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# Assessing the potential of vehicle-to-grid (V2G) systems using dynamic simulation and life cycle assessment

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## ABSTRACT

The increasing deployment of variable renewable energy (VRE) is essential for achieving a sustainable society; however, its inherent variability poses challenges for maintaining a stable electricity supply. Vehicle-to-grid (V2G) technology enables bidirectional electricity exchange between electric vehicles (EVs) and the power grid and can enhance the utilization of renewable electricity by charging EVs during periods of VRE output curtailment. This study developed a regional V2G system model and evaluated its potential through energy flow simulations and life cycle assessment (LCA). The model explicitly considered hourly operation schedules of individual EVs, the spatial distribution of V2G infrastructure, and minimum output constraints of thermal power generation. The number of EVs is assumed to increase to up to 10, 000 units. In the energy flow simulations, EV charging and discharging were calculated on an hourly basis over one year. LCA was conducted to assess greenhouse gas (GHG) emissions of regional V2G system. Fuel consumption, VRE utilization, and GHG emissions were quantitatively evaluated. The results demonstrated that regional V2G systems could reduce VRE output curtailment and GHG emissions and, under certain conditions, could also reduce thermal power generation. The developed model enabled a quantitative evaluation of the potential of regional V2G systems. For practical deployment, integrated regional platforms would be required to coordinate electricity flows and to manage financial transactions. By assessing the potential of regional V2G systems, this study would provide valuable insights to support the design and implementation of environmentally sustainable V2G systems.

**Keywords**: Electric vehicle, Variable renewable energy, Output curtailment, Energy flow simulation

## INTRODUCTION

To achieve a sustainable society, variable renewable energy (VRE) is being increasingly installed. However, the inherent variability of VRE makes it challenging to maintain a stable electricity supply. In some regions, VRE generation is curtailed when electricity generation exceeds demand. Electric vehicles (EVs), which are equipped with batteries, offer an opportunity to address this issue: charging EVs during periods of VRE output curtailment can enhance the effective utilization of renewable electricity. Furthermore, vehicle-to-grid (V2G) technology enables bidirectional electricity exchange between EVs and the power grid. Previous studies have shown that the deployment of V2G can reduce greenhouse gas (GHG) emissions, energy consumption and cost at national level [1].

However, the environmental impacts of introducing new energy supply technologies depend on the regional conditions, even for the same technology. Thus, energy systems should be designed considering the regional characteristics [2]. Tanegashima, an island in southern Japan, was the first region in Japan to experience VRE output curtailment. A previous study suggests that V2G deployment in Tanegashima has the potential to reduce GHG emissions [3]. However, that study does not consider the locations of V2G installation or the operational schedules of individual EVs.

In this study, we develop a regional V2G system model and evaluate its potential using energy flow simulations and life cycle assessment (LCA). A regional V2G system is defined as an energy system that integrates EVs and V2G technology within a target region. To evaluate the potential of the system, fuel consumption, VRE utilization, and GHG emissions are quantitatively evaluated under cases with and without EVs and V2G. The proposed model is applied to Tanegashima in Japan.

The model explicitly considers (i) hourly operation schedules of individual EVs, (ii) the spatial distribution of V2H/V2B infrastructure, and (iii) minimum output constraints of thermal power generation. By integrating dynamic energy flow simulation with LCA, the proposed approach enables a quantitative evaluation of the environmental performance of regional V2G systems.

# MATERIALS AND METHODS

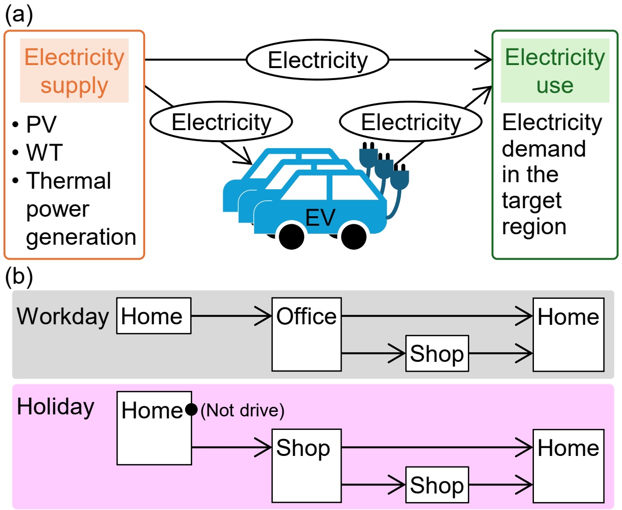
## Model of Regional V2G system

This study constructed a model of a regional V2G system in which EVs and V2G technologies are deployed within a target region. To evaluate the potential of V2G, a large number of vehicle-to-home (V2H) and vehicle-to-building (V2B) systems were assumed to be installed. **Figure 1** (a) shows the concept of the regional V2G system constructed in this study. EVs were assumed to replace internal combustion engine vehicles (ICEVs) and to utilize electricity derived from VRE as much as possible.

Electricity supply in the model consisted of photovoltaic (PV) and wind turbine (WT) as VRE sources and thermal power generation as shown in **Figure 1** (a). Thermal power generation was used to balance electricity demand and supply. Total electricity consumption was estimated based on electricity demand in the target region. The minimum output of thermal power generation is assumed to be unchanged before and after EV deployment. EVs were assumed to charge proactively during periods of VRE output curtailment and to discharge electricity to the power grid via V2H/V2B systems when VRE generation was insufficient.

The model is based on several simplifying assumptions. All EVs are assumed to be use for commuter and to return home every night and to be connected to V2H/V2B systems whenever available. Electricity prices and user-driven charging behavior are not explicitly considered.

Individual vehicle operation schedules and the commuting distances between homes and workplaces were defined. The operation schedules were assumed to be identical for EVs and ICEVs. **Figure 1** (b) shows the vehicle operation schedule and the list of installed equipment. On workdays, individuals were assumed to work from 9:00 to 17:00, with typical driving time at 8:00 and at 18:00. Some individuals randomly worked earlier or later than these hours and may stop at other locations, such as shops, on their way home. Each individual was assumed to have 20 days of paid leave per year, with the dates assigned randomly. On weekends and paid leaves, individuals were assumed either to stay at home (i.e., not drive) or to visit one or two shops. Destinations, departure times, and return times on these days were determined randomly.



Installed equipment

| Home | Office | Shop |
|---|---|---|
| Standard charger | Standard charger | Fast charger |
| V2H | V2B | Nothing |

**Figure 1**. (a) Concept of regional V2G system. (b) EV drive schedule and installed equipment list.

If an individual owned an EV, their home was assumed to be equipped with either standard EV charger or V2H system. The offices were similarly assumed to have either standard EV charger or V2B system, as shown in **Figure 1** (b). At shops visited after work or on holidays, the presence of EV fast chargers was assigned randomly. When EVs were parked at locations equipped with V2H or V2B systems, they were always assumed to be connected to those systems.

## Energy Flow Simulation

In the energy flow simulation, the amounts of EV charging and discharging were calculated on an hourly basis for one year. Based on these results, annual VRE output curtailment, EV electricity discharge to the power grid, electricity demand and thermal power generation were analyzed. Simulation cases were examined both with and without EVs and the V2G systems.

Electricity demand and supply must be balanced at all times to ensure stable grid operation; otherwise, disturbances in system frequency could compromise electricity supply. Before the introduction of EVs, the regional electricity demand at time $t$, $P^{\mathrm{use}}(t)$, was supplied by VRE-

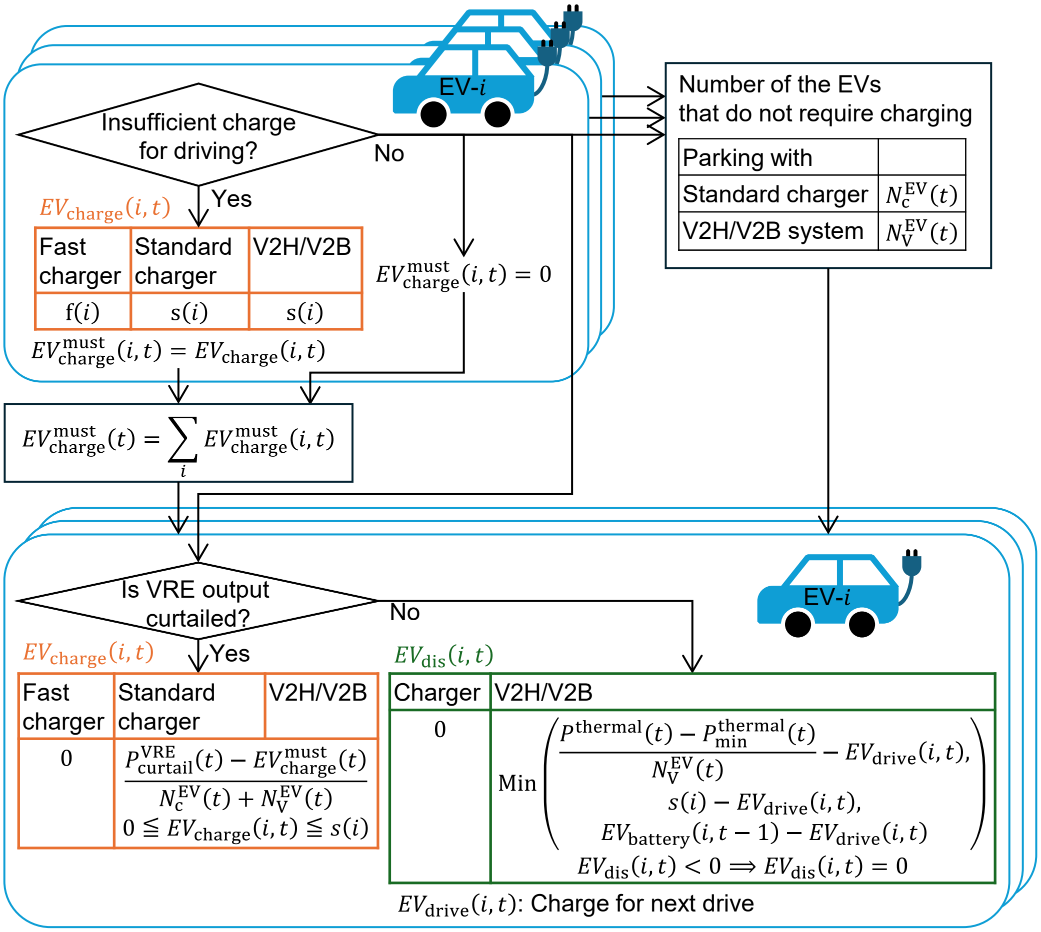


**Figure 2.** Procedure for determining the charge/discharge amount of EVs parked at the locations with chargers or V2H/V2B at time $t$. $f(i)$ and $s(i)$ represents charging speed of fast charger and standard charger, respectively.

based electricity, $P^{\mathrm{VRE}}(t)$, and thermal power generation, $P^{\mathrm{thermal}}(t)$ as expressed in Equation (1).

$$P^{\mathrm{use}}(t) \leqq P^{\mathrm{VRE}}(t) + P^{\mathrm{thermal}}(t) \tag{1}$$

In practice, left-hand and right-hand sides of Equation (1) are balanced. When VRE-based electricity generation was high, a portion of VRE electricity was curtailed because the output of thermal power plants could be reduced below a certain minimum level. The amount of VRE output curtailment, $P_{\mathrm{curtail}}^{VRE}(t)$, was calculated using Equation (2).

$$P_{\mathrm{curtail}}^{VRE}(t) = P^{\mathrm{VRE}}(t) + P_{\min}^{\mathrm{thermal}}(t) - P^{\mathrm{use}}(t) \tag{2}$$

Here, $P_{\min}^{\mathrm{thermal}}(t)$ represented the minimum output of thermal power generation. The minimum output was determined by various factors such as VRE electricity generation and electricity demand. In this study, $P_{\min}^{\mathrm{thermal}}(t)$ was assumed to remain before and after the installation of EVs. Similarly, baseline electricity demand excluding EV charging, $P^{\mathrm{use}}(t)$ was assumed to be the same regardless of EVs deployment.

Thermal power generation, $P^{\mathrm{thermal}}(t)$, was determined by the difference between the electricity demand and VRE electricity generation as shown in Equation (3). However, if this difference was smaller than minimum thermal output, thermal power generation was set equal to the minimum output:

$$P^{\mathrm{thermal}}(t) = \mathrm{Max}\left(P^{\mathrm{use}}(t) - P^{\mathrm{VRE}}(t), P_{\min}^{\mathrm{thermal}}(t)\right) \tag{3}$$

## Simulation for EV charging and discharging

EV charging and discharging behavior was mathematically expressed as follows. While driving, an EV discharges electricity in proportion to travel distance. When parked, an EV may charge or discharge depending on whether the parking location was equipped with a charger (including V2H/V2B systems) whether VRE electricity generation was being curtailed. The battery state of EV-$i$ at time $t$ was calculated using Equation (4).

$$EV_{\mathrm{battery}}(i,t) = EV_{\mathrm{battery}}(i,t-1) + EV_{\mathrm{charge}}(i,t) - EV_{\mathrm{dis}}(i,t) \tag{4}$$

Here, $EV_{\text{battery}}(i,t)$ represented the amount of electricity stored in the battery of EV-$i$ at time $t$, while $EV_{\text{charge}}(i,t)$ and $EV_{\text{dis}}(i,t)$ denoted the amount of charging and discharging at time $t$, respectively.

During driving, EV discharges according to the travel distance. When parked, the charging or discharging behavior was determined by whether the EV was parked at a location equipped with a charger or V2H/V2B system, and whether VRE output curtailment occurred at that time. If an EV was parked at a location without a charger or V2H/V2B, no charging and discharging occurs. When an EV was parked at a location equipped with a charger or V2H/V2B, the calculation procedure for $EV_{\text{charge}}(i,t)$ and $EV_{\text{dis}}(i,t)$ followed the process shown in **Figure 2**.

Before driving, EVs were charged based on the distance between the current parking location at time $t$ and the next destination that had a charger or V2H/V2B. The charging start time and required charging amount were determined by the travel distance. The total amount of electricity that all EVs must charge before driving is defined as $EV_{\text{charge}}^{\text{must}}(t)$ (see **Figure 2**). EVs that did not need to charge at time $t$ were available to function as distributed batteries for the power grid. The numbers of such EVs were counted as $N_{\text{c}}^{\text{EV}}(t)$ and $N_{\text{V}}^{\text{EV}}(t)$, depending on the parking location.

When VRE output was curtailed, EVs parked at the location equipped with standard chargers or V2H/V2B systems were charged. EVs were always connected to V2H or V2B when parked at homes or offices that had such equipment. When EVs were parked at homes or offices with standard chargers, they were charged at a high rate if the battery state of charge was below 50% or if VRE output curtailment occurred. When EVs were parked at locations with fast charger, which meant the EVs were parked at the shops, charging occurred only when the battery state of charge was low.

The amount of EV charging, $EV_{\text{charge}}(i,t)$ was adjusted according to VRE output curtailment, $P_{\text{curtail}}^{VRE}(t)$, and the numbers of EVs available as grid batteries, $N_{\text{c}}^{\text{EV}}(t)$ and $N_{\text{V}}^{\text{EV}}(t)$. The upper limit of $EV_{\text{charge}}(i,t)$ was set to $s(i)$, which represented the charging speed of the standard charger determined by charger performance.

EVs discharged electricity when VRE output was not curtailed and when they were connected to V2H or V2B systems. The discharge amount was calculated based on the controllable output of thermal power generation, $P^{\text{thermal}}(t) - P_{\text{min}}^{\text{thermal}}(t)$, the charging/discharging capacity of the charger, $s(i)$, and the amount of electricity stored in the EV battery, as shown in **Figure 2**. In addition, $EV_{\text{dis}}(i,t)$ was constrained to ensure that sufficient battery charge, $EV_{\text{drive}}(i,t)$, remained for the next driving event, thereby preventing situations in which the EV would need to be recharged immediately before driving due to insufficient remaining battery capacity.

The calculations were repeated on an hourly basis from 0:00 on January 1 to 24:00 on December 31. In cases with EV deployment, hourly values of VRE output curtailment, electricity discharged from EVs to the power grid, and total electricity demand (including EV charging) were calculated. Subsequently, thermal power generation output was determined to balance electricity demand and supply. Annual results were then compared between cases with and without the V2G system.

## LCA for the V2G system evaluation

LCA was conducted to evaluate GHG emissions before and after the installation of EVs. This study targeted electricity supply for the target region as well as vehicle production and operation. The functional unit was set as the annual electricity demand of the region together with the production and operation of vehicles. Vehicle operation schedules were assumed to be identical for EVs and ICEVs. The VRE capacity was assumed to be the same before and after EV deployment.

Foreground data, such as the amount of thermal power generation, were obtained from the energy flow simulations. Data related to vehicle production were derived from a previous study [4]. Background data, including thermal power generation and fuel consumption of ICEVs, were sourced from the Japanese LCA Inventory Database for Environmental Analysis (IDEA) Version 3.5.1 [5] and ecoinvent v.3.11 [6].

## Analysis Settings

This study focused on Tanegashima island, where VRE output was curtailed for the first time in Japan and where VRE output curtailment frequently occurs at present. Tanegashima has a population of approximately 27,000. Several cases were defined to compare the potential of the regional V2G system. **Table 1** presents five cases representing different configurations of EV deployment and charging infrastructure.

**Table 1:** Case settings.

| Case | EV | Home | Office |
|---|---|---|---|
| 0 | No | - | - |
| 1 | Yes | Standard charger | Standard charger |
| 2 | Yes | Standard charger | V2B |
| 3 | Yes | V2H | Standard charger |
| 4 | Yes | V2H | V2B |

The installed capacities of VRE were set to be PV 13,000 kW and WT 700 kW, reflecting the local conditions of Tanegashima [7]. Hourly electricity outputs from PV and WT were estimated using solar radiation and wind speed data. Electricity demand in Tanegashima was estimated by allocating the total electricity demand of Kyushu region [8] in proportion to population. The minimum output of thermal power generation, $P_{\text{min}}^{\text{thermal}}(t)$, was estimated using a regression equation based on VRE output, $P^{\mathrm{VRE}}(t)$, electricity demand, $P^{\mathrm{use}}(t)$, and reported data on the minimum thermal power output released by electric power company [9].

The target vehicle type was the Japanese Kei car, which is the most commonly used vehicle in Tanegashima [3]. The number of EVs was assumed to increase to up to 10, 000 units. EV battery capacities and EV efficiencies were set based on an industrial data source [10].

## RESULTS AND DISCUSSION

### Overview of energy flow simulation with V2G

Energy demand and supply were calculated on an hourly basis using the energy flow simulation model. Under current conditions without EV deployment, VRE output curtailment occurred on 128 days per year. In comparison, 118 days of VRE output curtailment were reported in 2023 [9]. This close agreement suggests that the model developed in this study reasonably represents the actual electricity system of the region.

**Figure 3** shows the temporal dynamics of electricity generation and demand on April 27 with 1, 000 EVs in case 4. The difference in electricity demand between cases with and without EVs is attributable to EV charging. On this day, VRE output was curtailed during the middle of the day. The installation of EVs reduced VRE output curtailment by EV charging. At that time, electricity demand increased in the morning due to EV charging before commuting to work, which led to increase in thermal power generation to meet this additional demand. In the evening, after returning home, EVs discharged electricity to the power grid.

### Annual changes in electricity generation

The simulation shown in **Figure 3** was conducted for one year. Figure 4 shows the annual amounts of electricity demand, thermal power generation, VRE output curtailment, and EV discharge to the power grid. The number of installed EVs was varied from 0 to 10, 000 units.

EV deployment reduced VRE output curtailment (**Figure 4 (a)**). In case 4 with 10, 000-EVs, VRE output curtailment was reduced to 0.26%. The installation of V2H and V2B further decreased VRE output curtailment. EVs were able to charge electricity derived from VRE that would otherwise have been curtailed in case 0, because EV batteries had available capacity created by discharging electricity to the power grid on the previous day.

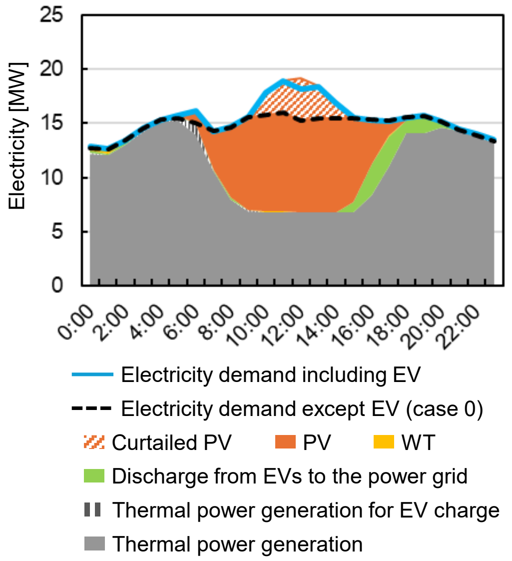


**Figure 3**. Temporal dynamics of electricity generation and demand on April 27th with 1, 000 EVs in case 4.

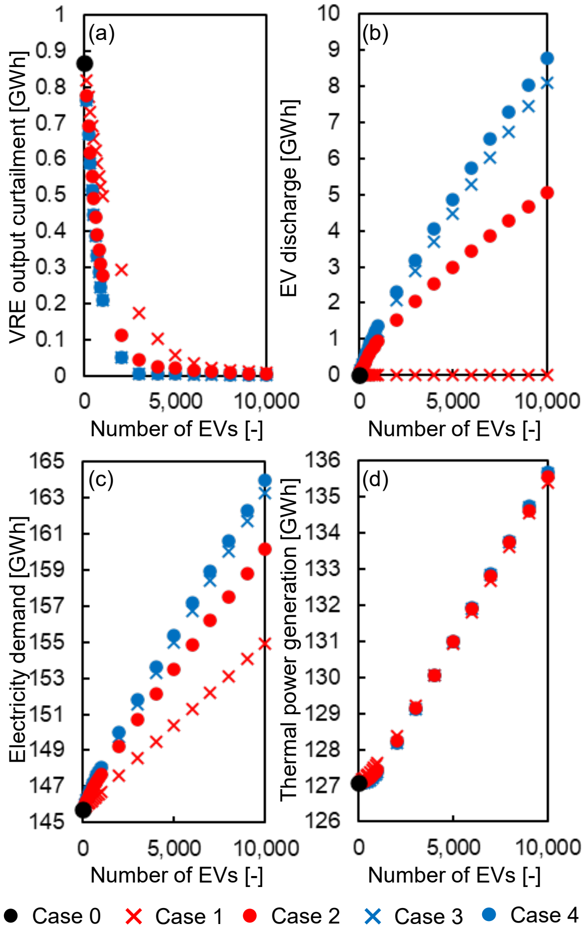


**Figure 4.** Effects of the regional V2G system. Note that the vertical axis scales differ. (a) VRE output curtailment. (b) EV discharge to the power grid. (c) Electricity demand. (d) Thermal power generation.

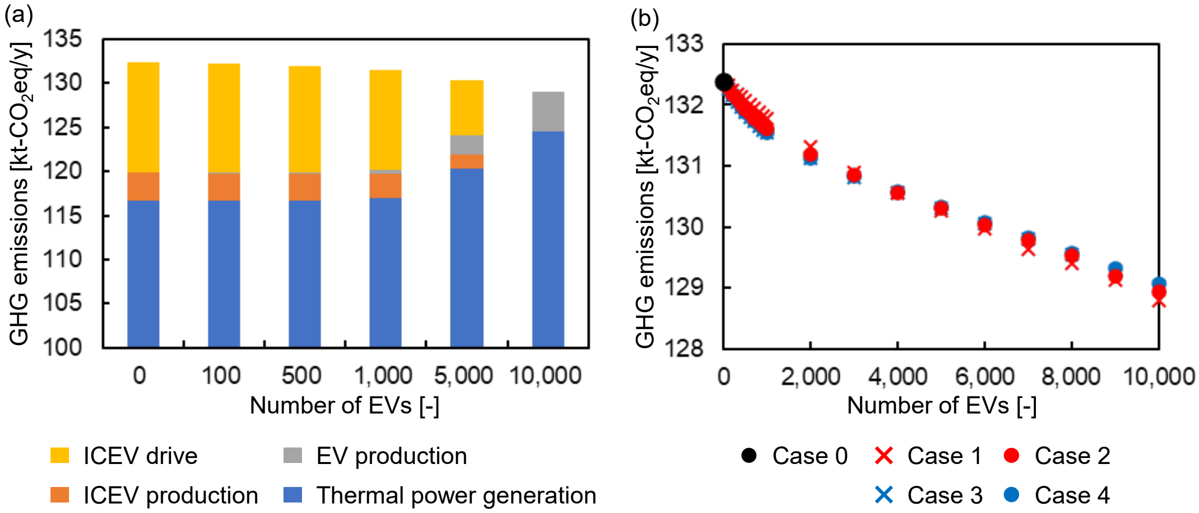


**Figure 5.** GHG emissions from the regional V2G system. Note that the vertical axis scales differ between (a) and (b). (a) GHG emissions from the regional V2G system in case 4. (b) GHG emissions from the regional V2G system among all cases.

By installing V2H and V2B, electricity stored in EV battery could be utilized at homes and offices (**Figure 4 (b)**). VRE output curtailment typically occurred during midday, so EVs mainly charged during this period and discharged in the evening. A comparison between cases 2 and 3 showed that EV discharge to the power grid was smaller in case 2. If EVs were parked at offices overnight, such as company owned vehicles, EV discharge to the power grid would be expected to increase.

The annual electricity demand in Tanegashima is shown in **Figure 4 (c)**. When EVs were deployed, total electricity demand increased due to electricity consumption for EV driving. In cases 2-4, electricity demand increased more than in case 1. This additional increase was caused by EV discharging to the power grid, which in turn created additional opportunities for EV charging.

**Figure 4 (d)** presents the annual amount of thermal power generation. In general, thermal power generation increased with EV deployment because EVs required electricity for driving and charging. However, when fewer than 200 EVs were installed in Cases 3 and 4, thermal power generation decreased compared with Case 0. This reduction occurred because EVs charged electricity that would otherwise have been curtailed and discharged electricity to the power grid during evening hours, thereby reducing the need for thermal power generation.

When fewer than 200 EVs were installed, thermal power generation in case 4 was the lowest among all cases (**Figure 4 (d)**). However, when a large number of EVs were deployed, thermal power generation in case 4 became the highest. This inversion phenomenon was observed at approximately 4, 000-EVs. As shown in **Figure 4 (a)**, VRE output curtailment in cases 2-4 was almost zero at this level of EV penetration. Therefore, when the number of EVs exceeds 4, 000, thermal power generation must increase to meet the electricity demand, because the surplus electricity that was curtailed in Case 0 had already been fully absorbed by EV charging. These results indicate that the environmental effectiveness of regional V2G systems strongly depends on the balance between available surplus VRE and additional electricity demand induced by EV deployment. Beyond a certain penetration level, further EV deployment no longer contributes to GHG reduction unless additional renewable capacity or system-level control is introduced.

These results suggested that the regional V2G system could reduce VRE output curtailment and had the potential to decrease thermal power generation by enabling electricity discharge from EVs to the power grid. However, it should be noted that EV operation also tended to increase thermal power generation due to EV driving.

## GHG emissions of regional V2G system

GHG emissions from the regional V2G system were evaluated using LCA. **Figure 5 (a)** shows the GHG emissions for case 4. As the number of EVs increased, GHG emissions from thermal power generation and EV production also increased. However, total GHG emissions decreased because GHG emissions from ICEV operation were substantially reduced.

**Figure 5 (b)** compares GHG emissions all cases. When a small number of EVs were installed, case 4 exhibited the lowest GHG emissions among all cases. However, as the number of installed EVs increased, case 1 resulted in the lowest GHG emissions. This inversion phenomenon was observed at approximately 4, 000-EVs, which is consistent with the trend observed for thermal power generation. At low EV penetration levels, GHG emissions could be reduced effectively because EVs were able to utilize surplus VRE that was curtailed in case 0. In contrast, at high EV penetration levels, electricity demand from EVs exceeded the amount of surplus VRE available, leading to increased reliance on thermal power generation.

GHG emissions associated with EV production were higher than those from ICEV production. Although this study did not include vehicles disposal, recycling could further reduce overall GHG emissions. In particular, recycling batteries used in EVs could reduce the environmental impact through appropriate recycling [11].

## Possible role of regional V2G system

In regions distant from major urban centers, particularly remote islands, fuel for ICEV operation must be transformed from remote production facilities, resulting in relatively high fuel costs. If EVs and V2G systems were deployed and locally available VRE was utilized for EV operation, both regional GHG emissions and fuel cost could be reduced. In addition, increased utilization of locally generated energy had the potential to stimulate the local economy.

Furthermore, the installation of regional V2G systems was expected to promote local economic activity and contribute to regional revitalization. The local socio-economic impacts of adopting new technologies can be evaluated using Input-Output (IO) models [12]. The results of this study provided quantitative parameters that can be used to assess these local socio-economic effects.

Beyond reducing life cycle environmental impacts, V2G systems could also enhance energy resilience by mitigating the risk of electricity supply disruptions during natural disasters. In regions equipped with V2G systems, residents could continue to access electricity even in the event of blackouts caused by natural disasters such as typhoons. Therefore, regional V2G systems would be well suited for the development of resilient local energy systems.

Regional V2G systems could reduce VRE output curtailment and GHG emissions and, depending on the number of deployed EVs, may also decrease thermal power generation. In addition, such systems had the potential to stimulate the local economic activity and contributed to the development of resilient local energy systems.

## Limitations of this study

The deployment of V2G system at the regional level was examined in this study. It assumed that a regional V2G system centrally controlled the charging and discharging of individual EVs by comprehensively considering the amount of regional VRE output curtailment, the number of EVs connected chargers and V2H/V2B systems in real time. Without such coordinated control, EVs may demand electricity beyond the available surplus VRE, potentially leading to unnecessary increases in thermal power generation. Under current conditions, individual V2H/V2B systems cannot access regional electricity system information in real time. Therefore, an advanced control system would be required to utilize regional V2G systems effectively.

Even though the model incorporated real-time information on regional electricity system, some EVs discharge electricity to the power grid that had been charged into their batteries during periods without VRE output curtailment. This behavior increased the load on thermal power generation.

The regional V2G system model developed in this study focused exclusively on Japanese Kei cars used for commuting purposes and did not account for differences in vehicle types or usage patterns. All EV owners and their workplaces were assumed to install identical charging equipment, such as standard chargers and V2H systems. Furthermore, the model could be enhanced by incorporating material flow analysis (MFA) to account for the timing of EV deployment, vehicle lifetimes including battery degradation, as well as variations in vehicle types, charging infrastructure, and usage patterns.

To enable the practical deployment of regional V2G systems, an economic framework must also be established. If EVs were allowed to charge and discharge freely at any location, individual EV owners could buy and sell electricity anywhere, leading to complex financial transactions. The development of a dedicated financial system, such as applications or platforms for V2G users, would help facilitate and accelerate the deployment of V2G systems.

For these reasons, regional V2G systems should manage regional electricity demand and supply by accounting for real-time system conditions, while coordinating the individual operation of V2H and V2B systems. Furthermore, the load of thermal power generation could be reduced by distinguishing whether the electricity stored in EV batteries was derived from VRE or from thermal power generation. Such an approach would promote more effective utilization of VRE. Therefore, integrated regional systems capable of controlling electricity flows and managing financial transactions were essential for the successful implementation of regional V2G systems.

# CONCLUSIONS

This study developed a regional V2G system model and evaluated the potential of EVs and V2G systems using energy flow simulations and LCA. Fuel consumption, VRE utilization, and GHG emissions were quantitatively assessed to examine the potential of regional V2G system.

The results revealed that the deployment of EVs and V2G systems could effectively reduce VRE output curtailment and GHG emissions. In the case of 10, 000-EVs equipped with V2H and V2B systems, VRE output curtailment was reduced to 0.26%. Moreover, when fewer than 200 EVs were installed with V2H, thermal power generation decreased compared with the case without EVs. These findings indicated that regional V2G systems had the potential to reduce VRE output curtailment, GHG emissions, and, under certain conditions, thermal power generation.

The model developed in this study enabled a quantitative evaluation of the potential of regional V2G systems. For the practical deployment of such systems, integrated regional platforms were required to coordinate electricity flows and manage financial transactions. By evaluating the environmental performance of regional V2G systems, this study provided valuable insights to support the design and the implementation of environmentally sustainable V2G systems.

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