Keywords: Electric power sharing; Multi-Agent Simulation; Artificial market

1 Introduction

In Japan, the surplus power purchase system (FIT [Feed-in Tariff]) started in 2009 as part of the promotion of solar power generation (PV generation). FIT guarantees customers' surplus electricity obtained by subtracting residential consumption from PV generation purchased at a fixed unit price during 10 years. Therefore, households whose guarantee period ends (graduate FIT households) have appeared since November 2019. This guaranteed price has been lower year by year from 48 yen/kWh in 2009 to 26 yen/kWh in 2018. New surplus power purchase services for graduate FIT households have been announced by some electricity retailers, but the price is currently about 10 yen/kWh at most, and is expected to be significantly lower than the guaranteed price of FIT. For this reason, and in order to increase the value of surplus power in graduate FIT households, the promotion of self-consumption by introducing storage batteries and the sharing of electric power are being studied. The latter option allows households to sell surplus power to other households [1].

The electric power sharing principle is profitable to households if surplus electricity is sold to other households at a higher price than sold to the electricity retailer. Households that do not have PV can also benefit when they purchase electricity from other households at a lower price than the purchase price from the electricity retailer. One of the merits other than money is environmental value. For example, if households that do not have PV purchases electricity generated by PV from other households via the electric power sharing, their ratio of renewable energy can be increased.

As demand (total amount of surplus power from households) and supply (total amount of in-house consumption of households) do not always match, a method determining the trading partner for monetary value and environmental value of electricity is required. Such trading methods include the bidding method used for trading between power generation companies and electricity retailers on JEPX (Japan Electric Power Exchange) [2]. There is a possibility that the monetary value and the environmental value of electricity can be flexibly allocated according to the household's situation and mindset such as profit pursuit and eco-friendliness, through electric power sharing by the bidding method.

Since there is almost no existing service for electric power sharing, verification of service feasibility is required, such as the profits of households and electricity retailers, the stability of market prices, and the number of service subscribers required for market establishment. However, the bidding behavior of household changes depending on the environment such as weather and seasons, and interacts with the bidding of other households. This type of system is called as a complex system, and verification of the electric power sharing assuming bidding is not an easy task. One promising way to analyze such a complex system is to use MAS (Multi-Agent Simulation) [3].

In this paper, we present a MAS model for electrical power sharing designed for verifying the feasibility of electrical power sharing assuming bidding. One of the features of the proposed MAS model is that the bid strategy reflects the household's mindset such as profit pursuit and eco-friendliness. We validate our MAS model through some simulations under multiple conditions with varying PV ownership ratio, bid strategy ratio and so forth. Specifically, we confirm that market price stability. In addition, we confirm that household profits and contract rate are as expected, in order to see the potential of the electrical power sharing by bidding to allocate the monetary value and environmental value of electricity to households.

2 Related Works

As a main application example of MAS in the field of electric power and energy, there is research to evaluate and verify the new system concerning the electric power market and transmission and distribution system from the viewpoint of stability, efficiency and effectiveness. As for the electric power market, agent simulation is used in many researches in Japan and overseas [4][5]. In the US, an agent-based large-scale electricity market test bed AMES has already been established and used for the evaluation and verification of the electricity market system [6].

Regarding power transmission and distribution systems, the efficiency of smart grid systems which determine the behavior of power consumption agents using actual home consumption data and PV power generation data is evaluated [7]. One study [8] verifies the effective use of PV generation and household profit, assuming power sharing via bidding among households in a small community. A bid strategy that changes the bid price depending on the available capacity of the storage battery has been modeled.

As described above, there are not many known examples of MAS application that assumes electricity sharing between households by bidding. The study [8] has similar assumptions, but the main purpose was the evaluation of effective use of PV generation and bid strategy covers battery status. On the other hand, the purpose of this paper is to verify the feasibility of the power sharing service. We have designed a MAS model that places emphasis on evaluation and verification from the service perspective, such as modeling different household mindsets, such as profit pursuit and eco-friendliness, and evaluating household profits. In addition, this paper examines the stability of market prices and changes in household profit when the ratio of bid strategies and the supply-demand balance are different.

3 ASSUMPTION of ELECTRIC POWER SHARING

3.1 Outline of Electric Power Sharing Service

Electricity is purchased and sold through bidding from/to households. Buy and sell bids are each made of 48 frames a day, with 30 minutes as one frame, with reference to JEPX [2]. Each frame is given a frame ID (1 to 48). The electricity that can be sold is the surplus power of PV generation. Accordingly, PV-owned households can be sellers in the service. The electric power charged in the storage battery cannot be sold on the service. This is because reverse power flow of storage batteries is not currently allowed in Japan. All households can become buyers in the service. They can buy electricity from other households for in-house consumption.

3.2 Assumptions

Contract with Electricity Retailer

It is assumed that, in addition to the electric power sharing service, each household has contracted with an electricity retailer. In fact, it is not possible to cover the consumption of each household by electric power sharing alone, especially at night when there is no PV generation. In addition, considering that all selling bids may not be contracted, it is assumed that households that can be sellers have a contract with an electricity retailer for fixed price surplus purchase service.

Mindset on Electricity

This paper considers three different mindsets on electricity for a household: profit pursuit, eco-friendly, and indifference.

Profit pursuit households have an interest in money and seek to increase profits through electric power sharing. In fact, interest in money is expected to be high, since some retailers offer electricity services that highlight differences in electricity fee.

Eco-friendly households aim to improve their ratio of renewable energy consumption through electrical power sharing. It buys and sells via the electric power sharing

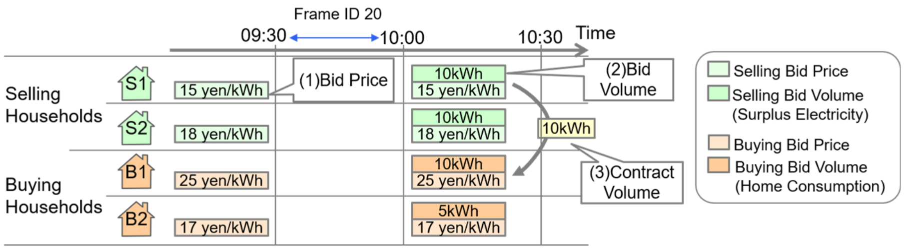

Figure 1: Flow from Bid to Contract in the case of Frame ID 20

with a price range that does not cause a loss compared to the fixed price of an electricity retailer. It is assumed that there are a certain number of eco-friendly households, since some retailers has launched electricity services with a high proportion of renewable energy. It is also expected that the number of eco-friendly households will increase in the future due to the growing interest in global warming and CO_2 reduction.

Indifference households do not care only if there is no loss compared to the fixed price of their electricity retailer. Households who joins the electricity power sharing service casually because they do not lose, or who have been less interested in the service over time.

Contract Method

A blind single price auction is considered as the contract method. This is because this auction is used in many electricity markets among electricity retailers and electricity power generation companies both at domestic and abroad, e.g., JEPX and EPEX (European Power Exchange). In addition, this auction has a feature that the market price at each frame time is determined as one. Hence, the market price can be considered as the electricity value of the frame. This makes it easy to analyze changes in market prices.

Electric Power Flow

There are two possible power flows. The first one is a direct electricity flow between households along with electric power sharing transactions. Second one is the virtual transaction of electric power sharing without changing the existing electric power flow. As the former requires large-scale renovation of the existing power infrastructure, it is unrealistic to assume that a wide range of electric power sharing will be performed. Therefore, this paper is considering the latter.

Transaction Flow

The household whose bid is contracted buys electricity from and sells to other households at a contract price. Households whose bid is not contracted buy and sell electricity at a fixed price from/to electricity retailers.

There are two ways to execute contract: (1) before and (2) after the time when electricity actually flows. In the first case, each household decides the amounts of bids based on the predicted values of in-house consumption and PV generation. The contract amount is determined based on this bid amount. If there is a prediction error in in-house consumption and PV generation, it may not be possible to buy and sell exactly as contracted, making transactions complicated. This paper is considering the second case, so that the amounts of bids are based on actual value, making transactions simple.

The flow from bidding to contract is shown in Fig. 1, taking as an example of a frame ID 20 (9:30 to 10:00) in one day. Selling households S1 and S2 and buying households B1 and B2 determine bid prices before 9:30 (Fig. 1(1)). The bid amount of each household is determined after the fact based on PV power generation and home consumption from 9:30 to 10:00 (Fig. 1(2)). The contract is then calculated based on the bid price and bid amount (Fig. 1(3)). Based on the price priority principle of the blind single price auction, a selling bid of 10kWh from S1 and a buying bid of 10kWh from B1 are contracted. The remaining S2's bid and B2's bid are not contracted because the bid prices do not match. Then, S2 sells its 10kWh of electricity to an electricity retailer at a fixed price, and B2 buys the required 5kWh of electricity from an electricity retailer at a fixed price.

4 DESIGN of MAS MODEL

We designed a MAS model that simulates the electric power sharing and associated transactions. The model consists of household agents and an electricity retailer agent.

4.1 Household Agent

A household agent has three attributes information that can be set: the owned equipment, the contract information with the electricity retailer, and the bid strategy.

Owned Equipment
Information of owned equipment, such as PV and storage battery, can be set. If owned, specification information of the owned equipment such as the rated output value [kW] for PV and the capacity [kWh] for a storage battery is set.

Contract Information with Electricity Retailer
Information on the unit price of both electricity purchased from the electricity retailer [yen/kWh] and electricity sold to an electricity retailer [yen/kWh] is set. These unit prices can be set for each frame. This means that these can be a fixed value, regardless of the frame, or they can be different during the day and at night.

Bid Strategy
One strategy among profit pursuit, eco-friendliness, and indifference is selected as a bid strategy corresponding to the household's mindset on electricity. The household determines the bid price according to the selected bid strategy. Here, a buying bid price higher than the unit price of electricity purchased from an electricity retailer is irrational. Similarly, a selling bid price lower than the unit price of electricity sold to an electricity retailer is irrational. Therefore, common to all bidding strategies, the upper

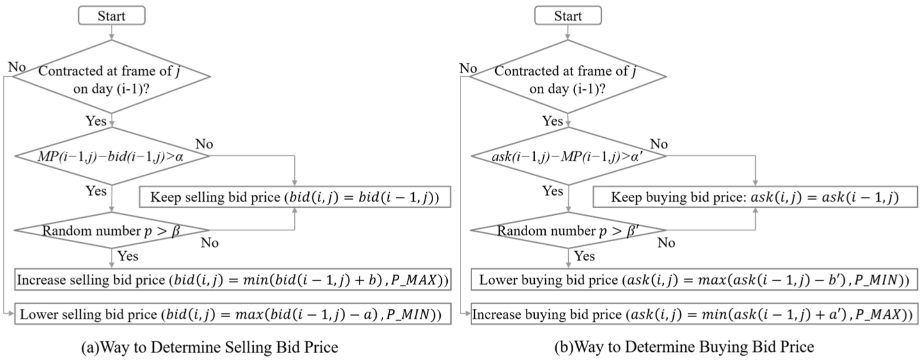

Figure 2: Way to Determine Bid Price for Profit Pursuit Strategy

limit P_MAX of the bid price is the unit price of electricity purchased from the electricity retailer, and the lower limit P_MIN is the unit price of electricity sold to the electricity retailer.

Profit Pursuit

The profit pursuit strategy changes the bid price according to past contract results and market prices, in order to increase profit.

Let $bid(i,j)$ be the selling bid price of a household at frame ID j ($j = 1,2,\cdots,48$) on day i. $bid(i,j)$ is calculated using information about the selling bid price of the same household for the previous day at the same frame $bid(i-1,j)$, market price $MP(i-1,j)$, and contract result of the same household for the previous day at the same frame, as shown in Fig. 2(a). If it is not contracted at the same frame on the previous day, the selling bid price is lowered by parameter a [yen/kWh] to facilitate the contract. On the other hand, if it is contracted at the same frame on the previous day, the difference between $MP(i-1,j)$ and $bid(i,j)$ is checked. If this difference is less than or equal to the threshold α, the selling bid price is maintained. This is because it is relatively likely that the selling bid will not be contracted if the selling bid price is raised. Whereas, if the difference is larger than the threshold α, the selling bid price is probabilistically increased by a parameter b [yen/kWh] to increase profits. As a means of probabilistically increasing the selling bid price, a random number p (0 to 1) is used and it is increased when $p >$ threshold β. Parameters a, b, α, and β are real number greater than 0, respectively.

The buying bid price of the profit pursuit strategy $ask(i,j)$ is determined in a similar way to that for the selling bid price of a household $bid(i,j)$, using the buying bid price of the same household for the previous day at the same frame $ask(i-1,j)$, market price $MP(i-1,j)$, parameters a', b', α′, and β′, as shown in Fig.2 (b). These parameters are real number greater than 0.

Eco-Friendly

The eco-friendly strategy always executes market orders to increase the contract rate. A market order is a bidding method that does not specify a bid price, and is contracted prior to a bid by other strategies that specify a bid price. Now, we consider the contract price for the bid of a market order. As with other bids that specify prices, if the contract price of the market order is also the market price, the market order is the optimal strategy for profit as well as for the contract rate. To make the bid strategy different for profit pursuit and eco-friendly, the contract price of the market order is set to the 80th percentile of the bid price of the bid contracted in the transaction. Hence, eco-friendly strategy is easier to be contracted, but its profit per contract is lower, compared to profit pursuit strategy.

Indifference
The indifference strategy always executes bidding at the same bid price.

Common to profit pursuit and indifference strategies, the initial bid price for each household is given as a uniform distribution between the unit price of electricity purchased from the electricity retailer and the unit price of electricity sold to the electricity retailer.

4.2 Electricity Retailer Agent

The electricity retailer agent aggregates both buying and selling bids of the household, and performs the contract calculation. Then, it notifies each household agent of its contract result and market price information. Based on the contract results, the electricity retailer aggregates both buying and selling volume as well as price through electric power sharing. In addition, the electricity retailer agent calculates buying and selling volumes via the electricity retailer. Finally, it calculates expenditures for electricity purchases and income from selling electricity for each household.

5 Basic Evaluation of Electric Power Sharing MAS model

5.1 Evaluation Policy

With the goal of using the model to verify the feasibility of the electric power sharing service, the validity of the model is confirmed through basic evaluation. Specifically, the following two points are confirmed.

1. The market price of electric power sharing is formed stably according to the supply and demand balance of the selling bid and the buying bid
2. The household profit and contract rate for each profit pursuit, eco-friendly and indifferent bid strategy is as designed (Section 4.1 Bid Strategy)

5.2 Evaluation Indicator

The market price trend, supply and demand balance, household profit, and contract rate are used as evaluation indicators. The market price is calculated through the contract calculation by matching both buying bid and selling bid in each frame. The balance between supply and demand is calculated as (bid volume for selling [kWh] / bid volume

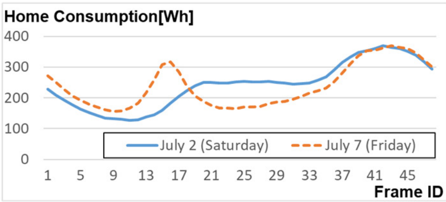

Figure 3: Home Consumption Data

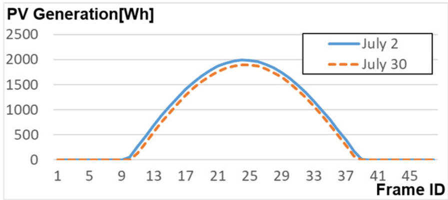

Figure 4: PV Generation Data

for buying [kWh]). The balance between supply and demand is zero at night and increases with the increase in PV generation during the day.

For easy analysis, household profit is aggregated as the amount of money obtained by sharing electricity, starting from the income and expenditure when all electricity is bought and sold with an electricity retailer. As a result, the household profit is 0 yen or more. For example, the profit for households that do not buy or sell electricity through electric power sharing is 0 yen. The contract rate is calculated as the contract amount [kWh] / bid amount [kWh].

5.3 Input Data

Figure 3 shows an example of home consumption data, which is created by statistical processing based on actual home consumption data of an electrical service. On weekdays, there is a peak after getting up around frame ID from 15 to 17 (7:00-8:30), and it is decreased after going out around frame ID 18 (8:30-9:00). Whereas, on Saturdays, Sundays, and holidays, the peak due to wake-up is slower than on weekdays, and in-day home consumption tends to be higher than on weekdays.

Figure 4 shows an example of PV generation data. PV generation data was created from 1st July to 31st July in Tokyo, using numerical simulations using sunrise and sunset times and solar altitude information. The rated output of PV is set at 4 kW, which is a general level, and peaked at noon on the summer solstice, and other days and time zones are reduced according to the solar altitude. Reflecting the amount of sunshine on PV generation is a topic for future investigation.

5.4 Conditions for Basic Evaluation

Table 1 shows the conditions for the basic evaluation. The simulation period is 1 month from July 1 to July 31, and the number of households is 10,000. The unit price of electricity bought from an electricity retailer is 26 yen/kWh, and the unit price of electricity sold to an electricity retailer is 5 yen/kWh, with reference to the general price in Japan. These unit prices are fixed values common to 48 frames a day.

The ratios of bid strategy are 10:10:80 and 80:20:0 for profit pursuit strategy, eco-friendly strategy and indifference strategy. The former is for easy analysis, because indifference households which have the simplest bid strategy account for 80%. The latter is for one of realistic examples.

Table 1: Conditions for Basic Evaluation

Simulation Period	1 month from July 1 to July 31
Number of Households	10,000
Unit price of Electricity bought from Electricity Retailer	26yen/kWh
Unit Price of Electricity sold to Electricity Retailer	5 yen/kWh
PV Ownership Rate	2%, 10%, 20%
Bid Strategy Rate (Profit Pursuit : Eco-friendly : Indifference)	10:10:80, 80:20:0

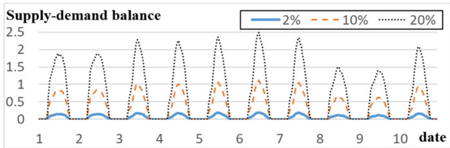

Figure 5: Supply-Demand Balance of each Frame

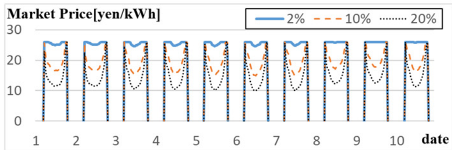

Figure 6: Market Price of each Frame (Bid Strategy Rate of 10:10:80)

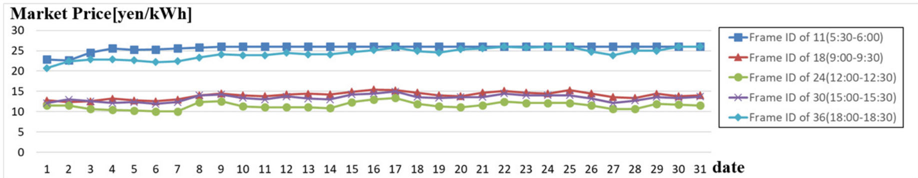

Figure 7: Daily Market Price Trends of Some Frames (Bid Strategy Rate of 10:10:80, PV ownership rate is 20%)

The PV ownership rate is set to 2%, 10% and 20%, in order to see changes in market prices and household profits when the supply-demand balance is different. The ownership rate of storage batteries is assumed to be 0%, for the sake of facilitating analysis.

The parameters of the profit pursuit strategy have been set as follows, $a = 1$ yen/kWh, $b = 1$ yen/kWh, $\alpha = 3$ yen/kWh, and $\beta = 0.3$. $a' = 1$ yen/kWh, $b' = 1$ yen/kWh, $\alpha' = 3$ yen/kWh, and $\beta' = 0.3$.

5.5 Evaluation Results

Market price trends and supply-demand balance

Figure 5 shows supply-demand balance for each frame in the first 10 days when the PV ownership rate is 2%, 10% and 20%. Figure 6 shows the market price trends in the first 10 days in case of bid strategy rate of 10:10:80. For the sake of simplicity, the market price of the frame where there is no contract is set at 0 yen/kWh. Regardless of the PV ownership ratio, the supply-demand balance is zero every night due to no PV generation. On the other hand, the supply-demand balance is larger than 0 and some bids are contracted from around 5:30 sunrise to around 18:00 sunset.

When the PV ownership rate is 2%, the supply-demand balance is in the range of 0 to 0.19, and the selling bid volume is extremely small, at most 1/5 of the buying bid volume. The market price is relatively high and ranges from 22.0 to 26.0 yen/kWh. In the case of the PV ownership rate being 10%, the supply-demand balance is in the range of 0 to 1.11, and there are frames where the selling bid amount exceeds the buying bid amount. The market price is in the wide range of 14.9-26.0 yen/kWh. When the PV ownership rate is 20%, the supply-demand balance is in the range of 0 to 2.48, and there is a frame where the selling bid amount is 2.48 times the buying bid amount. The market price is 10.0-26.0 yen/kWh, which is more widespread than when PV is 10%.

Next, Fig. 7 shows the daily market price trends of some frames when the PV ownership rate is 20%. The sunrise (Frame ID 11) and sunset (Frame ID 36) have a higher market price than 20 yen/kWh. This is because the supply-demand balance is small due to the low amount of PV generation. During that time (Frame ID 18, 24, 30), both the PV generation amount and the supply-demand balance are large, hence the market price is around 10-15 yen/kWh.

As described above, the market price is high when the supply-demand balance is low, and the market price is in the low range when the supply-demand balance is high. In addition, the market price fluctuates as much as 10 to 26 yen/kWh depending on the Frame ID in one day in the case of PV ownership rate of 20%, but the daily market price of each frame is stable. When looking at the same frame, the daily supply-demand balance does not change significantly. Therefore, it can be said that the market price is stably formed by the supply-demand balance.

Household Profit

Figures 8 shows household average profit [yen/month] for each bid strategy for households with and without PV. In case of the bid strategy ratio of 10:10:80, regardless of the PV ownership rate, the profit of pursuit profit is the largest, as designed. In case of the bid strategy ratio of 80:20:0, there are two cases in which eco-friendly is more profitable than profit pursuit. We will analyze these cases in Section 5.6.

As the PV ownership rate increases, the profits of PV-owned households become smaller, while the profits of non-PV-owned households become larger. This is consistent with the result (Fig. 5) that the market price shifts to a lower range as the PV ownership rate increases.

Contract Rate

Figure 9 shows the contract rate for each bid strategy for PV-owned and non-PV-owned households. Regardless of the bid strategy rate and the PV ownership rate, the eco-friendly contract rate is the largest, and the results are as designed. As the PV ownership rate is higher, the contracted rate of PV-owned households is lower, while the contracted rate of non-PV-owned households increase. This is consistent with the fact that the higher the PV ownership rate, the greater the supply-demand balance (Fig. 5).

5.6 Analysis

Profit pursuit gets the largest profit under many conditions, but eco-friendly profits may be higher under certain conditions (Fig.8 Case 1 and Case 2). We analyze these cases. Figures 10 shows the profit and the contract rate for each frame in Case 1 and Case 2, respectively. Figure 10 (a) indicates that the magnitude relationship between

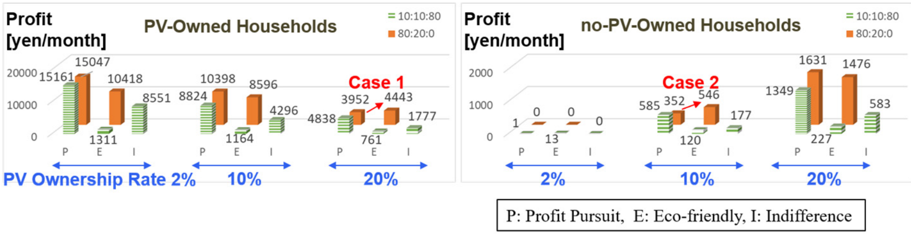

Figure 8: Profit of PV-owned and non-PV-owned Households for each Bid Strategy

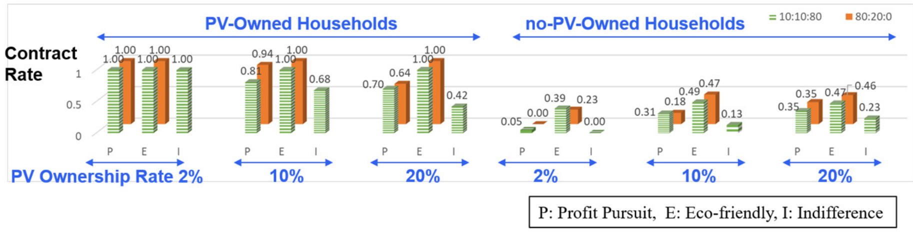

Figure 9: Contract Rate for each Bid Strategy (Bid Strategy Rate of 10:10:80)

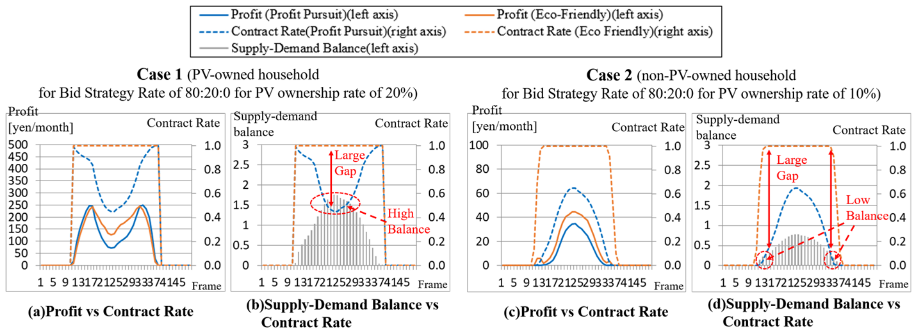

Figure 10: Profit and Contract Rate for each Bid Strategy for each Frame in Case 1 and Case 2

the profit pursuit and eco-friendly is switched by the frame in Case 1. Figure 10 (c) shows that the eco-friendly profit is larger than the profit pursuit in all the frames in Case 2. Figure 10 (a) and (c) also shows that there was a big gap in the contract rate between eco-friendly and profit pursuit.

Profit pursuit strategy is more profitable than eco-friendly strategy per contract, as designed in Section 4.1 Bid Strategy. But it is speculated that profit pursuit obtains a lower profit when the contract rate is significantly smaller than eco-friendly. These large gaps in the contract rate occurred in selling bids when the supply-demand balance was high (Case 1) as shown in Fig. 10 (b), and in buying bids when the supply-demand balance was low (Case 2) as shown in Fig. 10 (d). In addition to supply-demand balance, bid strategy ratios will be compared. In the case of a bid strategy ratio of 10:10:80, profit pursuit households were able to maintain the contract rate and profits by contracting with indifferent households, which accounted for the majority. In the case of a bid strategy ratio of 80:20:0, the profit pursuing households that occupy the majority contend for profits, and the contract rate is considered to have declined. As a result, the profit of eco-friendly household becomes larger than that of profit pursuit household.

We can conclude from the above the bid strategy for eco-friendly households always follows the market order. On the other hand, it turned out that the bid strategy for profit pursuit may change depending on the supply-demand balance and the ratio of bid strategies of other participants.

6 Conclusion

In order to verify the feasibility of electric power sharing service, we newly designed a multi-agent simulation model. One of the features of the proposed MAS model is that the bid strategy reflects the household’s mindset such as profit pursuit and eco-friendliness. Through evaluations of the MAS model, it is confirmed that the market price on this service stably changes according to the supply-demand balance. In addition to that, the results of household profit and contract rate of this service showed that the design for bid strategies works in most conditions. This mean that the monetary value and the environmental value of electricity can be allocated according to the household's mindset such as profit pursuit and eco-friendliness. The optimal bid strategy for profit pursuit may change depending on the supply-demand balance and the ratio of bid strategies, and the new bid strategy that can increase profits under various conditions is a subject for future study. Evaluations with various ratios of both bid strategy and PV ownership are also future works.

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