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PAPER

EV Aggregation Framework for Spatiotemporal Energy Shifting to Reduce Solar Energy Waste*

Kenshiro KATO†a), Daichi WATARI†b), *Nonmembers*, Ittetsu TANIGUCHI†c), *and* Takao ONOYE†d), *Members*

SUMMARY Solar energy is an important energy resource for a sustainable society and is massively introduced these days. Household generally sells their excess solar energy by the reverse power flow, but the massive reverse power flow usually sacrifices the grid stability. In order to utilize renewable energy effectively and reduce solar energy waste, electric vehicles (EVs) takes an important role to fill in the spatiotemporal gap of solar energy. This paper proposes a novel EV aggregation framework for spatiotemporal shifting of solar energy without any reverse power flow. The proposed framework causes charging and discharging via an EV aggregator by intentionally changing the price, and the solar energy waste is expected to reduce by the energy trade. Simulation results show the proposed framework reduced the solar energy waste by 68%.

key words: *EV (Electric vehicle), EV aggregator, mixed integer programming*

1. Introduction

Solar energy is promising for a sustainable society and is massively introduced these days. In order to utilize solar energy effectively, the temporal and spatial gaps between demand and supply become often problem. Photovoltaic (PV) panel generates solar power during only the daytime, and the temporal gap becomes a problem to use the energy at the night. Spatial gap is another challenge because the renewable energy source is often distributed. The battery takes an important role to fill in the temporal gap and is often equipped for each house as well as the PV panel. Such facilities effectively fill the temporal gap, and renewable energy can be used even at the night. In case the solar power cannot be consumed/charged at the household due to unavoidable situations, the excess energy is often sold by the reverse power flow to the grid. Selling the excess energy brings the new opportunity to utilize the wasted renewable energy at the other place, and the spatial gap is also filled by this framework. However, the massive reverse power flow usually sacrifices the grid stability, and the other effective way is expected to utilize the solar energy without any reverse power flow.

Electric vehicles (EVs) are becoming more and more popular for low carbon emission, and charging stations are placed everywhere these days. The EVs usually have a large battery size for the long cruise distance, but the battery is not used up in daily use in most cases. This means the EVs battery offers the opportunity to fill in the temporal and spatial gaps between demand and supply, and many researches exist related to solar energy and EVs [1]–[12]. These researches mainly focus on the peak shaving and profit maximization, and no research exists to minimize solar energy waste.

In this paper, we propose the novel EV aggregation framework to reduce solar energy waste. Cui et al. proposed the optimization framework of the EV's battery scheduling for the peak shaving [5]. Cui's framework enables the EVs not only to charge but also discharge on-site. Our EV aggregation framework is inspired by Cui's framework, which enables the EVs to both charge and discharge on-site, and buyouts the energy waste from energy-rich households. This brings the reduction of solar energy waste without any reverse power flow. The trade of solar energy waste is caused by the proposed pricing strategy. In order to collect the energy waste from the energy-rich and to distribute the waste to the energy-poor, different prices are prepared for energy-rich and energy-poor households, respectively.

The contributions of this paper are summarized as follows.

- We proposed the novel EV aggregation framework for the reduction of solar energy waste. As a result, the solar energy waste was reduced by up to 68% and the purchased energy is also reduced by 13%.
- The tradeoff between the battery size and the impact of EV aggregation is discussed.

The rest of the paper is organized as follows. Section 2 introduces the related work. The system model and proposed method are explained in Sect. 3 and Sect. 4, respectively. The experimental results are shown in Sect. 5, and this paper is concluded in Sect. 6.

2. Related Work

2.1 Researches on EV Aggregators

EVs have become increasingly popular in recent years, and

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†The authors are with the Graduate School of Information Science and Technology, Osaka University, Suita-shi, 565-0871 Japan.

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a) E-mail: kato.kenshiro@ist.osaka-u.ac.jp
b) E-mail: watari.daichi@ist.osaka-u.ac.jp
c) E-mail: i-tanigu@ist.osaka-u.ac.jp
d) E-mail: onoye@ist.osaka-u.ac.jp

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Table 1 Researches on EV Aggregators.

Ref.	Year	Object	Approach
[1]	2010	Peak shaving	Charge/discharge scheduling
[2]	2010	Peak shaving	Charge scheduling
[3]	2015	Maximizing profits	Dynamic pricing
[4]	2017	Maximizing profits	Dynamic pricing
[5]	2017	Peak shaving	Charge/discharge scheduling
[6]	2018	Load reduction	Dynamic pricing
[7]	2018	Peak shaving	Charge/discharge scheduling
[8]	2018	Peak shaving	Charge scheduling
[9]	2018	Peak shaving	Dynamic pricing
[10]	2020	Maximizing profits	Dynamic pricing
[11]	2020	Maximizing profits & Peak shaving	Dynamic pricing
[12]	2021	Maximizing profits	Dynamic pricing

the demand load of the EVs charge is not negligible anymore. The impact of many EVs charges may unstabilize the grid, and EV aggregation is the potential way to alleviate them. Table 1 summarizes the EV aggregation researches. The first paper on EV aggregator was presented in 2010, and the demand peak shaving was the important object. After that, profit maximization became another important object, and many researches were proposed under the various models such as EV model, grid model, price model, traffic model, etc. until now. Such aggregation was firstly performed by the scheduling-based approach, but current cases are done by the dynamic pricing-based approach. Based on the dynamic pricing, the charging and discharging behaviors are controlled indirectly.

EV aggregation method toward the peak shaving has been proposed [1], [2], [5], [7]–[9]. Sadeghianpourhamami et al. [7] analyzed the usage patterns of EV charging stations, and the charging/discharging schedule is optimized by this knowledge. This research investigated the possibility of peak shaving by controlling the charging of EVs based on this data. Chen et al. [8] modeled and simulated EV charging schedule patterns under different energy-consuming conditions, and analyzed how EV's charging behavior can affect the global load characteristics. This research achieved to shave the peak load by applying the appropriate charging patterns for EVs.

The pricing method on EV aggregator is proposed to maximize the benefit of electricity trade [3], [4], [10]–[12]. Moghaddam et al. [11] proposed a price control method using reinforcement learning. This research achieved both peak shaving and profit maximization for EV aggregators. However, these studies do not take into account the reduction of solar energy waste. In our research, we aim to transmit solar energy waste between households by EV's charge/discharge via EV aggregators. To the best of our knowledge, this is the first paper to reduce solar energy waste by EV aggregation.

2.2 Researches on Consumer-Side Energy Management

Energy management methods of consumer-side such as home, office building, etc. have been also investigated to utilize the solar energy effectively. In [13]–[16], the main object of these researches includes demand reduction and peak shaving by the scheduling of the battery and smart home appliances. Watari et al. [14] proposed an energy

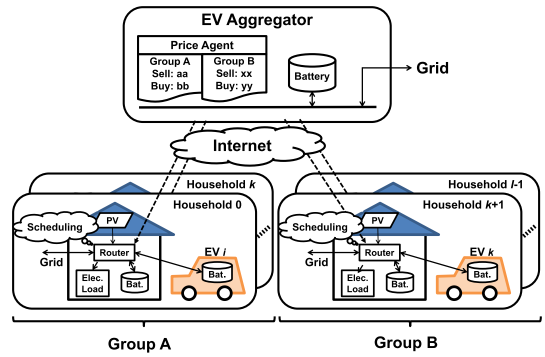

Fig. 1 System model: household model and EV aggregator model.

management method that takes into account battery management. This research achieved efficient battery management and household profit maximization. This research is complementary research on EV aggregator because this paper focuses mainly on EV and EV aggregator. In our research, we suppose the household model includes the house and EV, and the effective EV aggregation framework is proposed between EV aggregator and EVs belonging to these household models. Our household model assumes the energy management support to maximize the benefit, and the EV's behavior is decided by them.

3. System Model

This section introduces the system model of the proposed EV aggregation framework. In this research, we assume a scenario in which a conventional charging station is replaced by EV aggregator which is capable of charging and discharging with EVs. Figure 1 shows the system model of the proposed framework. The system model is composed of I household models including the EV and one EV aggregator model. The purpose of this research is to reduce the solar energy waste by spatiotemporal shifting of them through EVs based on the interaction between the household model and EV aggregator model.

3.1 Household Model

As shown in Fig. 1, each household has PV panel, electric load, battery, power router, and EV. The residents use the EV to travel between their homes and the EV aggregator. The EV is regarded as another fixed battery when the EV is connected to the house. The power router receives the price information of the EV aggregator, and the EV can sell/buy the energy by discharging/charging at the EV aggregator. The power router calculates the battery scheduling to minimize the electricity bill and to maximize the profit. During on-peak hours, i.e., when the grid is over-generated in the daytime, selling electricity at households (reverse power flow) is prohibited because it has a negative impact on the grid. During off-peak hours, households can reverse power flow their excess solar energy to the grid. If the batteries are full and the PV generation cannot be consumed, the excess solar energy is

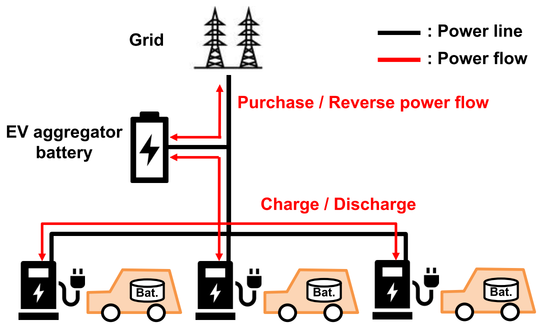

Fig. 2 Physical structure of the EV aggregator.

discarded as wasted energy or sell electricity to the grid. The power router sends the EV battery schedule (the schedule of charge/discharge at EV aggregator) and the energy budget to the EV aggregator for every time interval. Additionally, the power router receives the latest price information from the EV aggregator, and the scheduling is iteratively performed under the latest information. The household model and EV aggregator model iteratively perform these interactions.

3.2 EV Aggregator Model

The EV aggregator is assumed to serve as both a large-scale parking facility and a charging station. Figure 2 shows the physical structure of EV aggregator. We assume a physical structure a parking lot with a large battery connected to it. The EV aggregator is equipped with charging and discharging facilities and a large fixed battery. The system is in which batteries and charging/discharging facilities are connected under the connecting point to the grid. A sufficient number of charging/discharging facilities are equipped, and the EVs connect anytime arrived. Hence, multiple EVs can charge and discharge the electricity at the same time. The EV aggregator also has the price agent to decide the price information for energy trade with EVs. The EV aggregator receives the EV battery schedule and the energy budget from the household in advance. All the energy requests of EV charging/discharging is handled by the fixed battery of the EV aggregator. If the EV's charging demand cannot be satisfied due to the battery shortage of the EV aggregator, the EV aggregator purchases the energy from the grid. Conversely, if the EV's discharging energy cannot be charged to the EV aggregator battery because of fully charged, the excess energy is sold to the power company.

In electricity trading, we assumed that the EV aggregator set the selling electricity price higher than the buying price from EVs. Under this assumption, the energy-rich households are expected to sell their wasted energy to the EV aggregator rather than wasted it inside households. On the other hand, the energy-poor households are expected to purchase electricity from EV aggregators because the selling price of EV aggregators is lower than the price of the grid. In this way, the EV aggregator gets a profit through electricity trading. However, the main objective of EV aggregators is only how much wasted energy can be shifted. Therefore,

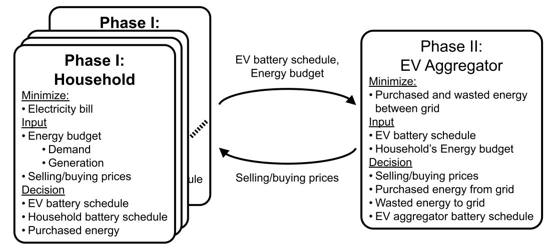

Fig. 3 Overview of the spatiotemporal energy shifting method.

the EV aggregator determines the prices according to its objectives. In order to collect the energy waste from the energy-rich and to distribute the waste to the energy-poor, the EV aggregator classifies the EVs into two groups based on the energy budget. If the households plan to waste the energy, the households are classified into Group A – energy-rich group. If the households have no energy waste, the households are classified into Group B – energy-poor group. The price agent settles two types of prices for Group A and Group B, and the corresponding price is sent to the household model. The price agent updates these prices based on the battery sufficiency level of the EV aggregator and the power sufficiency of each household. These prices are sent to households via the internet.

4. Spatiotemporal Energy Shifting Method

This section proposes the spatiotemporal shifting method of solar energy waste. The objective is to reduce the solar energy waste by spatiotemporally shifting the waste between the households and the EV aggregator via the EV. To this end, we focus on the interaction between household and EV aggregator. Figure 3 shows an overview of our proposed method. The proposed method is divided into two phases; Phase I: household battery scheduling for electricity bill minimization and Phase II: battery scheduling and price update at EV aggregator. Phase I and Phase II are iteratively executed to induce a spatiotemporal shift of wasted energy. In this research, online algorithm is assumed. This means that the household can flexibly update their behavior at each control time according to the household's energy situation and the EV aggregator's price. The EV aggregator's prices and household behavior are corrected by iterative calculations, then they naturally converge.

In Phase I, each household decides the battery schedule and purchased energy to minimize their electricity bill. Input is selling/buying prices at the aggregator and forecasting data of PV generation and electricity demand. Each household sends the EV battery schedule and the energy budget to the EV aggregator.

In Phase II, the EV aggregator collects all EV battery schedules, which represent the requests to charge/discharge, and the energy budget. Based on the requests, the EV aggregator schedules the own battery and purchased energy from the grid and wasted energy to the grid. Then, the EV aggregator updates the selling and buying prices. The EV

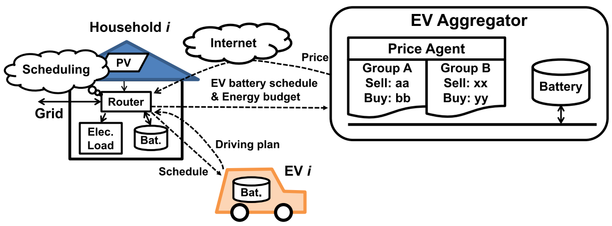

Fig. 4 Phase I: Scheduling to minimize the electricity bill of the household.

aggregator prepares two prices for the energy-rich and the energy-poor groups, which is classified based on the energy budget, and corresponding price is sent to the household. Then the EV battery schedules are updated with the new prices again. Following subsections explain the details of each phase.

4.1 Phase I: Household Battery Scheduling for Electricity Bill Minimization

Figure 4 shows an overview of Phase I. In Phase I, each household performs the battery scheduling to minimize the electricity bill. We formulate the problem by MIP (Mixed Integer Programming) for each household, and the planning period is $0 \leq u < U$. The problem formulation is based on the previous research [17].

Let $Bh_u^{IN}, Bh_u^{OUT}, Bv_u^{IN}, Bv_u^{OUT}, S_u, B_u, Q_u, Y_u, Z_u$ be the household battery's charged/discharged energy, the EV battery's charged/discharged energy while connected to household, the selling/buying energy at EV aggregator, the energy of reverse power flow, the wasted energy, and the purchased energy at time u, respectively. These variables become the decision variables.

Let $BS^h, \overline{SOC^h}, \underline{SOC^h}$ be the household battery size, the upper/lower bounds of the state of charge (SOC) level, respectively. The remaining energy of the household battery Xh_u must satisfy the following formula for every time u.

$$\underline{SOC^h} \leq \frac{Xh_u}{BS^h} \leq \overline{SOC^h} \qquad 0 \leq u < U \tag{1}$$

Additionally, the remaining energy Xh_u can be updated by the following equation.

$$Xh_{u+1} = Xh_u + Bh_u^{IN} - Bh_u^{OUT} \quad 0 \leq u < U-1 \tag{2}$$

The remaining energy in the EV's battery Xv_u is represented in the same way. Let $BS^v, \overline{SOC^v}, \underline{SOC^v}$ be the EV's battery size, the upper/lower bounds of the SOC level, respectively. The remaining energy Xv_u must satisfy the following formula for every time u.

$$\underline{SOC^v} \leq \frac{Xv_u}{BS^v} \leq \overline{SOC^v} \qquad 0 \leq u < U \tag{3}$$

Since the EV drives between the household and the EV aggregator, the remaining energy can be updated in a different way under the situation. The situation of EV is represented by the variable ds_u, and ds_u takes zero, one, and two in the case connected to the household, driving, and connected to EV aggregator, respectively. Then the EV's remaining energy Xv_u can be updated by the following equation.

$$Xv_{u+1} = \begin{cases} Xv_u + Bv_u^{IN} - Bv_u^{OUT} & \text{if } ds_u = 0 \\ Xv_u - H & \text{if } ds_u = 1 \\ Xv_u - S_u + B_u & \text{if } ds_u = 2 \end{cases} \qquad 0 \leq u < U-1 \tag{4}$$

Notice that the driving energy consumed for every time step can be represented by the constant value H for simplicity. The charge/discharge to the EV's battery are only allowed in case $ds_u = 0$, in case the EV is connected to the household. This means that Bv_u^{IN} and Bv_u^{OUT} are kept zero in case ds_u takes one or two, in case the EV is not connected to the household. In the same way, the energy selling/buying at EV aggregator are also allowed in case $ds_u = 2$, in case the EV is connected to the EV aggregator. Thus S_u and B_u are kept zero in case ds_u takes zero or one, in case the EV is not connected to the EV aggregator.

Let G_u, D_u be the PV generation, the electricity demand at time u, respectively. The power flow within the household should keep the following constraint.

$$Z_u + G_u + Bh_u^{OUT} + Bv_u^{OUT} - (Q_u + Y_u + D_u + Bh_u^{IN} + Bv_u^{IN}) = 0 \quad 0 \leq u < U \tag{5}$$

The constraint equations about excess solar energy are defined as follows.

$$Q_u = 0 \qquad \text{if on-peak} \tag{6}$$

$$Y_u = 0 \qquad \text{otherwise} \tag{7}$$

During on-peak hours, i.e., when the grid is over-generated in the daytime, the household is prohibited to reverse power flow to keep the grid stable. Therefore, the excess solar energy is discarded as wasted energy. During off-peak hours, reverse power flow is possible, then there is no wasted energy.

An object of this problem is to minimize the electricity bill. In case R_u, Ps_u, and Pb_u represent the electricity price of the grid, selling/buying prices at the EV aggregator at time u, respectively, the objective function can be represented as follows.

minimize :

$$\sum_{u=0}^{U-1} \{R_u \cdot Z_u - (Ps_u \cdot S_u - Pb_u \cdot B_u)\} \tag{8}$$

The objective function does not consider reverse power flow. Japanese electric power companies (e.g., Kansai Electric Power Company, Inc.) generally allow reverse power flow only for PV generation energy. Therefore, this model does not include reverse power flow in the objective function to prevent reverse power flow from batteries. In this model, we assumed Time-of-Use (TOU) pricing. TOU pricing offers two types of pricing based on time: peak price and out of

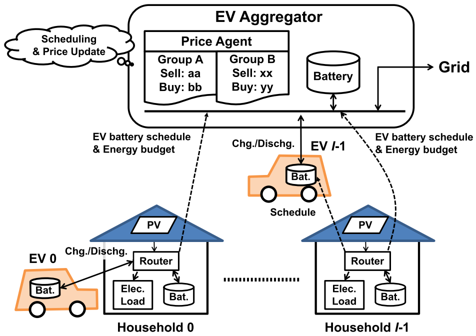

Fig. 5 Phase II: Scheduling of aggregator battery and price update based on the battery sufficiency.

peak price. Then R_u is defined as follows. Then R_u is defined as follows.

$$R_u = \begin{cases} R_{high} & \text{if peak-time} \\ R_{low} & \text{otherwise} \end{cases} \quad (9)$$

where R_{high} and R_{low} mean the peak price and out of peak price, respectively.

As explained in previous section, the household model sends the EV battery schedule and the energy budget to EV aggregator at every time intervals. S_u, B_u, G_u and D_u are sent to the EV aggregator as the EV battery schedule and the energy budget.

4.2 Phase II: Battery Scheduling and Price Update at EV Aggregator

Figure 5 shows an overview of Phase II. In Phase II, the EV aggregator collects all EV battery schedules, which represent the request to charge/discharge, and the energy budget. Based on the requests, the EV aggregator optimizes the own battery schedule and updates the selling and buying prices based on the battery remaining amount. The EV aggregator prepares two prices for Group A and Group B, the energy-rich and the energy-poor groups which is classified based on the energy budget. Then the corresponding price is sent to the household, and the EV battery schedule is updated again. Through these iteration, this research aims that the energy waste from the energy-rich is indirectly supplied to the energy-poor via EVs and EV aggregator.

4.2.1 Battery Scheduling

In this section, we formulate the battery scheduling of the EV aggregator based on MIP (Mixed Integer Programming). For given all EV battery schedules, the EV aggregator decides the own battery schedule to minimize the sum of the purchased energy and the reverse power flow. The planning period is $0 \leq u < U$. The EV aggregator received the EV battery schedule and the energy budget from EV i, and the range of i is $0 \leq i < I$. In this section, S_u, B_u, G_u and D_u from EV i are renamed as $S_{i,u}$, $B_{i,u}$, $G_{i,u}$ and $D_{i,u}$, respectively.

Let V_u, W_u be the purchased energy from the grid, the reverse power flow to the grid from EV aggregator at time u, respectively. These variables V_u and W_u become the decision variables.

Let $BS^{st}, \overline{SOC^{st}}, \underline{SOC^{st}}$ be the EV aggregator's battery size, the upper/lower bounds of the SOC level, respectively. The remaining energy of the EV aggregator's battery Xs_u must satisfy the following formula for every time u.

$$\underline{SOC^{st}} \leq \frac{Xs_u}{BS^{st}} \leq \overline{SOC^{st}} \qquad 0 \leq u < U \quad (10)$$

The remaining energy of the EV aggregator's battery Xs_u can be updated by the following equation.

$$Xs_{u+1} = Xs_u + V_u - W_u + \sum_{i=0}^{I-1}(S_{i,u} - B_{i,u}) \qquad 0 \leq u < U-1 \quad (11)$$

The objective function is also defined as follows.

$$\text{minimize}: \sum_{u=0}^{U-1} V_u + \sum_{u=0}^{U-1} W_u \quad (12)$$

Solving this problem, the EV aggregator decide the own battery schedule for given all EV battery schedules.

4.2.2 Price Update

In order to minimize the energy waste by supplying from the energy-rich to the energy-poor via EVs and EV aggregator, EV aggregator classified the arriving EVs into two groups based on the energy budget: Group A – energy-rich group and Group B – energy-poor group. EV aggregator discriminates group A and group B based on the balance of daily household's generation and demand at each control time. Households that more generate energy are classified into Group A. Conversely, households that more demand are classified into Group B. Let EV_A, EV_B be the set of EVs in Group A and Group B, respectively. EV_A and EV_B are defined as follows.

$$EV_A = \left\{ i \in I \,\middle|\, \sum_{u=0}^{U-1} D_{i,u} \leq \sum_{u=0}^{U-1} G_{i,u} \right\} \quad (13)$$

$$EV_B = \left\{ i \in I \,\middle|\, \sum_{u=0}^{U-1} D_{i,u} > \sum_{u=0}^{U-1} G_{i,u} \right\} \quad (14)$$

EV aggregator prepares the two prices for EV_A and EV_B, and this section introduce the price update method for these groups.

In this research, the households discard the excess solar energy as wasted energy during on-peak hours. Not to waste the solar energy in the households, EV aggregators buy energy from households via EVs. Let Pb_u^A and Pb_u^B be the buying prices from the households in Group A and Group B, respectively. Pb_u^A and Pb_u^B become as follows.

$$Pb_u^A = PB \qquad 0 \le u < U \qquad (15)$$

$$Pb_u^B = PB \qquad 0 \le u < U \qquad (16)$$

where PB means the constant price to buy the wasted energy.

As explained in Sect. 4.1, Time-of-Use (TOU) pricing is supposed in this research, and two type of prices are prepared: R_{low} and R_{high}. To cause the spatiotemporal shifting of solar energy waste, EV aggregator needs to distribute the wasted energy mainly to the energy-poor. In addition, EV aggregator set the selling electricity price higher than the buying price from EVs in order not to lose money. Thus, EV aggregator prepares the constant buying price PB and three constant selling prices PS_{low}, PS_{middle} and PS_{high} to keep the following relation.

$$PB \le PS_{low} < R_{low} \le PS_{middle} < R_{high} \le PS_{high} \qquad (17)$$

PS_{low}, PS_{middle} and PS_{high} are selected for EV_A and EV_B.

Let Ps_u^A, Ps_u^B be the selling prices to the households in Group A and Group B, respectively. Ps_u^A and Ps_u^B are selected as follows.

$$Ps_u^A = PS_{high} \qquad 0 \le u < U \qquad (18)$$

$$Ps_u^B = \begin{cases} PS_{high} & \text{if } \frac{Xs_u}{BS^{st}} < SOC_{LB}^{st} \\ PS_{middle} & \text{if } SOC_{LB}^{st} \le \frac{Xs_u}{BS^{st}} < SOC_{UB}^{st} \\ PS_{low} & \text{otherwise} \end{cases}$$

$$0 \le u < U, \qquad (19)$$

where SOC_{LB}^{st} and SOC_{UB}^{st} mean the lower-border and upper-border of the SOC level. This pricing policy is expected to distribute the collected solar energy waste mainly to the household in EV_B. Therefore, the highest selling price PS_{high} is always applied to the household in EV_A. In this way, the EV aggregator collects wasted energy from Group A and distributes it to Group B.

5. Experimental Results

In this section, we explain simulation experiments to demonstrate the effectiveness of our proposed framework. The experimental setup is first described, and then the case studies are performed under different scenarios. In Sect. 5.1, we show the effectiveness of the proposed framework in reducing solar energy waste. In Sect. 5.2, we discuss the trade-off between the battery size and the impact of the EV aggregator.

In this experiment, the number of households I in the framework is 100. A planning period of the optimization problem is 24 hours with 30 minutes resolution, i.e., $U = 48$. The simulation period is 90 days, and the proposed method run once every 30 minutes during simulation period. The optimization problem is described and solved using the mathematical programming solver IBM ILOG CPLEX Optimization studio v.12.7 [18]. The other parameter settings are shown in Table 2. The on-peak hours (when reverse power flow is prohibited) were set to be 7 am to 11 pm the same as the peak-time of the Time-of-Use (TOU) price. The grid's TOU price divides prices between daytime and nighttime, so we followed this setting. BS^h and BS^v are chosen one parameter from Table 2, respectively. The initial state of charge (SOC) of the household battery, EV battery, and EV aggregator battery is set to 0.5. We assume that the EV is randomly used from 9:00 to 22:00 with an average of 5 hours, and its period includes driving and parking. The power demand and power generation data used as household profiles are measured in New South Wales, Australia [19].

Table 2 Parameter setting.

Parameter	Value	Unit
BS^h	5, 10, 15	kWh
$\overline{SOC^h}$	1.0	-
$\underline{SOC^h}$	0.1	-
BS^v	40, 60, 80, 100	kWh
$\overline{SOC^v}$	1.0	-
$\underline{SOC^v}$	0.1	-
on-peak	7 : 00 – 23 : 00	-
peak-time	7 : 00 – 23 : 00	-
R_{high}	21.27	JPY/kWh
R_{low}	10.51	JPY/kWh
BS^{st}	1000	kWh
$\overline{SOC^{st}}$	1.0	-
$\underline{SOC^{st}}$	0.1	-
PB	5	JPY/kWh
PS_{low}	8	JPY/kWh
PS_{middle}	16	JPY/kWh
PS_{high}	21.27	JPY/kWh
SOC_{LB}^{st}	0.5	-
SOC_{UB}^{st}	0.75	-

In this experiment, we confirm whether the proposed method can effectively utilize wasted energy. For this purpose, in addition to the proposed method, we also simulated the case where only charging stations are used without EV aggregator.

5.1 Effectiveness in Reducing Wasted Energy

In this section, we evaluate the effectiveness of the proposed framework in reducing solar energy waste. We use nine scenarios with different EV utilization frequencies and numbers of Group A and Group B respectively, as shown in Table 3. In these scenarios, we assume that the EV is used 2 or 4 times per week, or every weekday and random weekend. For example, Scenario 5 shows that all households use an EV aggregator four times a week, and 50 out of 100 households are Group A. In the experimental scenarios, we discriminate between Group A and Group B by the total balance of electricity demand and generation over a 90-day period, based on Eqs. (13) and (14). We set BS^h and BS^v to 10 kWh and to 40 kWh, respectively.

Firstly, we introduce some metrics to evaluate the performance of the proposed framework. An overview of the simulation outputs is shown in Fig. 6, and the detailed description of the outputs is given in Table 5. Fig. 6 shows the flow of energy between EV aggregators, households, and

Table 3 Scenarios.

	EV utilization frequency			Number of households in Group A / Group B
	Twice a week	Four times a week	Every weekday +Random weekends	
Scenario 1	×			30 / 70
Scenario 2		×		30 / 70
Scenario 3			×	30 / 70
Scenario 4	×			50 / 50
Scenario 5		×		50 / 50
Scenario 6			×	50 / 50
Scenario 7	×			70 / 30
Scenario 8		×		70 / 30
Scenario 9			×	70 / 30

Table 4 EV aggregator's power balance and reduction percentages of purchased energy and wasted energy of households.

	E_1 (kWh)	E_2 (kWh)	E_3 (kWh)	E_4 (kWh)	EV aggregator's profit (JPY)	$\alpha_{purchase}$ (%)	α_{wasted} (%)
Scenario 1	5,651	5,664	0	0	64,449	4	59
Scenario 2	4,568	4,715	0	0	71,908	3	62
Scenario 3	2,328	2,419	0	0	40,165	1	43
Scenario 4	10,018	10,036	0	0	80,278	9	57
Scenario 5	8,486	8,682	0	0	124,861	7	67
Scenario 6	4,821	4,942	0	0	81,017	3	51
Scenario 7	15,622	15,582	0	0	69,311	18	55
Scenario 8	14,303	14,445	0	0	169,590	13	68
Scenario 9	8,778	8,894	0	0	143,843	8	57

Table 5 Summary of output.

Output	Description
E_1	Amount of electricity supplied from Group A to EV aggregator
E_2	Amount of electricity supplied from EV aggregator to Group B
E_3	Amount of electricity supplied from EV aggregator to grid
E_4	Amount of electricity supplied from grid to EV aggregator

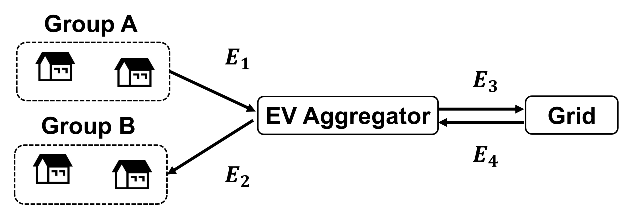

Fig. 6 Overview of energy shifting.

the power grid. The reduction percentage of wasted energy α_{wasted} and the reduction percentage of purchased energy $\alpha_{purchase}$ are given by Eqs. (20) and (21). Y_i and Y_i' represent the total amount of wasted energy of household i in the case with and without EV aggregator, respectively. Z_i and Z_i' also represent the total amount of purchased energy from only the grid of household i in the case with and without EV aggregator, respectively. This means that the purchased energy at the EV aggregator is not included in Z_i.

$$\alpha_{wasted} = \frac{\sum_{i=0}^{I-1} Y_i' - \sum_{i=0}^{I-1} Y_i}{\sum_{i=0}^{I-1} Y_i'} \cdot 100 \tag{20}$$

$$\alpha_{purchase} = \frac{\sum_{i=0}^{I-1} Z_i' - \sum_{i=0}^{I-1} Z_i}{\sum_{i=0}^{I-1} Z_i'} \cdot 100 \tag{21}$$

The experimental results for each scenario are shown in Table 4. The results in Table 4 show that households trade electricity in the EV aggregator in all scenarios. The result of E_1 shows that energy is transmitted from Group A to EV aggregators. The result of E_2 shows that energy is transmitted from EV aggregators to Group B. In all scenario, E_1 almost equal to E_2. In the EV aggregator pricing, when the EV aggregator purchases energy from Group A, the EV aggregator shows a lower price to Group B than the price of the grid. As a result, Group B buys almost all the energy that Group A sells to EV aggregator. In addition, the EV aggregator did not sell the energy purchased from Group A to the grid. This is because the EV aggregator minimized the energy purchased and sold with the grid, as set in the EV aggregator's objective function. Therefore, E1 and E2 are almost the same amounts. The results of E_3 and E_4 in Table 4 confirm that the EV aggregator neither sold power to the power grid nor purchased energy from the power grid. The results of the EV aggregator's profit in Table 4 show that the EV aggregator gets profits for all scenarios even though the objective function of our proposed method does not consider maximizing profits. However, profit is not large because it is not the main objective to be profitable. These results indicate that the energy shifting through the EV aggregator has been achieved without the purchased/sold energy from/to the grid.

As shown in Table 4, $\alpha_{purchase}$ and α_{wasted} are positive. In all scenarios, the purchased energy and wasted energy of households are reduced by using the proposed method. In Scenario 8, it is confirmed that the proposed method can reduce the wasted energy by 68% at most without reverse power flow. In the same scenario, by shifting the

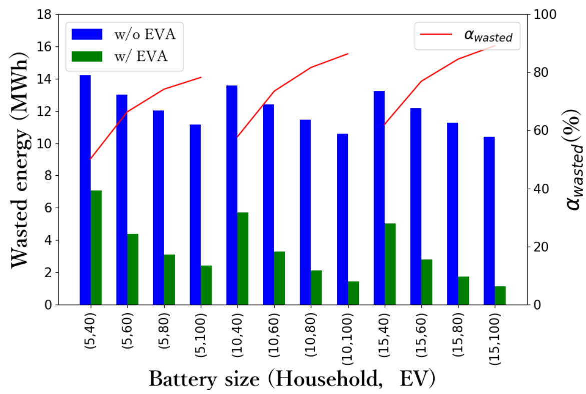

Fig. 7 Wasted energy per battery size in Scenario 4.

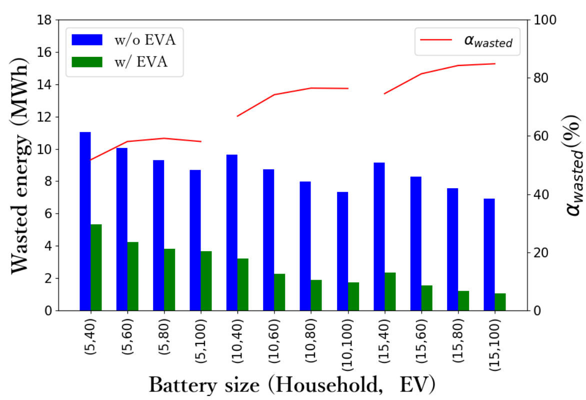

Fig. 8 Wasted energy per battery size in Scenario 5.

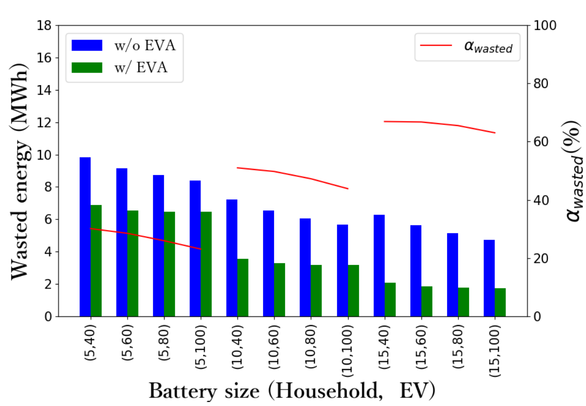

Fig. 9 Wasted energy per battery size in Scenario 6.

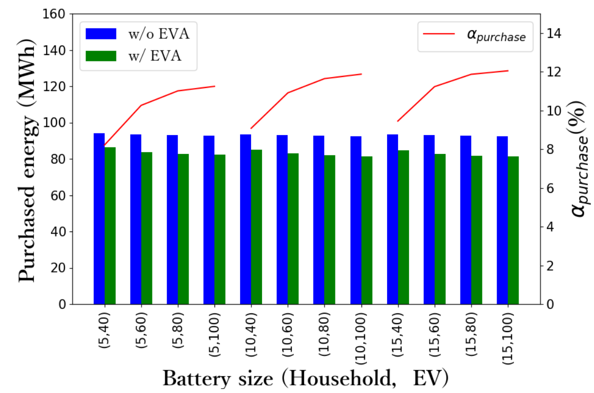

Fig. 10 Purchased energy per battery size in Scenario 4.

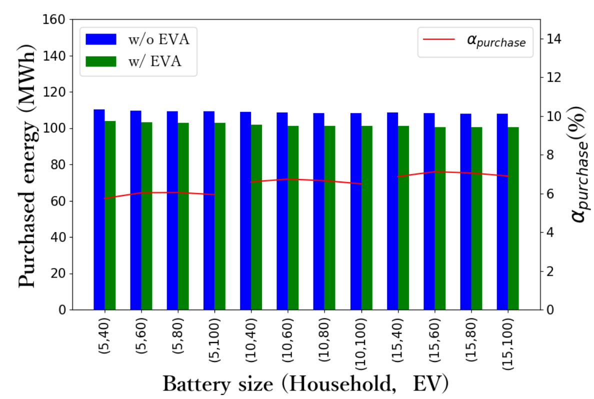

Fig. 11 Purchased energy per battery size in Scenario 5.

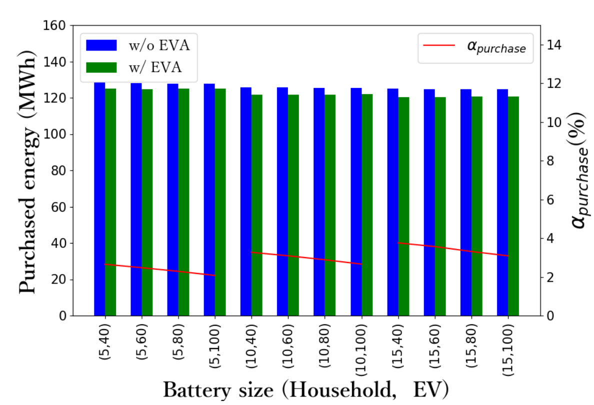

Fig. 12 Purchased energy per battery size in Scenario 6.

reduced wasted energy to Group B, purchased energy from the grid was reduced by 13%. In comparison between Scenario 1 and Scenario 7, $\alpha_{purchase}$ increase while α_{wasted} is almost the same when the Group A ratio is increased. An increase in $\alpha_{purchase}$ indicates a reduction in the amount of purchased energy from the grid by households. Comparing Scenarios 1 and 7, the number of energy-rich households increases in Scenario 7. This means that the number of households with more PV generation is increased, so the total amount of wasted energy is increasing. Therefore, the proposed method can shift more energy from Group A to Group B via EV aggregator. As a result, the amount of purchased energy reduced in Group B, and $\alpha_{purchase}$ also reduced. On the other hand, while the total amount of wasted energy is increasing in Scenario 7, the energy that is transmitted from Group A to EV aggregators (E1) is also increased. Therefore, the reduction percentage of wasted energy remained the same, and there is almost no change in α_{wasted}. These results show that, under all scenarios, the proposed method can shift solar energy waste between Group A and Group B through an EV aggregator without reverse power flow.

5.2 Impact of Battery Size on Proposed Method

In this section, we discuss the impact of the battery size on the proposed method with the different sizes of EV batteries and household batteries. In this experiment, we use Scenarios 4, 5, and 6 in Table 3. We evaluated the all combinations of BS^h and BS^v for these scenarios.

Figure 7, Fig. 8 and Fig. 9 show the amount of wasted energy in case with and without EV aggregator in Scenarios 4, 5, and 6, respectively. The x-axis means the battery size combination. The left y-axis gives the amount of wasted energy, and the right y-axis indicates the reduction percentage of wasted energy α_{wasted}. The red line indicates α_{wasted}, and the blue and green bars denote the amount of wasted energy in case without EV aggregator and with EV aggregator, respectively.

In all cases, we can see the amount of wasted energy is successfully reduced by introducing the EV aggregator. The amount of reduction depends on the battery size combination and the scenarios. In Scenario 4, EVs are not utilized frequently, and the impact of EV aggregator and large battery size is quite high. On the other hand, in Scenario 6, EVs are frequently utilized, and the impact of the EV aggregator is relatively not so high because the wasted energy is smaller than the other scenarios.

Figure 10, Fig. 11 and Fig. 12 show the amount of purchased energy in case with and without EV aggregator in Scenarios 4, 5, and 6, respectively. The x-axis means the battery size combination. The left y-axis gives the amount of purchased energy, and the right y-axis indicates the reduction percentage of purchased energy $\alpha_{purchased}$. The red line indicates $\alpha_{purchased}$, and the blue and green bars denote the amount of purchased energy in case without EV aggregator and with EV aggregator, respectively.

In all cases, the purchased energy is slightly reduced by EV aggregator. The amount of purchased energy is overwhelmingly larger than that of wasted energy, and we can see the reduction percentage as relatively small. However, the reduced wasted energy by EV aggregator is utilized by the energy-poor, and this means the energy-poor needs not to purchase that of energy. Thus we can observe that the reduced amount of wasted energy caused by the EV aggregator corresponds to that of purchased energy. $\alpha_{purchase}$ decreases as EV battery size increases in Scenario 6 in Fig. 12 as opposed to Scenarios 4 and 5. In Scenario 6, EVs are frequently utilized, and shifted energy via EV aggregator decreases because the wasted energy is smaller than in the other scenarios. $\alpha_{purchase}$ decreases because shifted energy decreases for purchased energy reduction.

From the above experimental results, it was confirmed that the proposed method is useful in terms of the reduction of wasted solar energy and distribution of them, regardless of the battery size.

6. Conclusion and Future Work

We proposed the novel EV aggregation framework for spatiotemporal shifting of solar energy without any reverse power flow to the grid. In this framework, the spatiotemporal shifting of solar energy waste is caused based on the interaction between the household model and the EV aggregator model. For the shifting of wasted energy, we also proposed a pricing method at EV aggregator. Experimental results have shown that the proposed method can be used to reduce wasted energy through the EV aggregator under any scenario. In the best case, we achieved a 68% reduction in solar wasted energy. The future work includes the improvement of the system model by taking into account price elasticity on the household side in electricity trading at EV aggregator. In addition, more detailed EV battery models and EV usage models must be considered.

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Kenshiro Kato received the B.E. and M.E. degree from Osaka University, Japan, in 2019 and 2021, respectively. He is currently a doctoral student of Osaka University. His research interests include linkage between electric vehicles and the smart grid. He is a student member of IEEE.

Daichi Watari received the B.E. and M.E. degrees from Osaka University, Japan, in 2018 and 2020, respectively. He is currently a Doctoral student of Osaka University. His research interests include a decision-making using mathematical optimization and reinforcement learning for energy management system. He is a student member of IEEE. He is also receiving support from JSPS Research Fellowship for Young Scientists (DC2).

Ittetsu Taniguchi received B.E., M.E., and Ph.D degrees from Osaka University in 2004, 2006, and 2009, respectively. From 2007 to 2008, he was an international scholar at Katholieke Universiteit Leuven (IMEC), Belgium. In 2009, he joined the College of Science and Engineering, Ritsumeikan University as an assistant professor, and became a lecturer in 2014. In 2017, he joined the Graduate School of Information Science and Technology, Osaka University as an associate professor. His research interests include system level design methodology, design methodologies for cyber-physical systems, etc. He is a member of IEEE, ACM, IEICE, and IPSJ.

Takao Onoye received B.E. and M.E. degrees in Electronic Engineering, and Dr.Eng. degree in Information Systems Engineering all from Osaka University, Japan, in 1991, 1993 and 1997, respectively. He is presently a professor and dean of Graduate School of Information Science and Technology, Osaka University. His research interests include media-centric low power system architecture and implementation. He has also taken various volunteer positions in academic societies, such as Editor-in-chief of IEICE Trans. Fundamentals (Japanese edition), IEEE CAS Society board of governors, IEEE Region 10 Treasurer, IEEE Region 10 Vice Chair, and IEEE Japan Council Chair. Dr. Onoye is a member of IEEE, IEICE, IPSJ, and ITE-J.