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Peer to Peer (P2P) Energy Trading System including PHV

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Summary

The amount of power generated by solar energy has increased in recent decades causing the famous duck curve problem. One way to solve this is to charge batteries with oversupplied power in the daytime and discharge for heavy load. In this paper we explore whether buying and selling the electricity peer to peer according to the market principle would charge the batteries of Plug-in Hybrid Vehicles (PHV) in the daytime as expected. The simulation was used to check the potential before starting a pilot project with real assets. The pilot project revealed a few specific functions preferable for electric vehicles.

Keywords: smart grid, smart charging, case-study, user behavior, V2G (vehicle to grid)

1 Introduction

The solar energy production has increased in recent 10 years causing “duck curve” [1]. In order to reduce the effect of the duck curve, the solar energy shall be stored in distributed batteries in the daytime and discharged when the demand is high. The electric vehicles (EV) are expected as storage devices which may mitigate impacts on the power system caused by unstable distributed energy resources. The electric vehicles also may give impacts on the power system when they charge at the same time in a local area [3][4]. It is important to control the behavior of the charging in order to benefit both EV users and society. The system should not disturb EV from traveling. The users would prefer to charge reasonably. The financial and environmental aspect should be considered for the society. A basic architecture of EV based virtual power plant (VPP) has been discussed to manage the integration of a fleet of EVs in the electrical grid [5]. The possibility of electric vehicles participating in the peer-to-peer electricity trading using blockchain was studied virtually [6]. It was proposed that EVs should charge with time distribution. A case study based on real asset was reported [7], however, such case studies with actual electric vehicle has not yet been reported. In this paper we focus on Peer to Peer (P2P) Energy Trading System to control electricity demands in accordance with an auction based market mechanism [8] [9]. The basic concept was checked by using a simulator. The electricity price minimization algorithm was applied for EVs. The effect of P2P energy trading with Plug-in Hybrid Vehicles (PHV) was discussed and the actual challenges were revealed through a case study in Higashifuji Research Center region [2].

2 P2P Energy Trading Simulation

2.1 Construction of the simulator

The market for P2P energy trading was based on continuous double auction. Market participants bid to the market via agent specifying buy or sell requirement, the price, electricity amount, and time. The market matches the bidding constantly according to price-time priority. The P2P energy trading simulator was constructed using python 3. Agents of the market can bid to the present market and to the market up to 24 hours later. One market is open for 30 minutes. 48 markets are constantly open. Each market is numbered and it is called the market number (MN). One MN is divided into 6 time frames (TF). The agents have chance to bid to the present market 6 times.

2.2 Agents and the market

The market participants bid to the market through agents. The relationship between the market and the agents are described in Fig. 1. The agents measure and predict demands, then strategize according to their objectives such as to minimize the electricity cost. Home, vehicle, and office have their own agents. The agents bid so as to fulfil their electricity demands. Home agents are categorized into consumers and prosumers. The bidding price for prosumer is determined by the following formula (1). MU in the formula is an abbreviation of monetary unit.

$$\left.\begin{aligned} Y_{buy} &= -28.8\, X_{SOC} + 25.8 \text{ (MU/kWh)}, \\ Y_{sell} &= -32.5\, X_{SOC} + 36.2 \text{ (MU/kWh)} \end{aligned}\right\} \quad (1)$$

Where X_{SOC} represents state of charge of stationary batteries. A low bid price is presented by consumers for markets of distant future, and as high as 26.0 MU/kWh for the closer markets. Office agents purchased the electricity at the price 22.0 MU/kWh from the grid, sold at 26.0 MU/kWh, and when the excess energy from solar panel was expected they sold at 14 MU/kWh. Grid always offers infinite amount of electricity to the market at the price of 22.0 MU/kWh for the office, and 26.0 MU/kWh for the other participants. Grid buys the electricity at 13.0 MU/kWh.

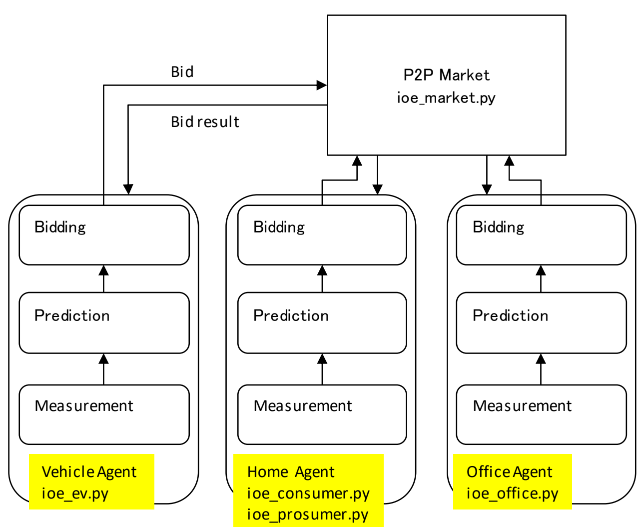

Figure 1 Market and Agents

2.3 Vehicle agent

A vehicle agent is designed to absorb excess solar energy by cost minimum optimization strategy. Vehicle agents have abilities to measure and predict the trip to determine the vehicle location and the capability of charging or discharging. The basic formula for the optimization is shown in the formula (2).

$$\arg\min \sum_{i=MN}^{MN+MN_{range}} \left\{ E_{buy}(i)\left(Y_{predict}(i)+Y_{rand}+Y_{fee}-Y_{payback}\right)-E_{Sell}(i)\left(Y_{predict}(i)+Y_{rand}\right)\right\} \qquad (2)$$

This is a linear optimization algorithm. E_{buy} and E_{sell} are electricity amount to buy and to sell, respectively. $Y_{predict}$ is a bidding price. Y_{rand} is a random number to make each agent bid to different market if the price is the same. Y_{fee} is 8 MU/kWh representing wheeling charge. $Y_{payback}$ is a payback expected to be given when a wheeling charge shall not be applied. E_{buy}, E_{sell}, and $Y_{predict}$ are fixed from the formula (2) and will be bidden to each MN. The initial SOC of the vehicles were set to 50 % at MN=0 and a final required SOC of 50 % at MN=47. The bidding procedure is shown in Fig. 2. The bidding price was determined by using the preset price chart (Fig. 3).

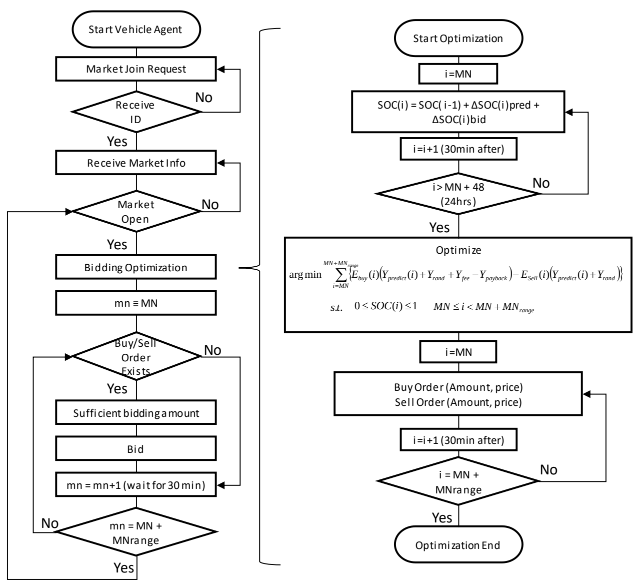

Figure 2 Vehicle Agent Algorithm

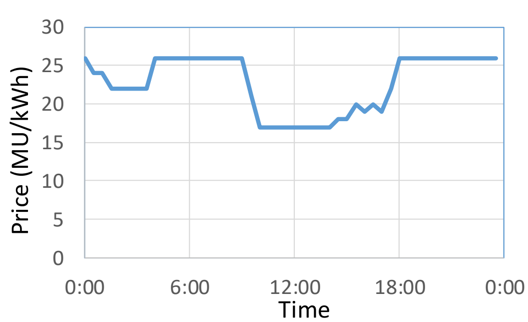

Figure 3 Price chart

2.4 P2P participants

The number of participants and their property used for the simulation is shown in Table 1. Different electricity demand profiles and power generation profiles were given to each consumers and prosumers. The electric vehicles assumed were commuter vehicles.

Table 1 Participants

	Number of Participants	Solar (kW)	Battery (kWh)
Prosumer	7	6	5
Consumer	13	0	0
PHV	10	0	8.8
Office	1	50	0

2.5 Simulated results: P2P trading prices

The result of the price transition of P2P electricity trading simulation is shown in Fig. 4. In the daytime around 12:00 the drop of the price was examined, which indicates that market forces are properly functioning. The participants could purchase electricity at the price lower than that of the grid (26.0 MU/kWh). The prosumer purchased electricity at 22.4 MU/kWh, consumer at 22.9 MU/kWh, and electric vehicles 14.4 MU/kWh in average.

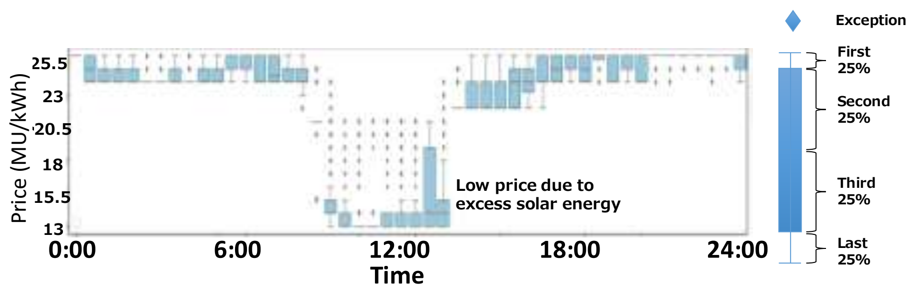

Figure 4 P2P Trading Price Transition

2.6 Simulated results: Green energy consumption and SOC transition

The accumulation of the electricity amount and type purchased is shown in Fig. 5. Fig. 6 is the transition of SOC of 10 vehicles. It is noticeable that they could buy the solar energy produced by prosumers and an office in the daytime as intended. Therefore, the same algorithm was implemented to the pilot test to check with real assets and human behaviors.

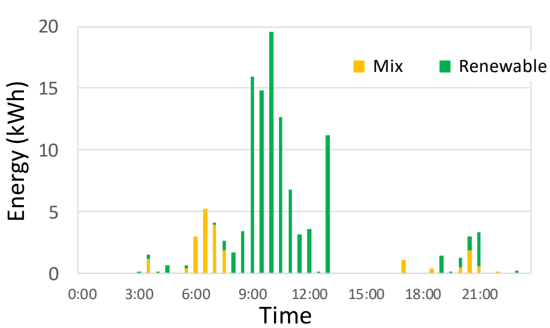

Figure 5 Renewable and Fossil Energy Purchased

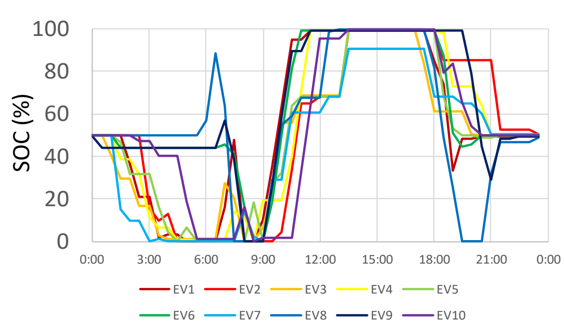

Figure 6 SOC Profile

3 P2P proof-of-concept test (PoC)

3.1 Overall System

4 servers were prepared representing market, office, home, and vehicle respectively (Fig. 7). In the vehicle server, for example, the vehicles' data and the vehicle agent function was allocated. Each server has an ability to collect data only from the related hardware, that is, a vehicle would not know the demand or solar power generation of home. The market rules used for the PoC was basically as same as what was used for the simulation. The market was constructed using Proof-of-authority based blockchain with Ethereum, including smart contracts. A similar scheme can be found in [10]. The information such as bidding and execution, as well as from whom to whom, whether it was renewable energy or not, was recorded into the blocks. The strategies of home and office were kept unknown to the vehicle agent, besides that the surplus solar energy will be sold rather inexpensive. Markets announce the execution time of charging to the charger. The charger then checks if the vehicles are physically connected. Finally, the charger was activated to begin charging after up to 15 seconds.

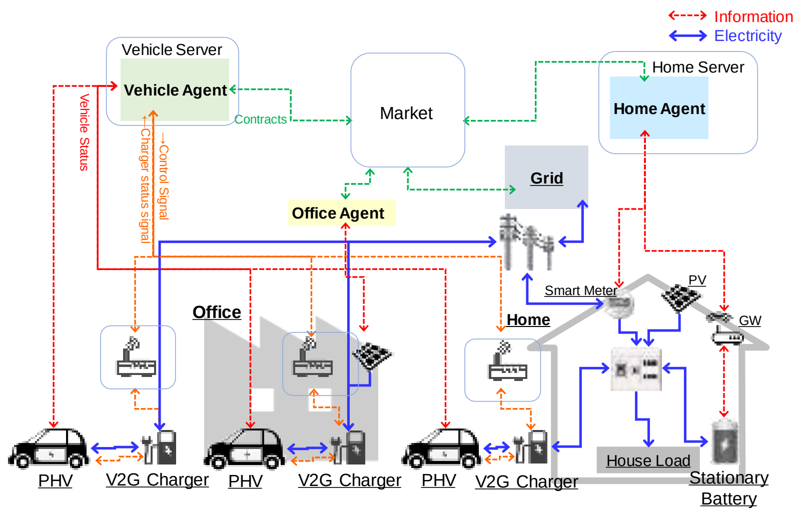

Figure 7 Information and electricity lines

3.2 PoC Participants

The proof-of-concept was conducted under research ethics committee's permission. 20 participants were selected from Toyota Motor Corporation employees who commute to Higashifuji Research Center in Shizuoka prefecture every weekday. Participants were limited to those who have detached houses of their proprietary. 6 of them were categorized to consumers without assets, 7 of them were categorized to consumers with PHV, 2 of them participated as prosumer with solar panels, 3 of them with solar panels and stationary batteries, and 1 of them with solar panels, stationary batteries, and PHV. The participants were not located in one region therefore the congestion of distribution line was not considered when deciding the amount of exchange. The amount of solar panels and other assets for each residence is shown in the Table 2. The solar panels were placed on the rooftop facing either south, east, or west depending on the orientation of the houses. The participants with PHVs were requested to connect the vehicle to V2G chargers every time they parked either at home or at the company's parking lot. A vehicle was allowed to connect only to a predetermined charger. The participants were also asked not to charge or discharge manually by pressing the button on the hardware. They were allowed to disconnect the charger when they wanted to drive even if the vehicles were charging.

Table 2 The Participants' assets

	PHV	Solar Panel	Stationary battery
Consumer 1	-	-	-
Consumer 2	8.8 kWh	-	-
Prosumer 1	-	4.2 kW, 4.8 kW	-
Prosumer 2	-	4.8 kW, 5.4 kW, 6.0 kW	9.8 kWh
Prosumer 3	8.8 kWh	5.9 kW, 7.2 kW	
Prosumer 4	8.8 kWh	7.2 kW	9.8 kWh

The real electricity demand of a certain building and PV generation within Higashifuji Research center was derived to be used for the PoC testing.

3.3 Hardware

Plug-in hybrid vehicles used for the PoC were Prius PHV (ZVW52-AHXGB) with V2H charging option. V2G chargers were prepared for every home and connected to existing grid lines and also located at the employee parking lot for each participant with PHV. The basic function was inherited from the commercial 6 kW V2H charger (DNEVC-D6075). Each charger comprises a communication unit to send a charger status, which includes timestamps, vehicle connection, the SOC of connected vehicles, charging, and discharging, to the server every five minutes. The communication units also enable to execute charging and discharging according to the system order.

3.4 Market rules

As mentioned previously, the basic market rules were as same as what was described in the 2.1 section. However, several new regulations were applied to reflect the rules of actual electricity market in Japan. As the peculiar characteristic of the distribution system, there are special-high voltage (higher than 20,000 V), high-voltage, and low-voltage (200 V) distribution lines [11]. The research center, which participates as an office in the PoC, derives electricity from special-high voltage distribution lines. On the other hand, residences are connected to low-voltage distribution lines. Therefore, the transaction of the office was limited to the vehicles parked at the office area or a special-high voltage retailer, and residences trade energy with other residences, vehicles parked at home, or a low-voltage retailer. This operation was done using tag system. 8.0 MU/kWh wheeling charge was imposed to the transactions of low-voltage distribution lines and low-voltage retailer sold electricity for 18.0 MU/kWh. Wheeling charge for special-high voltage electricity is 4.0 MU/kWh and its retailer sold electricity to the office at the price of 11.0 MU/kWh. Wheeling charge was not imposed to the trading within office parking lot since they used private cables. Electricity purchases done outside of the market were calculated separately and were imposed 26.0 MU/kWh.

3.5 Vehicle agent

The bidding procedure and feedback of execution result is shown in the Fig. 8. The bidding algorithm of vehicle agents for the PoC is as same as the simulator described in 2.3. The vehicle agent was created for every PHVs. For the PoC project, there were several things to consider. Vehicle agents only bid to the timeslot or TF which are more than 10 minutes away from the present TF to guarantee the communication time between server and charger. Although the 6 kW charger has an ability to deliver maximum 3 kWh in 30-minute-timeslot, the agent limited the bidding to 1.9 kWh in 30 minutes. This is because the charging time may vary according to the distribution line capacity of a certain time. The vehicle agent bid to the market regarding the optimized charge/discharge schedule, but for the future market the amount was reduced for they contain higher uncertainties. The participants were asked beforehand of their commuting time.

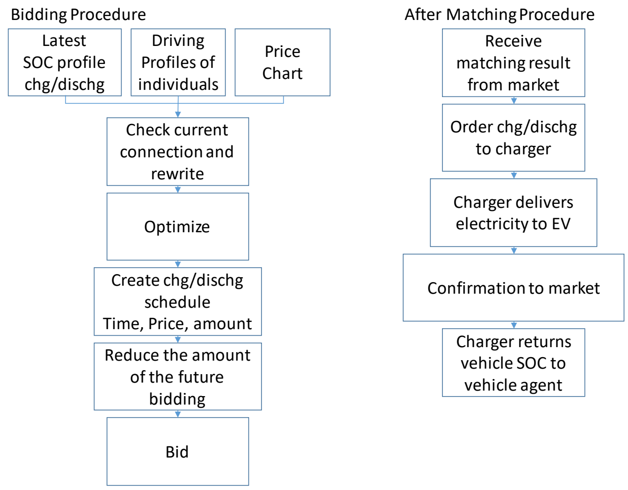

Figure 8 Vehicle agent procedures

4 PoC Results

4.1 Market Price

The market price transition of PoC was similar to the simulation (Fig. 9). The price decreased during the daytime when the solar energy was produced. The graph is the result of all the transactions proceeded both in low-voltage distribution and office parking lot. The wheeling charge is included for the low-voltage distribution transactions. The graph does not contain unexecuted biddings.

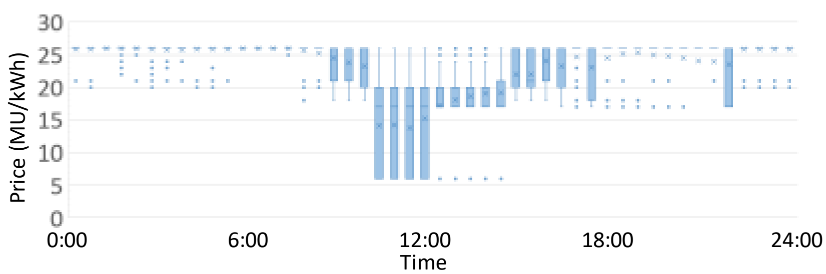

Figure 9 Executed price profile

4.2 Renewable energy consumption of vehicle

The mixed energy and renewable energy purchased by vehicles are shown in Fig. 10. All of the energy amount purchased during February, 2020, were accumulated and sorted into 30-minute-timeslot. 20.1 % of all the energy obtained by 10 vehicles was the renewable energy, which was offered by the office agent. The amount of surplus solar energy purchased by PHV was 13.7 % of all the surplus solar energy offered by office (Fig. 11). The surplus solar energy was delivered mainly on the sunny weekends, when the employees were out of work and the office had low electricity demand. When limited to weekday surplus, PHV absorbed 44 % of the offer. The ratio of surplus solar energy of office to the absorbed amount by PHV of weekdays, excluding 2/11 and 2/24 that are national holidays in Japan, was above 74 % (Fig. 12). The surplus solar energy was mainly delivered in the morning (Fig. 13) since the solar panels of the office building were facing southeast.

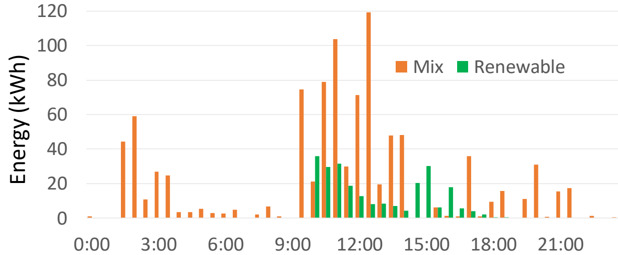

Figure 10 Energy type purchased

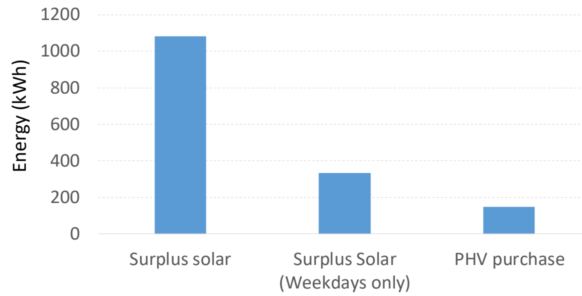

Figure 11 Surplus solar and purchased amount

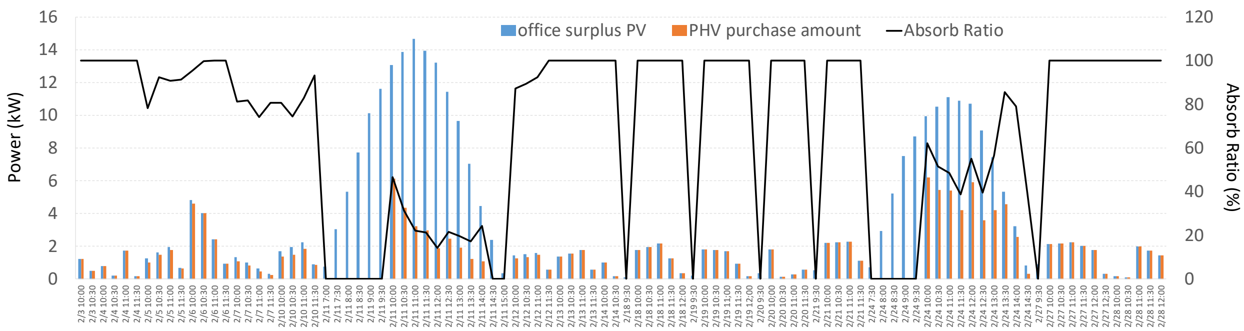

Figure 12 Supplied solar and amount purchased by PHV

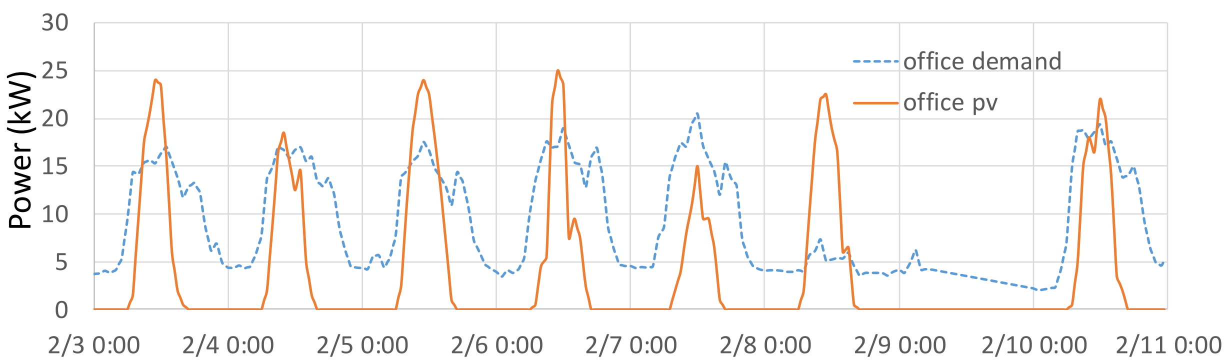

Figure 13 Demand and generation of office

The office offered surplus solar energy on some weekends, but was never purchased since the participants were not at work. The algorithm of price minimization was suitable for voluntary charging. A few challenges had remained.

4.3 Balance

It is desirable that a vehicle execute the market order to charge or discharge according to contracts, however, there were several cases related to human actions that vehicles could not obey the order: 1. Human errors such as misconnecting vehicles to chargers. 2. Human preference to press the button to charge whenever they want to charge. 3. Unexpected travels. Fig. 14 shows the amount of appropriate matching and execution of charging, and inappropriate contracts and charging.

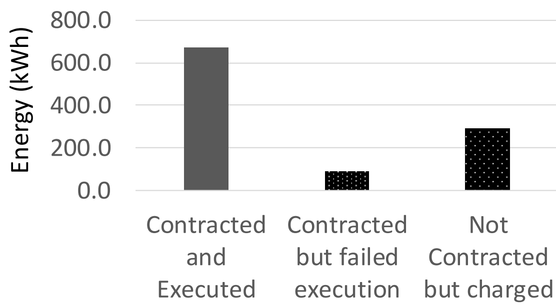

Figure 14 Contract and execution balance

5 Discussion

Bidding based on price minimization algorithm of the vehicle helped absorb the surplus solar energy. In the actual testing, it was important to be well aware of incorrect predictions and human activities. Although we had applied some steps to reduce the effect, the failure of contracts and execution had remained. For the future work it is important to take care of unpredictable failure. It could be done through various ways such as vehicles compensate each other by creating groups, and bid immediately after detecting unexpected human activities to recover. In this pilot project, the office had the pricing as shown in the Table 3.

Table 3 Office strategy

Type	Price MU/kWh	Buy/Sell	Tag
Surplus Solar Energy	6 MU/kWh	Sell	Green
Regular Solar Energy	18 MU/kWh	Sell	Green
Peak Cut	35 MU/kWh	Buy	Mix
Grid	17 MU/kWh	Sell	Mix

In February, office's demand peak cut was never needed, but the current vehicle strategy would not respond to the offer even though the purchase price would be proposed higher than the grid price. This is because the vehicle was never programmed to sell the electricity in the middle of the day. One way to respond to the office's peak cut is to communicate directly and obtain the peak cut price, then rewrite the price chart. As shown in Fig. 12, vehicles did not purchase surplus solar energy at 9:30 because they had assumed the electricity price was high according to Fig. 3 price chart. The process of creating their appropriate own price chart is also expected for the future work.

6 Conclusion

In this paper a continuous double auction P2P energy trading simulator was constructed to check whether the system will operate according to the market mechanism so that the electric vehicles would purchase the surplus solar energy when applying cost minimization algorithm. The market functioned as intended indicating that electric vehicles are capable of absorbing surplus solar energy which would contribute to mitigate the duck curve problem. The proof of concept testing was also conducted using actual servers and P2P market with blockchain technology, 10 Prius PHVs, 1 office, 20 residences, and a retailer. The PHV absorbed the surplus solar energy from the office as previously indicated in the simulator, however, the amount was not as much as expected. Through the pilot project several challenges were revealed. For the future works, it is desirable to add an algorithm to the vehicle agent so as to reduce the failure of execution and compensate the contract when charged by human activities.

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