Optimal operation of V2H and stationary storage batteries in a massive PV penetrated consumer group

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***Abstract*— The optimal operation method of EV battery and stationary battery that aims to improve the self-consumption rate of PV energy is proposed in this paper. The prosumers have stationary storage batteries and an electric vehicles (EVs). Various driving patterns are randomly assigned to all prosumers, and the state-of-charge (SOC) of each EV is limited before driving. The two storage batteries are operated while taking the convenience of the EV user into account. In addition, we consider a group of prosumers. If one consumer generates surplus electricity, other consumers in the same group will consume it effectively. As a result, the self-consumption rate for the entire consumer group increased 1.15 times when multiple prosumers were operated as a group than when they were operated individually. In addition, more EVs were charged using the power generated from PV.**

Keywords—electric vehicles (EVs), prosumer, group, environmental performance, self-consumption rate

I. Introduction

The purchase period of the surplus electricity of residential PV systems under feed-in tariff law is ten years, and the number of residential PV systems those purchase period expire will increase gradually from November 2019 in Japan. Therefore, prosumers may start shifting to a self-consuming lifestyle and using storage batteries for effective use of PV.

On the other hands, EVs are spreading worldwide due to rising environmental awareness. Some residents may use EV battery as home power supply and thus EVs contribute to self-consumption of PV. Such use is called Vehicle-to-Home (V2H). Currently the majority of power source in Japan is thermal power, so EVs are not particularly environmentally friendly in terms of Well-to-Wheel in case of charged by the Japanese grid.

In this paper, we proposed storage battery operation that aims to improve the self-consumption rate of PV energy, and consider the effect of V2H and aggregators (AGs). AGs bring multiple prosumers together and adjust their supply-demand balance. In case operating prosumers as a group, all prosumers can share PV energy. Moreover, difference in residents' driving pattern will create an opportunity for EVs to be charged by PV energy.

II. System Architecture

A. *Ponsumers' model*

The system in this study consists of six components based on the system shown in [1] as shown in Fig. 1. Each house has residential PV, electrical load, stationary battery and EV. Also, all houses are connected to the distribution grid. Moreover, when multiple prosumers are operated as a group, all prosumers in the same group are connected to each other through the distributed grid. If a prosumer generates surplus power, the other consumers in the same group can effectively consume their surplus power. The power balance can be expressed as (1):

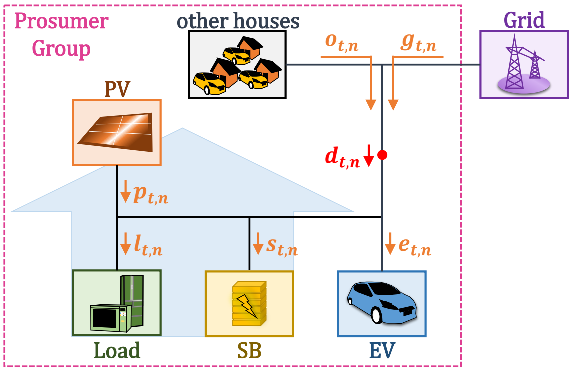

Figure 1. The system prosumer group

$$d_{t,n} = l_{t,n} + p_{t,n} + s_{t,n} + e_{t,n} = o_{t,n} + g_{t,n} \qquad (1)$$

where $d_{t,n}$ is the net demand at time *t*, $l_{t,n}$ is the electrical energy supplied to the load at time *t*, $p_{t,n}$ is the electrical energy generated from residential PV at time *t*, $s_{t,n}$ is the electrical energy charged to the stationary battery at time *t*, $e_{t,n}$ is the electrical energy charged to the EV battery at time *t*, $o_{t,n}$ is the electrical energy from other houses in the same group at time *t*, $g_{t,n}$ is the electrical energy from the distribution grid at time *t*, *n* is the number of houses or batteries.

It should be noted that a stationary battery and a EV battery are charged when $s_{t,n}$ and $e_{t,n}$ is in positive and discharged when $s_{t,n}$ and $e_{t,n}$ is in negative. In addition, $o_{t,n}$ is considered only when multiple prosumers were operated as a group. A consumer receives the power from the other prosumers in the same group when $o_{t,n}$ is in positive. A prosumer sends the surplus power to the other consumers in the same group when $o_{t,n}$ is in negative.

The operation of batteries should follow the constraints as below.

- Battery capacity limits of two batteries,

$$SOC_{t,n}^{sb-min} \leq SOC_{t,n}^{sb} \leq SOC_{t,n}^{sb-max} \qquad (2)$$

$$SOC_{t,n}^{ev-min} \leq SOC_{t,n}^{ev} \leq SOC_{t,n}^{ev-max} \qquad (3)$$

where $SOC^{sb}_{t,n}$ is the state of charge (SOC) of *n-th* stationary battery at time *t*. $SOC^{sb\text{-}min}_{n}$ and $SOC^{sb\text{-}max}_{n}$ are the minimum and maximum SOC limits of *n-th* stationary batteries respectively. $SOC^{ev}_{t,n}$ is the SOC of *n-th* EV battery at time *t*. $SOC^{ev\text{-}min}_{n}$ and $SOC^{ev\text{-}max}_{n}$ are the minimum and maximum SOC limits of *n-th* EV batteries respectively.

TABLE I. EV DRIVING PATTERN

	Pattern A : Weekend pattern		Pattern B : Four-day-a-week pattern		Pattern C : Weekday pattern	
	A1 ***Holiday leisure long distance type***	***A2*** ***Holiday leisure short distance type***	***B1*** ***Active driver type***	***B2*** ***Suburbs driver type***	***C1*** ***Long distance commuting type***	***C2*** ***Short distance commuting type***
Driving time	Sat.9am-Sun.9pm	Sat.10am-Sun. 8pm	10am-5pm	1pm-5pm	7am-7pm	8am-6pm
Driving distance	150km	50km	50km	5km	50km	15km
constraint time (EV battery)	Sat.12am-9am	Sat.7am-10am	7am-10am	12pm-1pm	4am-7am	7am-8am
Driving Constraint (EV battery)	82.5%	41%	41%	22.5%	41%	26.5%

- Charging and discharging rate limits of two batteries,

$$s^{min} \leq s_{t,n} \leq s^{max} \tag{4}$$

$$e^{min} \leq e_{t,n} \leq e^{max} \tag{5}$$

where s^{min} and e^{min} are the discharging rate limit of *n-th* stationary battery and EV battery respectively. s^{max} and e^{max} are the charging rate limit of *n-th* stationary battery and EV battery respectively.

B. EV driving Pattern

The purpose of using EV depends on the prosumer. Each prosumer uses an EV for different distances at different times. In this study, six driving patterns as shown in Table 1 are prepared to take the diversity of users into account. These driving patterns were set by referring to [2] and [3].

There are two ways to consider CO2 emissions from automobiles: Tank to Wheel considers CO2 emissions when driving. However, Well to Wheel considers not only driving but also considers CO2 emissions of the fuel from the well to the tank.

In the case of Well to Wheel, the environmental performance while driving EV depends on the environmental performance of the power supply while charging EV. Therefore, power sources with low CO2 emissions should be used when charging EVs. The environmental performance of EVs is better when it is charged by the energy from residential PV than when it is charged by the energy from thermal power supply. The difference in driving patterns provides the opportunity for the group's EVs to be charged with energy from residential PV. When surplus power is generated in a house without an EV, The power may be charged to EVs in other consumers in the same group.

The constraints about the SOC of EV batteries in each pattern are given to each EV. This constraint is called "Driving Constraint" in this paper. EV battery has this constraint during particular time. This constraint is set to maintain more energy in EV battery before driving time. As a result, EV users can drive on time, and the convenience for EV users can be ensured. Considering this constraint, EV battery capacity constraint is reformulated as follows:

$$SOC_{t,n}^{DC} \leq SOC_{t,n}^{ev} \leq SOC_{t,n}^{ev-max} \tag{6}$$

where $SOC^{DC}_{t,n}$ is the driving constraint of *n-th* EV battery at time *t*. $SOC^{DC}_{t,n}$ is equal to $SOC^{ev\text{-}min}_{t,n}$ if it is not the constraint time, but it is replaced with constraint value during the constraint time.

III. BATTERY OPERATION

The stationary batteries and EV batteries are operated to improve self-consumption rate of PV energy in the prosumer group. We consider the charging / discharging power in three steps and finally execute charging and discharging of batteries. Fig.2 shows an overview of battery operation. The batteries are operated in each time. If time *t* is the end time of simulation *T*, the battery operation ends.

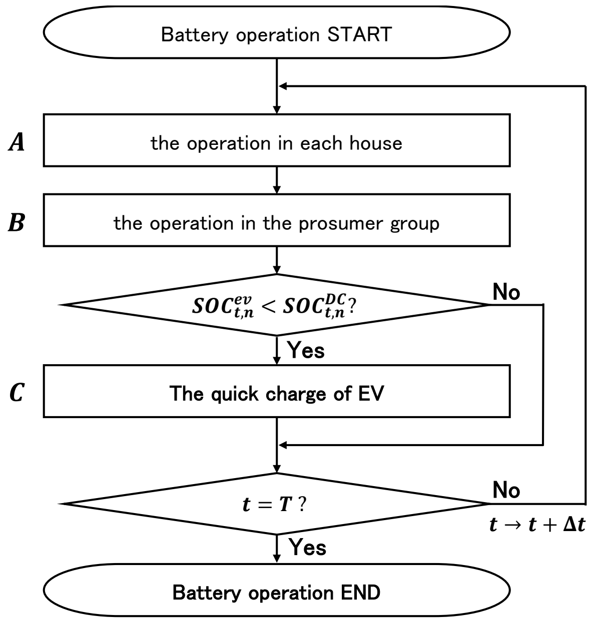

Figure 2. Flowchart of battery operation

A. Operation in each house

In this first step, all prosumers first consume their own PV power by home appliance. They use preferentially the power generated by residential PV for the load, and then consume it by operating stationary battery or EV.

The operation of the stationary batteries and EV batteries is determined according to the following two basic rules.

- Batteries are operated so as the net demand to be zero at all times as shown in Fig. 3.
- Keep sufficient SOC of EV battery for driving to ensure the convenience for EV users.

The batteries are discharged during the night and thus it can charge more PV energy during the daytime by first rule. Second rule is considered when a stationary battery and a EV battery are simultaneously operated. There are two storage batteries in a house so it is necessary to decide which one of two batteries is preferentially charged and discharged. First,

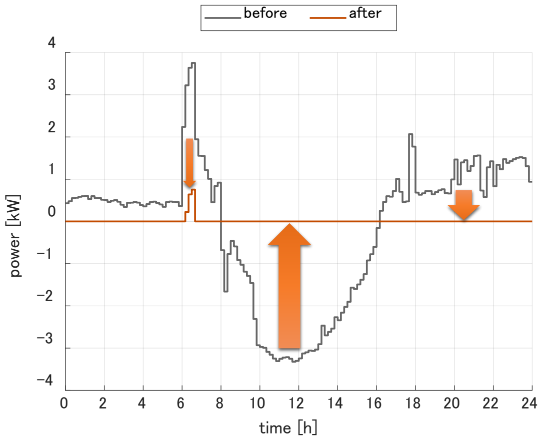

Figure 3. The net demand for one house on a day

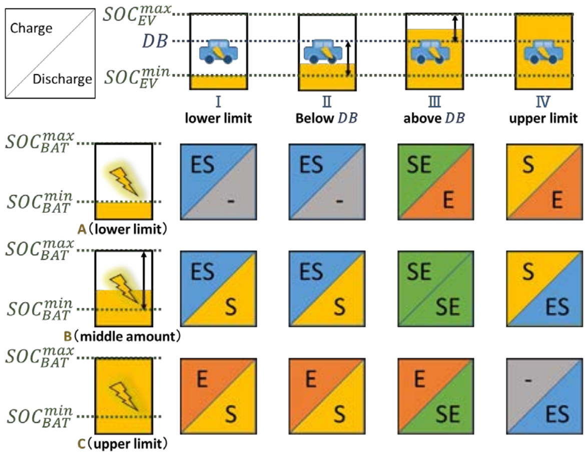

Figure 4. The state of two batteries and operation in each pattern

the stationary battery had three cases, and the EV battery had four cases as shown Fig, 4. The EV battery had one more SOC case than the stationary battery because of the Driving Constraint.

The stationary battery and an EV battery belong to either of above cases at any time. There were 12 combinations of two batteries in this study, and charge / discharge patterns were assigned to them. One charge / discharge pattern was assigned to each case, and thus five kinds of patterns were prepared for each of charge operation and discharge operation.

As shown in Fig. 4, The top left of each pattern represents the charging operation, and the bottom right represents the discharging operation. Each battery was charged when net demand is in negative and discharged when net demand is in positive. In addition, "E" means an EV battery was charged or discharged, "S" means a stationary battery was charged or discharged. Therefore, "ES" means a stationary battery was operated after an EV battery was operated. In each time zone, the storage battery operation was finally carried out by selecting an appropriate charge / discharge pattern. In other case, only stationary battery is charging / discharging when EV is out.

B. Operation in the prosumer group

After the operation in each house, some prosumers with surplus power send the surplus power to the other prosumers with insufficient PV power in the same prosumer group. Some prosumers generate surplus power, the other prosumers need more power at every time. It is natural because every prosumer has different lifestyles. When such consumers are aggregated into a consumer group, more PV energy may be consumed in the group by using this difference.

After operating batteries in each house, the surplus power, the shortage power, the net demand in the prosumer group is expressed as follows:

$$sP_t = \sum_{n=1}^{N} sp_{t,n} \tag{7}$$

$$sL_t = \sum_{n=1}^{N} sl_{t,n} \tag{8}$$

$$sD_t = sL_t - sP_t \tag{9}$$

where $sp_{t,n}$ and $sl_{t,n}$ are the surplus power and the shortage power of *n-th* prosumer at time *t*, sP_t and sL_t are the total surplus power and the total shortage power in the prosumer group at time *t*, sD_t is the net demand power in the prosumer group at time *t*.

The amount of power sent from prosumers with surplus power to consumers with insufficient power is determined by proportional distribution to each consumer's shortage ratio to total shortage, so the power in each house is expressed by (10).

$$if\ sD_t \geq 0\ \cap sL > 0$$

$$sp'_{t,n} = 0\,,\ \ sl'_{t,n} = sl_{t,n} - sP_t \times \frac{sl_{t,n}}{sL_t} \qquad (10-1)$$

$$else\ if\ sD_t < 0$$

$$sp'_{t,n} = sp_{t,n} - sL_t \times \frac{sp_{t,n}}{sP_t}\,,\ \ sl'_{t,n} = 0 \qquad (10-2)$$

$$else$$

$$sp'_{t,n} = sp_{t,n}\,,\ \ sl'_{t,n} = sl_{t,n} \qquad (10-3)$$

where $sp'_{t,n}$ and $sl'_{t,n}$ are the surplus power and the shortage power of *n-th* prosumer after the first group operation at time *t*. The shortage power $sl'_{t,n}$ is compensated with the purchased power from the grid.

If surplus power remains after the first group operation, such power is sent to EV batteries. At this time, the surplus power, the allowable charging power to the batteries and demand in the prosumer group is expressed as follows:

$$sP'_t = \sum_{n=1}^{N} sp'_{t,n} \tag{11}$$

$$sE_t = \sum_{n=1}^{N} se_{t,n} \tag{12}$$

$$sD'_t = sE_t - sP'_t \tag{13}$$

where $se_{t,n}$ is the allowable charging power to an EV battery of *n-th* prosumer at time *t*, $sE_{t,n}$ is the allowable charging power to EV batteries in the prosumer group.

The amount of power sent to the other consumers is determined by proportional distribution to each consumer's allowable charging ratio to total allowable charging power, so the power in each house is expressed by (14).

$$if\ sD_t \geq 0\ \cap sL > 0$$

$$sp''_{t,n} = 0\,,\ \ se'_{t,n} = se_{t,n} - sP'_t \times \frac{se_{t,n}}{sE_t} \qquad (14-1)$$

$$else\ if\ sD_t < 0$$

$$sp''_{t,n} = sp'_{t,n} - sE_t \times \frac{sp'_{t,n}}{sP'_t}\,,\ \ se'_{t,n} = 0 \qquad (14-2)$$

$else$

$$sp''_{t,n} = sp'_{t,n}\,,\ \ se'_{t,n} = se_{t,n} \qquad (14-3)$$

where $sp''_{t,n}$ and $se'_{t,n}$ are the surplus power and the allowable charging power of *n-th* prosumer after the second group operation at time *t.*

C. Quick charge of EV

EVs are used not only as storage batteries but also as a transportation. The SOC of EV must be more than the Driving Constraint at the beginning of driving. In this step. The SOC of all EV batteries are first checked. If an EV battery doesn't achieve the Driving Constraint, the EV battery is charged by the purchased power from the grid. Also, it is necessary to consider the maximum output of the inverter in this step. The power from the grid is:

$$g_{t,n} = \frac{e^{max} - oe^{ev}_{t,n} - og^{ev}_{t,n}}{\eta} \qquad (15)$$

where $g_{t,n}$ is the purchased power from the grid to *n-th* consumer at time *t*, $oe^{ev}_{t,n}$ is the power charged to *n-th* EV battery in operation in each house at time *t*, $og^{ev}_{t,n}$ is the power charged to *n-th* EV battery in operation in the prosumer group at time *t*, η is the charge efficiency of EV battery.

IV. Evaluation Indices

A. Self-consumption rate

One of the objectives of this study is the improvement of the self-consumption rate in the prosumer group. In this study, the sources of electricity consumed at each house are the residential PV and the distributed grid. Therefore, more power from residential PV should be consumed in the house and utility power from grid should be decreased. In addition, consumers send the surplus power to each other. If a prosumer generates the surplus power, the prosumer can send them to the other prosumers in the same group or the grid. When a prosumer sends the surplus power to the others, the sent power must be consumed by the consumers which receive the surplus power because the batteries will not discharge directly to the grid. However, such power is excluded from the self-consumption rate in one prosumer. On the other hand, they are included in the self-consumption rate in the group. Therefore, the self-consumption rate in one prosumer and in the prosumer group are expressed by (16) and (17), respectively.

$$SR_n = \frac{P^a_n - G^a_n}{P^a_n} \times 100 \qquad (16)$$

$$SR = \frac{P^a - G^a}{P^a} \times 100 \qquad (17)$$

where P^a_n is the total PV generation per year from *n-th* prosumer, G^a_n is the total power sent from *n-th* prosumer to the distributed grid per year, P^a is the total PV generation per year in consumer group, G^a is the total power sent from prosumer group to the distributed grid per year.

B. EV driving performance

The environmental performance while driving EV is evaluated by the ratio of PV energy and the power purchased from the grid in the power consumed during driving.

$$EP_n = \frac{E^{run}_n - E^G_n}{E^{run}_n} \times 100 \qquad (18)$$

here, EP_n is the environmental performance of *n-th* prosumer's EV, E^{run}_n is the total power consumed during driving of *n-th* prosumer's EV, E^G_n is the total the purchased power from the grid to *n-th* prosumer's EV.

C. CO2 emissions

CO2 emissions during power generation and driving are considered in this study. CO2 emissions are expressed as the product of CO2 emission coefficient and electric energy.

$$CE = CO2_C \times P \qquad (19)$$

here, the coefficient of CO2 emission is determined as shown in the Table. 2 for each type and case of electricity. These coefficients are based on [4].

TABLE II. The Coefficient of CO2 Emission

Content	**coefficient**	
	Case	***Value***
generation	PV power [g-CO2/kWh]	32.5
	Thermal power [g-CO2/kWh]	690
driving	EV (running by the PV power) [g-CO2/kWh]	Equal to PV power
	EV (running by the thermal power) [g-CO2/kWh]	Equal to thermal power
	GV(gasoline vehic) [g-CO2/km]	101

D. Power procurement cost

We calculated and compared the total electric energy fee for 1 year of residential houses. The cost can be obtained by (20). Cost of every term in below equation are expressed as the product of the unit price and electric energy.

$$C = C_P \cdot P^a_n + C_{O_r} \cdot {O_r}^a_n - C_{O_s} \cdot {O_s}^a_n + C_{G_r} \cdot {G_r}^a_n - C_{G_s} \cdot {G_s}^a_n \qquad (20)$$

Here, the unit price of each power is determined as shown in the Table. 3 for each type and case of electricity. These coefficients are based on [5]-[8].

TABLE III. Unit price of Each Power

Content	***Unit price* [JPY/kWh]**
PV power generated from residential PV	14
The power from the other prosumers	23
The power sent to the other prosumers	14
The power from the distributed grid	26
The power sent to the distributed grid	11

V. Simulation and Results

A. Used data and specifications of the home facility

The residential houses' demand data and PV generation data from [9] are used for the analysis. The data is a total amount of 534 houses with PV. The data is based on actual data of Ota City [10]. We made the number of EVs divided evenly to each pattern. Specifications of the home facility used for simulation are presented in Table. 4. In addition, Table. 5 summarizes the detail of each case considered in this study.

TABLE IV. Specification of Home Facilities

Content	*Value*
The capacity of Stationary batteries [kWh]	5
The capacity of EV batteries [kWh]	40
The minimum / maximum SOC of stationary batteries and EV batteries [%]	20 / 100
Charge / discharge efficiency [%]	90
EV fuel economy [km/kWh]	6
EV fuel economy [km/L]	23
Inverter maximum output [kW]	3

TABLE V. The Case Study

Case	**Content**	
	Operation	***Vehicle***
1	As a group	EV (V2H)
2	Each house	EV (V2H)
3	Each house	GV

B. The effect of operation as a group for demand

Fig. 5 shows the net demand $d_{t,n}$ in *302-th* house on three consecutive days in winter. This prosumer's EV was assigned to the driving pattern *A1*. The prosumer generated less surplus power in the case of the battery operation as the prosumer group than in the case of the battery operation in each house. Surplus electricity during the day were charged to the stationary battery or the EV battery and their power were used to meet the demand at night in the first day.

In Case2 and 3, there was a time when EV charging demand suddenly appears early in the morning in the second day because an EV battery was charged by the power from the grid. The power from the grid was less when prosumers were operated as a group than when they were operated individually.

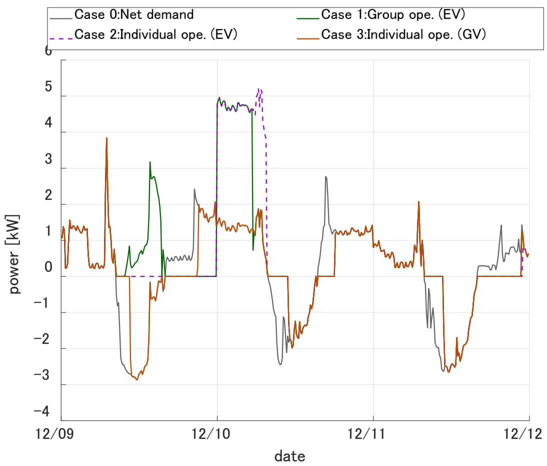

Figure 5. The net demand for one house on a weekend in winter

C. Oparation as a group and an EV

Fig. 6 shows the power from the other prosumers $o_{t,n}$ and the grid $g_{t,n}$ in *302-th* house on three consecutive days in winter. Moreover, Fig. 7 shows the SOC of EV battery on the same days as Fig. 6. In the first day, this consumer's EV was charged by the power from the other consumers in the same group at noon. Therefore, the SOC of EV at the end of the first day is higher when prosumers were operated as a group than when they were operated individually. In addition, EV battery discharged to the home appliance at night.

In weekend, the EV battery charge less power from the grid in the case of the battery operation as the prosumer group than in the case of the battery operation in each house, so more PV energy in EV battery was used for driving than case 2. In addition, surplus electricity by this prosumer was sent to the other consumers in the same group while the prosumer was going out using EV.

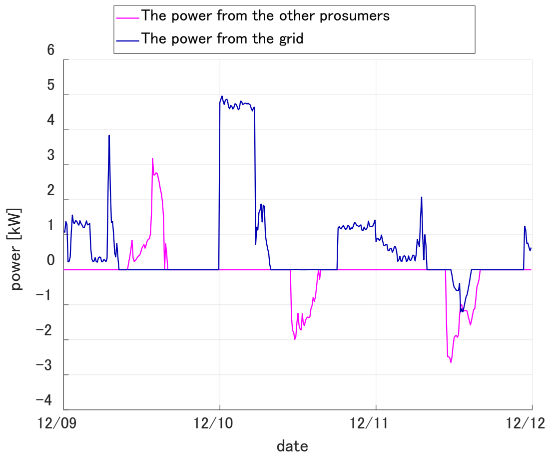

Figure 6. The power from the other prosumers and the grid in *302-th* house.

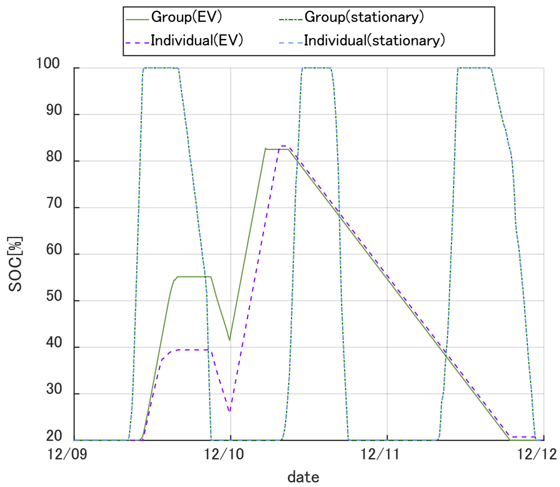

Figure 7. The comparison of the SOC of batteries in case 1 and 2

D. Evaluation indices

Fig. 8 shows the self-consumption rate of each house in the case of each operation by box plot. The top 5% of data and bottom 5% of data are plotted outside the box, respectively. The self-consumption rates were improved by operating prosumers as a group than by operating each prosumer. The self-consumption rates were over 90% in more than half of prosumers when prosumers were operated as a group. The self-consumption rates were improved in all houses except for *112-th* house. The self-consumption rate of *112-th* house was decreased by approximately 0.5%, but its value was 96.3%. The minimum value of self-consumption rates in the group was 86.9% in case 1 and this value was improved by 37.7% than that of case 2.

Fig. 9 shows the environmental performances of EVs. Case 3 was excluded from this figure because gasoline vehicles were used in that case. The environmental performances of EVs were improved when prosumers were operated as a group than they were operated individually. In the aggregated consumers, the approximately 90 % of the fuel of EVs is PV energy. The median value was 91.7% in case 1 and this value was improved by 3.9% than that of case 2.

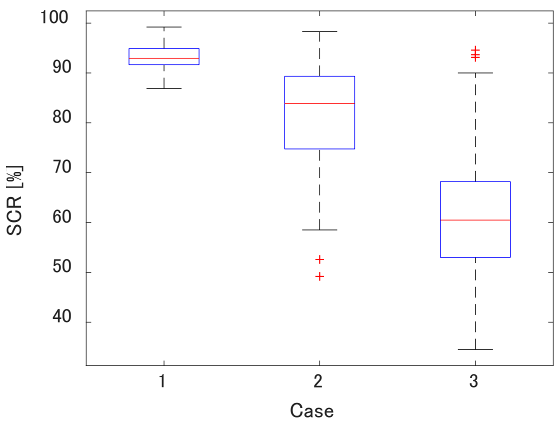

Figure 8. Boxplot of the self-consumption rate

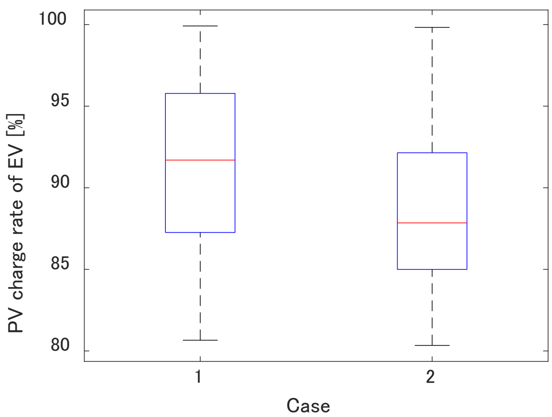

Figure 9. The environmental performance of EV

Table. 6 shows the result in the group. The self-consumption rate of PV energy was improved by 1.15 times by operating prosumers as a group. In addition, CO2 emission was reduced by approximately 14 % and electricity cost is reduced by approximately 40,000 yen per year compared with the operation in each house.

TABLE VI. RESULT SUMMARY

case	***Self-consumption rate* [%]**	***CO2 emission* [t-CO2]**	***Cost* [*millon* JPY]**
1	93.2	1101	8.01
2	81.0	1281	8.05
3	59.8	3005	19.6

VI. CONCLUSION

The optimal battery operation method to improve the self-consumption rate was proposed. The consumption rate of PV energy and the CO2 emissions was evaluated. As a result, the consumption rate of PV energy was improved by 1.15 times when multiple prosumers were operated as a group than when they were operated individually. Furthermore, CO2 emissions decreased and EV was charged by the more PV energy than the individual operation.

ACKNOWLEDGMENT

A part of this study was supported by CREST JST (issue number: JPMJCR15K1). We would like to thank everyone who supported this study.

REFERENCES

[1] Takaya Sadatome, Yuzuru Ueda, “Examination of improvement effect of self-consumption rate by introducing V2H system”, Grand Renewable Energy 2018 Proceedings.

[2] National road and street traffic situation survey, “FY2015 National road and street traffic situation survey / General traffic survey / summary table”, [Online]. Available: http://www.mlit.go.jp/road/census/h27/ (in Japanese)

[3] New Energy and Industrial Technology Development Organization, ”NEDO PV-Powered Vehicle Strategy Committee Interim Report”, January 2018. [Online]. Available: http://www.nedo.go.jp/content/100885777.pdf (in Japanese).

[4] Ministry of the Environment, Ministry of Economy, Trade, and Industry, Japan, “Emission factor by electric power company (for the calculation of greenhouse gas emissions of specified emitters) -FY2016 results-”, 18. Dec. 2017. [Online]. Available: https://www.env.go.jp/press/files/jp/109569.pdf (in Japanese)

[5] New Energy and Industrial Technology Development Organization, ”Solar power development strategy (NEDO PV Challenges)”, September 2014.

[6] The website of the Tokyo Electric Power Company (TEPCO), Japan, “About consignment fee equivalent, etc.”, 18. Dec. 2017. [Online]. Available: http://www.tepco.co.jp/ep/private/plan2/chargelist06.html (in Japanese).

[7] New Energy and Industrial Technology Development Organization, “Photovoltaic power generation roadmap for 2030”, 18. Dec. 2017. [Online]. Available: https://www.nedo.go.jp/content/100086787.pdf (in Japanese).

[8] The International Renewable Energy Agency, ”2017 renewable energy generation costs”, 2018. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_Summary_2018_JP_29052018.pdf?la=en&hash=BD0500DD2BE7C3779063E74F1248493D74AB98D6

[9] Eiki Arai, Yuzuru, Ueda, “Development of simple estimation model for aggregated residential load by using temperature data in multi-region,” 4th International Conference on Renewable Energy Research and Applications, #233, Italy, Nov. 22-25 (2015))

[10] S. Nishikawa and K. Kato “Demonstrative research on grid inte rconnection of clustered photovoltaic power generation systems” in Proc. 3rd WCPEC 2003, pp. 2652 2654.