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Impact of V2G Ancillary Services on the Spread of Variable Renewable Energy: Evaluation Using Electric Power System Simulation in Japan

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Summary

One barrier to the wider use of variable renewable energy (VRE) is the need for power system stabilization and reliability. In addition to smart charging or shift of energy charge/discharge, the use of electric vehicle (EV) batteries for ancillary services, known as Vehicle-to-Grid (V2G), is expected to solve this problem with its ubiquity and flexibility. Quantitative evaluations of the respective value in each country and region are necessary to encourage the spread of V2G. We modeled the effect of V2G on the integration of VRE, assuming a Japanese power system. Our results show that providing the capacity of load frequency control (LFC) by V2G can contribute to enhance economy, stability and reliability of the power system operation to realize a sustainable society.

Keywords: electric vehicle (EV), V2G (vehicle-to-grid), renewable, cost, environment

1 Introduction

Destabilization of power systems due to the variability and uncertainty of variable renewable energy (VRE) hampers the further deployment of VRE and the realization of a more sustainable society. This problem can be solved through the system integration of distributed power resources [1]. The use of electric vehicle (EV) batteries as a distributed and decentralized power resource for ancillary services is termed Vehicle-to-Grid (V2G) [2]. Many V2G technology demonstration projects have been conducted around the world [3], and some examples of successful participation in the power market have been reported [4]. Stakeholders need to understand and appreciate the quantitative evaluation of V2G to become more motivated to support the spread of V2G. This quantitative evaluation must adaptively consider future changes in the power supply and demand structure in each country and region. Reference [5] used a production cost simulation model of the Japanese power system and confirmed that the flexibility of the energy shift using V2G has both economic and environmental effects. In this study, we evaluate the impact of load frequency control (LFC) as one of the V2G ancillary services using the production cost simulation model of the Japanese power system developed by one of the authors [5]. We first review the economic and environmental value of LFC supply by non-operational EVs (V2G-LFC) under various power system assumptions. The value of V2G-LFC is then evaluated for cases when the available time of V2G is limited, such as by connecting only at the workplace during the daytime or at home during the night. The results of this research contribute to establishing the social value of V2G and the roll-out strategy of VRE and V2G.

2 Method

The Japanese power system is divided into ten areas that are connected through grid interconnector lines. In this study, we used an electric production cost simulation model that is formulated in a mix integer linear problem framework. The results showed the potential impact of EVs in Japan [5]. Our model optimized the amount of power generated by each generator and the charging/discharging operation of power storage. Production costs (equation (1)) can so be minimized according to the given power demand and power resource capacities. Constraints show the balance between supply and demand of energy per hour and the LFC capacity, the partial-load operation of the generators, and the capacity of the grid interconnector lines. The impact of V2G on supply and demand of electricity can be seen when reviewing EV driving and parking patterns, the state of charge (SOC) of EV batteries, and the total available power capacity of parked EVs. In this study, we considered the balancing of the LFC capacity as a constraint. This ensured that the available LFC capacity of the operating generators and the connected EVs exceeds, in each of the simulation time slot, the required LFC capacity calculated from the demand fluctuation, the photovoltaic (PV), and the wind power output.

As formulated in (1), unlike commercial electricity price-based valuations of V2G, this study values V2G based on the total annual production costs of a power system calculated from the costs of thermal power generators. This study does not consider the capital investment and maintenance costs of generators, transmission and distribution networks, and electric vehicle supply equipment (EVSE), and the operating costs of V2G aggregation.

$$\text{Minimize} \quad F = \sum_{t=1}^{8760} \sum_{i=1}^{N} P_{i,t} A_i + U_{i,t} B_i \qquad (1)$$

t: Time slot, N: Total number of power generator, $P_{i,t}$: Outputs of generator i at time t,

$U_{i,t}$: Unit commitment states of generator unit i at time t (0stop, 1start), A_i and B_i: Coefficients

3 Simulation Conditions

Considering the likely power system that will exist in Japan after 2030, we evaluate the effect of the total capacity of the VRE installed, required LFC capacity, and the flexibility of EVs using V2G.

3.1 Electricity Demand, Generation Capacity, and Interconnection Capacity

Figure 1 shows the average daily power demand in each region, assuming Japan post-2030. The power demand in each region was created by prorating the nationwide total power demand referenced from the long-term energy supply and demand outlook (2015) [6] based on the power generation results in FY2013. Table 1 shows the total annual demand in each region. EV power demand is not included and will be explained separately in section 3.3.

Figure 2 shows the assumed power generation capacity in each region. Table 2 lists the capacity of VRE (PV, wind) introduced, assuming two cases. The Base case of VRE capacity (PV: 103.4 GW, Wind: 32.2 GW) used the same assumption as the previous study [5]. PV was set based on prospects of feed-in-tariff (FIT)-certified capacity, and wind power was established based on the onshore and offshore potential and grid size of each area. The high case of VRE capacity (PV: 153.9 GW, Wind: 51.1 GW) was assumed as the midpoint of the VRE introduction of a previous study [7] as is expected for 2050. The generation capacities excluding VRE were determined based on new power plant construction and decommissioning referenced from long-term energy supply and demand outlook (2015) [6] and other publicly available information. The rated capacity, minimum load, and efficiency according to partial load characteristics were noted for each thermal power plant unit. A storage capacity of 8 hours, a minimum load of charge and discharge, and constant efficiency of 0.7 were assumed for each pumped storage hydro unit. Nuclear, biomass, geothermal, hydro, and cogeneration were treated as base load generation. The hourly power generation of these power plants was given exogenously and was excluded from the optimization target of the power generation in the optimization calculation.

Table 3 exhibits the capacity of inter-regional interconnection lines, considering the capacity of expansion planned by the end of 2030 [8]. The operational capacity differed depending on the forward and reverse directions. LFC ensuring through the inter-regional interchange was not considered in this study.

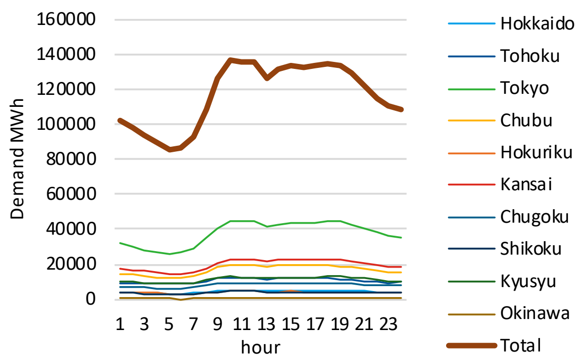

Figure 1: Average daily power demand

Table 1: Total power demand for 1 year

Name	Demand [GWh/y]
Hokkaido	36864.3
Tohoku	93256.5
Tokyo	330431.1
Chubu	147506.9
Hokuriku	33282.6
Kansai	171797.2
Chugoku	70871.4
Shikoku	33236.9
Kyusyu	98559.6
Okinawa	8344.1
Total	1024150.7

Table 2: Cases of PV and wind penetration capacity

	Penetration	Hokkaido	Tohoku	Tokyo	Chubu	Hokuriku	Kansai	Chugoku	Shikoku	Kyusyu	Okinawa	Total
Base	PV [GW]	4.5	13.5	27.4	12.9	1.8	14.2	7.5	3.6	17.3	0.6	103.4
	Wind [GW]	2.7	10.9	5.9	3.7	0.8	2.1	2.1	1.1	2.4	0.4	32.2
High	PV [GW]	6.8	20.3	41.1	19.3	2.7	21.3	11.3	5.4	26.0	0.9	155.1
	Wind [GW]	4.3	17.1	9.3	5.8	1.2	3.2	3.2	1.8	3.8	0.6	50.3

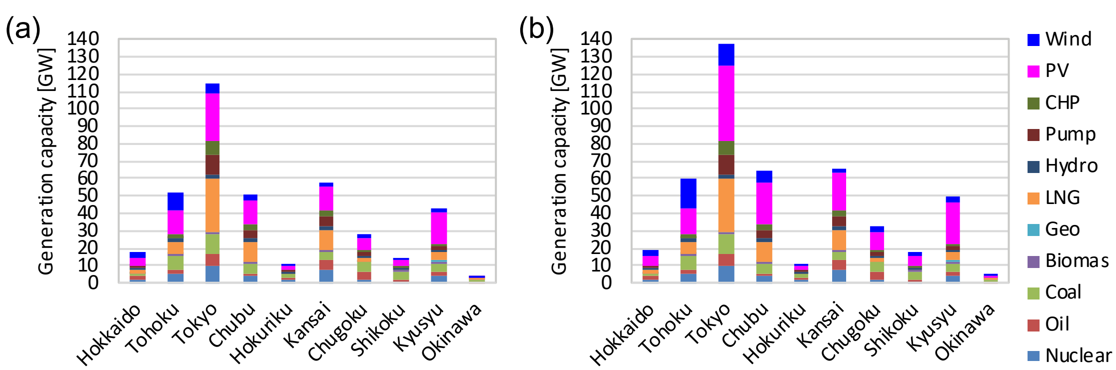

Figure 2: Generation capacity (a) Base case of VRE penetration (b) High case of VRE penetration

Table 3: Interconnection capacity

From	To	Energy Exchange Capacity [MW]	
		Send	Receive
Hokkaido	Tohoku	900	900
Tohoku	Tokyo	10280	2360
Tokyo	Chubu	3000	3000
Chubu	Hokuriku	300	300
Chubu	Kansai	1170	2500
Hokuriku	Kansai	1810	1300
Kansai	Chugoku	2780	4150
Kansai	Shikoku	1400	1400
Chugoku	Shikoku	1200	1200
Chugoku	Kyusyu	210	2780

3.2 LFC Capacity

3.2.1 Required LFC Capacity

Future LFC requirements are affected by both local characteristics of the installation area and the development of adjustment technologies within VRE. Measurements and analyses started, but this effort has not been enough. The required LFC capacity in each area was simply assumed as a linear sum of the capacity in proportion to hourly demand, solar power, and wind power. Two assumed cases are shown in Table 4. One is the Base case from previous studies [5], and the other is the low case, assuming that the required capacity is small due to the introduction of PV with adjustment technologies.

Table 4: Required LFC capacity Cases

	required LFC capacity
Base	±2% of the hourly demand fluctuation, ±10% of the PV output, and ±5% of the wind power output
Low	±2% of the hourly demand fluctuation, ±5% of the PV output, and ±5% of the wind power output

3.2.2 Deliverable Available LFC Capacity

The available LFC capacity was calculated from the rated capacity of the operating power plant (thermal, hydro, pumped storage) and the charge and discharge capacity of the EVs that are connected to the grid. The available LFC capacity of the generators was set to ±5% of the rated capacity of thermal power (coal, oil, liquefied natural gas (LNG)), ±20% of hydropower, ±20% of pumped storage in generating mode and ±20% of variable speed pumping in both generating and pumping modes. We assumed that, the coal power plants which are currently rarely supplying LFC capacity in Japan, supply it in the future. The available LFC capacity from EVs is described in the following section.

3.3 EV

We evaluated charging and discharging control (V2G) in reference to personal passenger EVs. Table 5 shows the number of private passenger cars in Japan in 2016. It is estimated for 2030 that 16% of personal vehicles in each region will be converted to electrically powered vehicles (8.96 million EVs nationwide) [6]. The EV driving pattern and parking time, and locations for each region were set based on the nationwide survey of road traffic in Japan [9], assuming the current characteristics of passenger cars will be the same. In Figure 4 (a) and (b), the hourly existence ratio of EVs at home or workplace, and the driving demand of each vehicle are shown on a national average for weekdays and holidays. The average annual mileage was 5326.5 km/year. With an EV efficiency of 7 km/kWh and the charging efficiency of 0.9, the annual power demand of the EV was 894.7

kWh/year. Estimating that the EVs start to charge 3.0 kW immediately after they return from a day trip, the "dumb" charging pattern sufficient for the driving demand was set in figure 4 (c).

We examined the purpose of two types of V2G: V2G-kWh that performs an energy shift in one hour, and V2G-LFC that supplies LFC capacity. In the case of simultaneous operation, we denoted it as V2G-kWh & LFC. The settings for each control were as follows:

- **V2G-kWh**: All EVs participated in V2G and were considered as one huge battery composed of EVs. We assumed that V2G was possible for EV at home and workplace. The EV specifications include the battery size of 40 kWh and the charge/discharge capacity of 3 kW; the efficiency was set to 0.9 / 0.9. The constraints of SOC included the power demand for driving per hour that was consumed from the battery each time (EV efficiency was set at 7 km / kWh). The SOC is always 0 or more and set to 50% for the end of the day. The upper limit of charge/discharge capacity was assumed to the product of 3 kW and the number of parked EVs.
- **V2G-LFC:** The ratio of vehicles that supply LFC was assumed at 7.5% in each area. This ratio is equivalent to the expected value of cars with an operating rate of less than one day per week in non-operated cars [10]. The EV penetration rate was set at 16%, so 672,000 EVs (56.01 million * 16% * 7.5%) could potentially supply LFC. The available LFC capacity per EV was set to ± 3 kW (total capacity: ± 3 kW * 672,000 EVs = ± 2016 MW). Based on the types of aggregated parked vehicles, the time ranges for supplying LFC capacity consisted of three types:
  - 1. *Non-operated cars: 0:00 - 24:00 on weekdays and holidays (8760 hour/year)*
  - 2. *Commuting cars at the workplace during the day: 9:00 - 17:00 on weekdays (1936 hour/year)*
  - 3. *Cars connected at home during the night: 23:00 - 5:00 on weekdays and holidays (2190 hour/year)*

  For purposes of comparison, the total available LFC capacity was set to 2016 MW, regardless of the type of vehicle.
- **V2G-kWh&LFC**: All EVs participate in V2G-kWh, while concurrently 7.5% of EVs participate in V2G-LFC. The capacity range of the EVs that perform two types of V2G simultaneously from -6 kW to +6 kW is within the specification range of a general bidirectional EVSE [11].

Table 5: Private passenger vehicles (million) by region

Hokkaido	Tohoku	Tokyo	Chubu	Hokuriku	Kansai	Chugoku	Shikoku	Kyusyu	Okinawa	Total
2.55	6.18	16.27	8.57	1.78	7.46	3.86	2.03	6.57	0.76	56.01

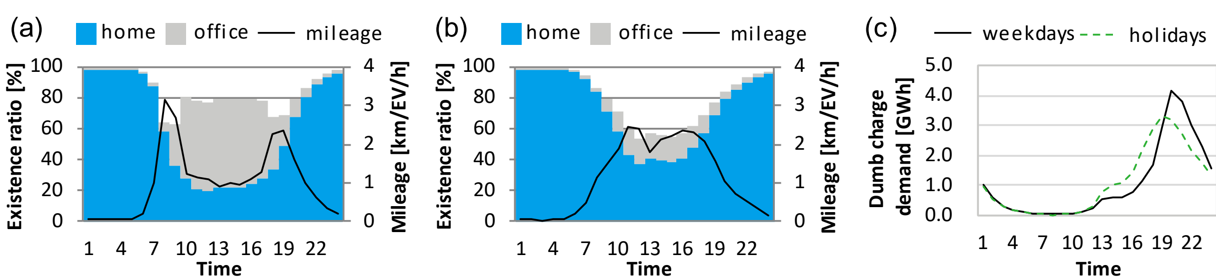

Figure 4: Average daily characteristics of EVs: (a) Hourly existence ratio and mileage per EV on weekdays, (b) Hourly existence ratio and mileage per EV on holidays, (c) Total electricity demand of dumb charging assuming 16% penetration

3.4 Simulations

Case A for V2G in table 6 was evaluated economically and environmentally using the production cost simulation model. Two cases were reviewed for VRE penetration and required LFC capacity and three cases of the EV control methods in each power system (12 conditions in total). The vehicles that perform V2G-LFC were non-operating vehicles.

Table 6: Simulation case A for evaluation of the value of EV control

Case name	VRE penetration	Required LFC capacity	EV control
A1 - A4	Base / High	Base / Low	dumb
A5 - A8	Base / High	Base / Low	V2G-kWh
A9 - A12	Base / High	Base / Low	V2G-kWh&LFC (non-operated cars)

Case B is shown in table 7. The value of LFC was evaluated when the available time of V2G was more limited, such as when the EV were only connected at the workplace during the day or only at home during the night. The Base case is a typical electric power system. The value of V2G-LFC differed with the types of vehicle that supplied LFC; the LFC supply time was different.

Table 7: Simulation case B for evaluation of aggregated EV type

Case name	VRE penetration	Required LFC capacity	EV control
B1	Base	Base	V2G-kWh&LFC (commuting cars at workplace)
B2	Base	Base	V2G-kWh&LFC (at home at night)
B3	Base	Base	V2G-kWh&LFC (non-operated cars)

4 Results & discussion

4.1 Evaluation of the Value of EV Control for System Integration

Figure 7 shows the annual fuel cost, CO_2 emissions, and the ratio of VRE curtailment nationwide for case A. The upper and lower borders of the rectangles indicated the value range taken depending on required LFC capacity (upper border: Base case, lower border: low case). The color of the rectangle indicated the cases of EV control. V2G-LFC could reduce fuel cost, CO_2 emissions, and the ratio of VRE curtailment, compared to V2G-kWh in all cases of power systems. In the case of high VRE penetration and large LFC capacity requirement, the value of V2G-LFC (different from V2G-kWh) was higher. This means that a higher value of V2G-LFC promotes the spread of VRE because of higher effectiveness in power systems with VRE curtailment.

Changes per vehicle in fuel cost, CO_2 emission, and VRE curtailment are shown in Figure 8. The value of V2G-kWh was calculated by dividing the difference from the dumb charge in Fig. 7 by the total number of EVs (8.97 million). The V2G-LFC value was calculated by dividing the difference from the V2G-kWh in Fig. 7 by the number of EVs that supply LFC (652,000 EVs). The effect of V2G-LFC was greater than V2G-kWh in all cases. Fuel cost reduction by V2G-LFC ranged from 1637 to 3130 USD/EV/year. This cost reduction represents the societal benefits from the decrease in thermal fuel cost, which is the upper limit of V2G business revenue and different from actual revenue. Revenue calculation is out of scope in this report, which should be considered including EVSE equipment cost, aggregator operation cost, price in the electricity market, and bidding strategy for other resources, etc. CO_2 emission reduction by V2G-LFC ranged from 9.6 to 30.8 ton/EV/year. The average conventional vehicle for Japan fueled by gasoline emits approximately 1,065 kg/year of CO_2 (the average mileage is 5326.5 km/year, the fuel efficiency is 11.9 km/L [12], the CO_2 emission intensity of gasoline is 2.38 kg/L).

That means one EV with V2G-LFC could reduce the CO_2 emissions of 9 to 29 such conventional vehicles. VRE curtailment reduction by V2G-LFC ranged from 14.3 to 47.5 MWh/EV/year. The reduction of VRE curtailment by one EV with V2G-LFC equaled to the power demand of 16 to 53 EVs since the power demand of EV is 894.7 kWh/year. When the reduction values in Fig. 8 were converted to the ones per available V2G-LFC capacity, the fuel cost ranged from 545.6 to 1043.3 USD/kW/year, CO_2 ranged from 3.2 to 10.3 ton/kW/year, and VRE curtailment ranged from 4.8 to 15.8 MWh/kW/year.

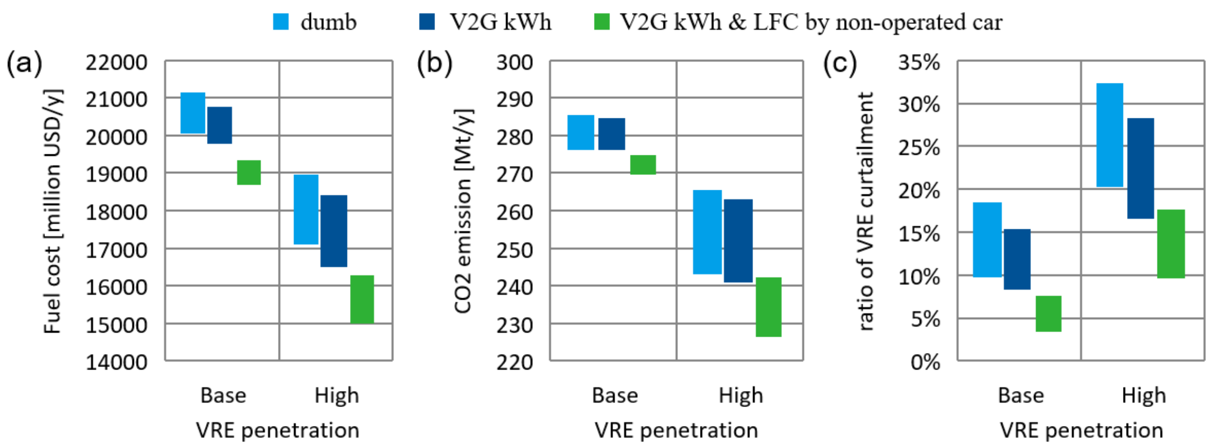

Figure 7: Economic and environmental impact of EV control on the national power system for Case A
(a) Fuel cost, (b) CO_2 emission, (c) Ratio of VRE curtailment

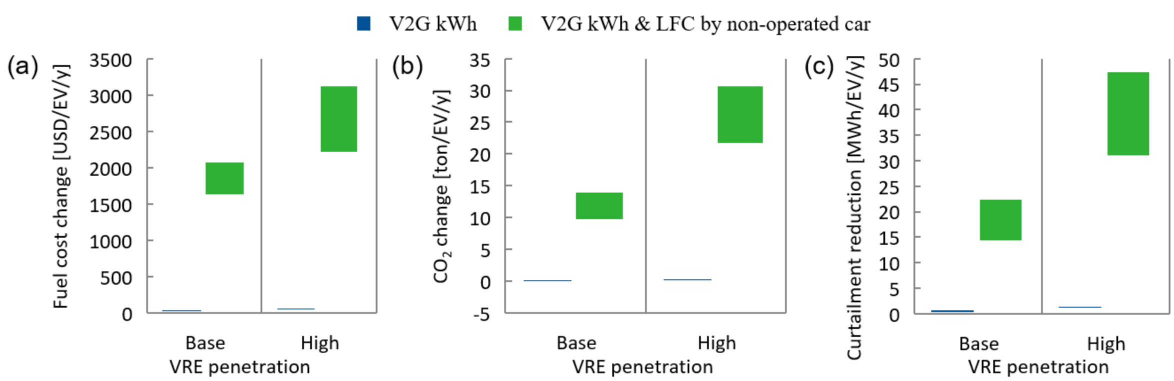

Figure 8: Economic and environmental value per EV of V2G-kWh and V2G-kWh & LFC by evaluation of Case A
(a) Fuel cost, (b) CO_2 emission, (c) VRE curtailment amount

Figures 9 and 10 show the average daily patterns of the supply and demand balance in kWh and the ensuring LFC capacity with each EV control for the Base case power system (VRE penetration: “Base”, Required LFC capacity: “Base”). In figure 9, the “net load” indicates the demand curve, subtracting PV, wind power generation, co-generation, and interchange power from original demand. The “adjusted net load” indicates the demand curve by reflecting the curtailment for VRE output, as well as the optimal EV charging and discharging. In Figure 9 (b), the EVs charged the VRE output that had been curtailed with a dumb charge of Figure 9 (a) during the day and discharged at the peak time of demand in the evening by optimal EV control with V2G-kWh. The resulting thermal load and the adjusted net load were more flattened than those of Figure 9 (a). The LFC capacity from

V2G-LFC reduced the supply of LFC by thermal power generation, as seen in Figure 10 (c). Consequently, the fuel consumption associated with the low-load and low-efficiency operation that occurs during LFC supply was reduced. The balance of supply and demand was established at low cost by replacing high-cost energy from inefficiently operated thermal power plants with VRE, which had been the target of curtailment. The charging and discharging of pumped storage power plants, which has a loss of 30% were mitigated by charging and discharging of EVs, because the loss of V2G is about 20%. This reduced fuel consumption and production costs further. It was confirmed that V2G-LFC in Fig. 9(c) reduced coal power by 5.2 TWh/year and LNG power by 15.8 TWh/year compared to V2G-kWh in Fig. 9(b).

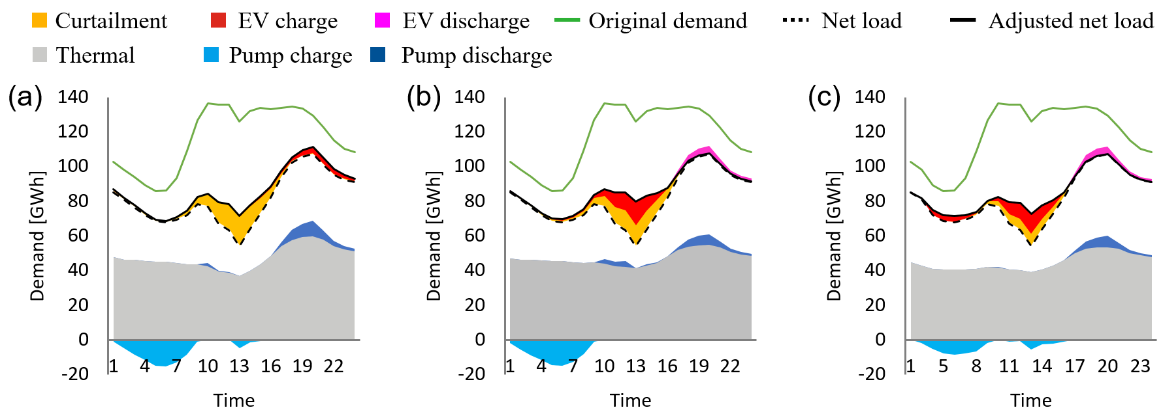

Figure 9: Average daily energy balance with EV control on Base case power system (a) dumb charge, (b) V2G-kWh, (c) V2G-kWh&LFC by non-operated car

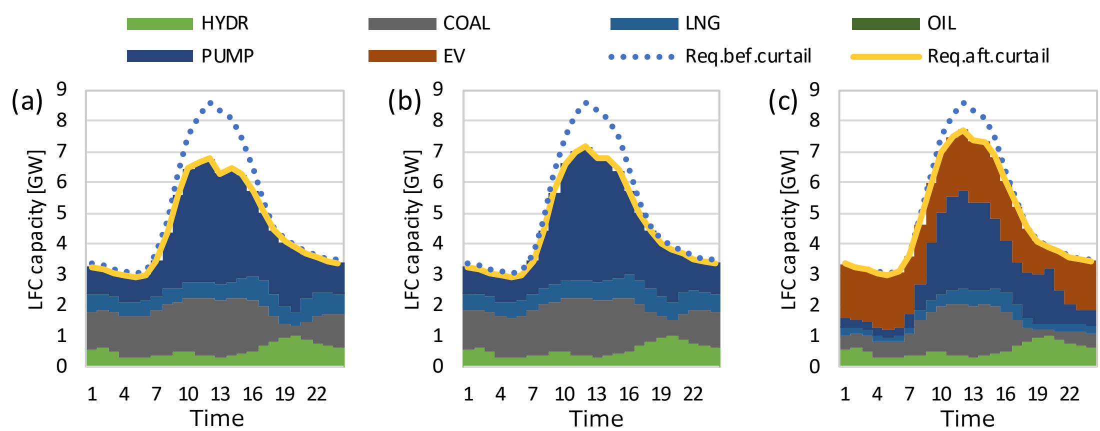

Figure 10: Average daily LFC capacity balance with EV control on Base case power system (a) dumb charge, (b) V2G-kWh, (c) V2G-kWh&LFC by non-operated car

In this study, the evaluation was based on one assumption that a total of 2016 MW in LFC capacity could be supplied from EVs. The maximum required LFC capacity of the Japanese power system was approximately 8600 MW (see the required LFC capacity before VRE curtailment in Fig. 10). If the available LFC capacity is larger, the value of V2G-LFC decreases. The same applies when the available LFC capacity by resources other than thermal power (stationary storage batteries, self-control of VRE, other demand response technologies, etc.) is larger. If the power system has enough flexibility and VRE curtailment is smaller, the value of LFC supply would be lower.

4.2 Influence of Supply Time on the Value of LFC

As a result of case B, Figure 11 shows the average daily LFC balance with V2G-LFC by daytime commuting EVs or parked cars at home during the at night. In Fig. 11(a), the V2G-LFC from commuting EVs contributed to a reduction in the curtailment of PV generation, the required LFC capacity increased during the day. In Fig. 11 (b), the LFC supply from parked cars at home at night reduced the LFC supply from the thermal power and the pumped storage plant. The result of case B3 (V2G-LFC by non-operated EVs) was already shown in Fig. 10 (c). Figure 12 shows the annual fuel costs, CO_2 emissions, and the ratio of VRE curtailment for each case. The results of V2G-kWh are indicated by dotted lines for comparison. The effect of V2G-LFC (difference from V2G-kWh) was greater in the order of V2G-LFC with non-operated cars, V2G-LFC with commuting cars during the day and V2G-LFC at home during the night. V2G-LFC at home at night reduced fuel costs due to improved thermal efficiency, but the VRE curtailment during that time was minor, so the effect of reducing CO_2 emissions and ratio of VRE curtailment was small. In other words, it was found that the value of V2G-LFC increased during the time when VRE curtailment occurred.

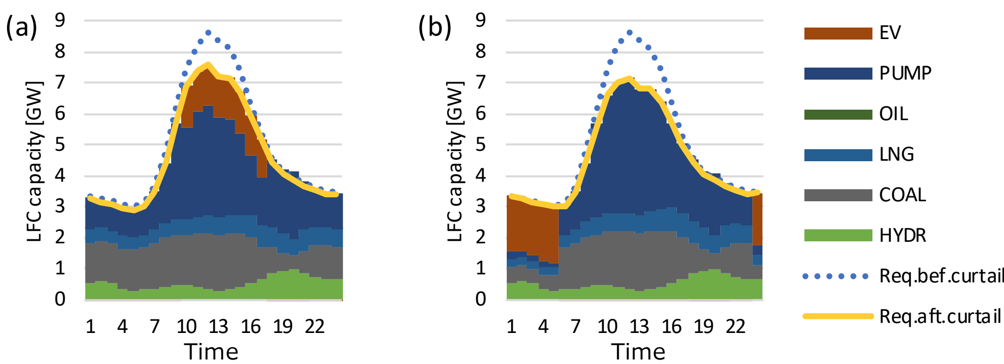

Figure 11: Average daily LFC capacity balance with EV control on Case B
(a) V2G-kWh&LFC by commuting cars parked at the workplace, (b) V2G-kWh&LFC by parked cars at home at night

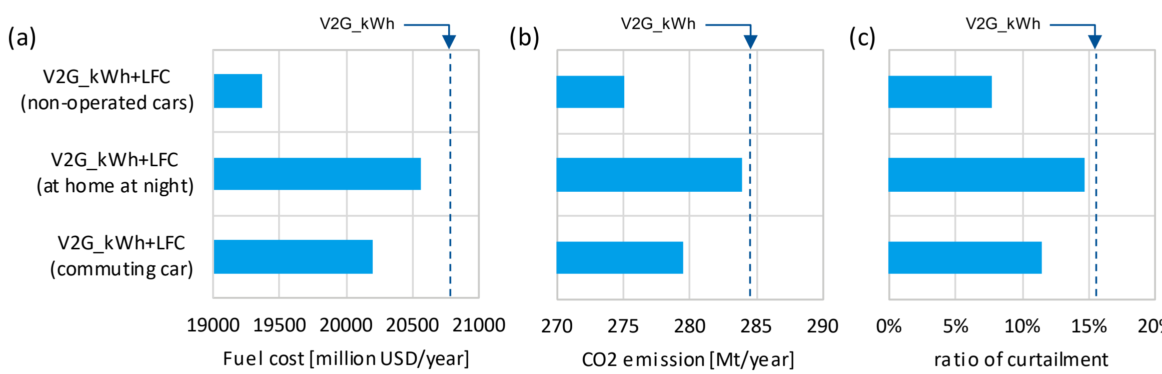

Figure 12: Effect of V2G-LFC type on economic and environmental value on Base case power system (a) Fuel cost, (b) CO_2 emission, (c) Ratio of VRE curtailment

There are probably more EVs in the workplace than EVSEs. It is thought that V2G-LFC by commuter car can secure a high plug-in rate in the daytime. V2G at home would be affected by the owners use schedule. If the daytime plug-in rate of non-operated vehicles for V2G-LFC cannot be secured, the situation of the V2G-LFC will be similar to that of the V2G-LFC at home by night. The value of V2G-LFC with cars parked at workplace and with non-operated cars at home all day can be reversed by daytime plug-in rates. The changes from V2G-kWh by V2G-LFC in Fig. 12 were rearranged as the value of V2G-LFC per EV. Figure 13 plots the value of V2G-LFC with each type of EV. This assumes that the number of EVs supplying LFC during the day was proportional to the daytime plug-in rate. In Fig. 13, the horizontal axis represents the plug-in rate from 5:00 to 23:00, and the plug-in rate from 23:00 to 5:00 is assumed to be 100%. That is, the value of V2G-LFC at home during the night was plotted where the daytime plug-in rate was 0%, and the value of V2G-LFC by non-operated cars was plotted where the daytime plug-in rate was 100%. Additional calculation was made at the daytime plug-in rate of 50%, and all the results were smoothly connected by a dotted line as in the Figure 13. The figure shows that the daytime plug-in rate at which the effect of V2G-LFC at home was greater than that at the workplace was as follows: fuel cost of 24% or more, CO_2 emissions of 45% or more, and VRE curtailment of 40% or more. If non-commuting EVs with a higher plug-in rate cannot be aggregated, aggregating commuter cars parked and plugged in at the workplace is considered more efficient.

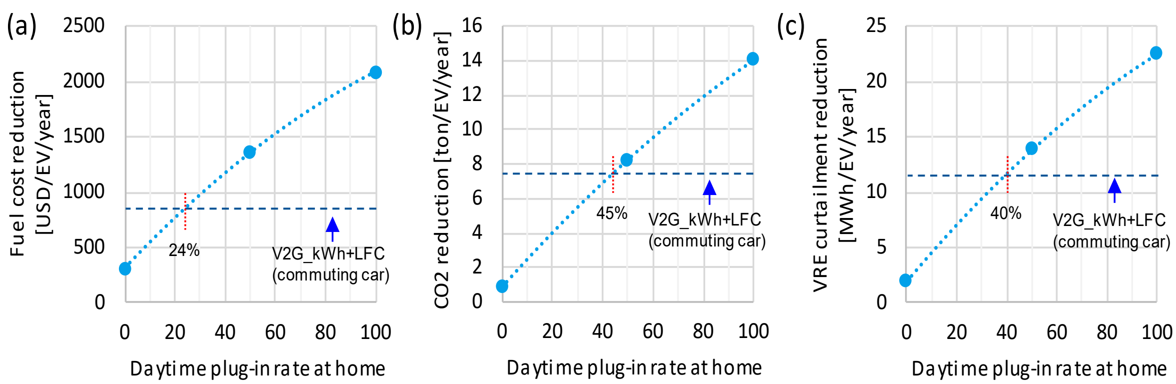

Figure 13: Influence of daytime plug-in rate on the value of V2G-LFC (a) Fuel cost, (b) CO_2 emission, (c) VRE curtailment

5 Conclusion

We evaluated the impact of LFC supply by V2G (V2G-LFC) on the spread of VRE by analyzing its economic and environmental value using production cost simulations for power systems in Japan starting in 2030. Our findings are:

- The social economic and environmental value of V2G-LFC stems from the mitigation of inefficient operation of thermal power generation in conventional LFC supply.
- Power systems that lack flexibility and have high curtailment of VRE and the required LFC capacity benefit the most from V2G-LFC by mitigating the curtailment and contributing to the expansion of VRE penetration.
- In our simulated case, the value of V2G-LFC with non-operated EVs was evaluated as an equivalent in reduction in fuel costs of 2084 USD/EV/year, CO_2 emissions of 14 ton/EV/year, and VRE curtailment of 22.5 MWh/EV/year.
- Non-operated private car aggregates for V2G LFC are most effective. Whenever this cannot be achieved during the day at home, V2G at the workplace may be more effective. The vehicle selection strategies need to be continually considered based on quantitative analysis.

In the next steps, we will work on the frequency control function of the VRE itself, the impact of LFC capacity trade over an interconnection line, the use of a stationary battery previously installed for other purposes, and comparison with other demand response technologies will compete for EV evaluation.

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