Carbon Hotspot Evaluation of Vehicle-to-grid System by Life Cycle Inventory Analysis

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Abstract: This study undertakes a life cycle inventory analysis to identify the carbon hotspots in a vehicle-to-grid (V2G) system and its CO_2 emissions advantage over a conventional counterpart equivalent. The V2G system comprises a residential house, a photovoltaic solar system, a battery electric vehicle and a charging system, whereas the conventional system includes a residential house, a gasoline vehicle and a petrol station. The system boundary of each component consists of its production, use and end-of-life stages, where data are available. The carbon dioxide (CO_2) emissions are calculated by applying component and life cycle stage data collected from statistics and literature surveys to the Japanese life cycle inventory database. The emissions differ by the assumptions made; therefore, a sensitivity analysis is also conducted to understand the potential CO_2 emissions variations. The results indicate that a 35%–42% CO_2 reduction can be expected for a V2G system in comparison with the conventional system. The main contributors to CO_2 emissions for both the V2G and the conventional system are the dwelling, residential house construction, vehicle cycle and fuel cycle stages. Hence, these stages should be included in the system boundary of the V2G system and it is important to select and design the appropriate components of these stages to assure the environmental merits of the V2G system in terms of life cycle CO_2 reduction.

Keywords: Vehicle to grid, Carbon hotspots, Life cycle inventory analysis.

1. Introduction

The high energy efficiency and zero emissions of the battery electric vehicle (BEV) mean that this technology is considered as a potential solution for the energy and environmental problems surrounding the automotive sector. Although BEV research and development started in the 1970s, such vehicles have not yet penetrated the market mainly because of their low practicality and high cost compared with the conventional internal combustion engine vehicles. In the late 2000s, however, there was a significant improvement in the performance of lithium-ion batteries for electric vehicles that ensures practical vehicle range and there is a resultant new focus on BEVs as a promising technology for future mobility. Some vehicle manufacturers launched sales of BEVs with lithium-ion battery in the Japanese vehicle market for fleet use in 2009 and for personal use in 2010.

There is a worldwide focus on smart grid technologies that can efficiently manage electricity demand and supply — including renewable energy use— through information and communication technologies that ensure energy grid stability and that work towards a low-carbon society. BEVs are identified as a key component for use as distributed energy storage devices in the smart grid system. The vehicle-to-grid (V2G) system allows mutual energy sharing between a vehicle and a home and is regarded as one of the key technologies in smart grid strategies. Although the system is limited in that a single vehicle can supply only a single house, the combination of a V2G system and a home energy management system enables a household to achieve both energy savings and greenhouse gas (GHG) reductions.

Japan faces power shortages in the wake of the Great East Japan Earthquake of March 2011, and there is an increased expectation of the full-scale promotion of renewable energy including solar photovoltaic (PV) and wind power. The Japanese government implemented a renewable energy feed-in-tariff scheme in July 2012 [1] to improve energy self-sufficiency, reduce GHG emissions and stimulate Japanese industries. The connection of such unstable power sources, whose output fluctuates with the weather, to the grid may cause imbalances between electricity generation and demand load and may lead to frequency and voltage fluctuations. Hence, demand–supply balancing capacities such as batteries (including those mounted on BEVs) are expected to play an important role to minimize the risk of a possible overload and resulting blackout and to stabilize the power supply. The V2G system can play a role in both contributing to a stable power supply and in providing electricity in emergency situations.

The environmental emissions attributed to vehicle and household energy use might be reduced in a V2G system compared with the conventional counterpart system; however, the construction of a residential house and the installation of V2G system components in it generate additional environmental emissions during their production and end-of-life stages. Therefore it is necessary that the emissions reduction effect of the total system be evaluated from a life cycle perspective. Life cycle assessment (LCA) is a quantitative means of evaluating the environmental aspects and the potential impacts associated with products, processes and services throughout their life span. LCA considers the assessment of products or services from a “cradle to grave” perspective. Well-to-wheel analyses [2-4] apply the LCA concept to estimate the environmental advantages of various alternative energy vehicles over the entire automotive fuel pathway. Many studies conduct LCAs and estimate the environmental burdens by each alternative fuel vehicle life cycle stage, including the well-to-wheel stages [5-7].

Few studies have conducted a LCA on a V2G system in terms of evaluating the environmental merits of a V2G system compared with a conventional system. For example, Sioshansi and Meisterling [8] estimate the life cycle reduction effect of carbon dioxide (CO_2), nitrogen oxides (NOx) and sulfur oxides (SOx) by introducing a V2G service using plug-in hybrid electric vehicles in Texas, United States. They use an electric power system model and detailed driving pattern data; however, they focus on vehicle batteries and power systems so that the emissions associated with the production and the end-of-life of the system components (including, among others, batteries and power systems) are not included in the LCA system boundary.

To design a V2G system that contributes to GHG reduction, it is important to understand which system components and life cycle stages account for the highest GHG emission proportions. Hence, this study focuses on the life cycle CO_2 emissions of a V2G system with a home solar PV system and a BEV. A life cycle inventory (LCI) analysis is conducted to estimate the potential CO_2 reduction compared with a counterpart conventional system and to identify the system's carbon hotspots.

Notably, the estimation is based upon statistics and literature survey data and not on actual V2G system or conventional system data owing to data restrictions.

2. Experimental

2.1 System components, system boundary and functional unit

Table 1 shows the study's target systems' components and their system boundaries for LCI analysis. The V2G system comprises a residential house, a solar PV system, a power control system (PCS) and a BEV. The PCS is a charging system that can not only charge the BEV but can also supply electricity to the house from the BEV. The counterpart conventional system consists of a residential house and a gasoline vehicle (GV). Since the PCS (the BEV energy charger) is included in the V2G system component, the petrol station is included in the conventional system component so that both systems are equal.

The system boundary of each component consists of its production, use and end-of-life stages; however, data restrictions mean that the BEV, GV and PCS end-of-life stages are not included in this study.

Since each component's lifetime differs, each component's life cycle CO_2 ($LCCO_2$) emissions are discounted over its lifetime and the study's functional unit is the annual CO_2 emissions from the system (household).

V2G system electricity generated by solar PV (either a demonstration or market version) can be charged first into the BEV and then used as dwelling energy. Notably, this effect is not considered in the study calculations as it was impossible to obtain the raw data from an actual system.

Table 1. System components and boundaries.

Target system	System components	System boundary
V2G and conventional system	Residential house	Construction
		Dwelling
		Demolition and end-of-life
	Vehicle (BEV and GV)	Production (Vehicle cycle)
		Use (Fuel cycle)
		Maintenance
V2G	PV	Production
		End-of-life
	PCS	Production
Conventional system	Petrol station	Construction
		Demolition and end-of-life

2.2 LCI database used

The Inventory Database for Environmental Analysis (IDEA) [9], developed by Japan's National Institute of Advanced Industrial Science and Technology, is used to calculate the $LCCO_2$ emissions from the target systems. The IDEA covers approximately 3,000 basic processes in Japan including energy, chemicals, metals and nonmetals, machinery, building materials and civil construction. The database is developed from statistical data, model calculations and literature. The embodied CO_2 emission intensities, including all of the upstream emissions, are given a process per activity unit (e.g., a physical or monetary unit); hence, the $LCCO_2$ emission amounts are calculated by multiplying the activity amount by the embodied emission intensity. The IDEA embodied CO_2 emission intensity was used as the default value for the 2009–2011 Japanese Carbon Footprint of Products (CFP) pilot project; further, the IDEA is the default database of the Japanese CFP communication program since 2012 [10].

3. Configuration of system components and their $LCCO_2$ emissions

3.1 Residential house

3.1.1 Construction stage

Japanese statistics from 2008 [11] show that 55% of all residential houses are detached and 59% are wooden: therefore this study considers a detached wooden house as its residence type.

The IDEA provides a CO_2 emission intensity of 434.89 [kg-CO2/m2] for the production of a wooden house. Assuming a gross floor area of 132.3 [m2] [11] and a lifetime of 35 years for Japanese residential houses, the CO_2 emissions associated with house construction can be calculated as 1,644 [kg-CO2/household/year].

3.1.2 Dwelling stage

Fig. 1 depicts the annual amount of each energy type used in the residential sector by Japanese region [12]. Combining these statistics with the number of households and the CO_2 intensity of each energy type included in IDEA datasets (Table 2) gives the annual CO_2 emissions from dwelling energy use shown in Fig. 2.

Fig. 2 confirms that the major dwelling stage emission contributor is electricity. A breakdown of energy use by energy type shows that over 70% of the electricity emissions are attributed to lighting and to power for home electrical appliances [13]. The other energy sources are mainly used for hot water and heating: kerosene is the main source for heating in cold areas (such as Hokkaido and Tohoku, which are located in northern Japan).

Figure 1. Japanese regions.

Table 2. CO_2 intensity data.

	Production	Combustion	Total
Kerosene [g-CO2/MJ]	4.84	67.9	72.7
LPG [g-CO2/MJ]	12.3	59.5	71.8
City gas [g-CO2/MJ]	14.9	49.8	64.7
Electricity [g-CO2/kWh]			463
Gasoline [g-CO2/MJ]	11.5	67.1	78.6

The $LCCO_2$ emissions calculated in this study use the Japanese average (Fig. 2) as a default; however, it should be noted that the residential sector emissions differ by the target area.

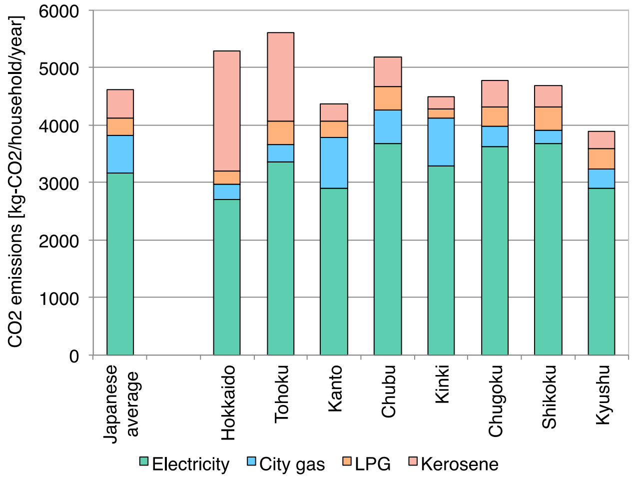

Figure 2. Dwelling stage CO_2 emissions.

3.1.3 Demolition and end-of-life stage

Generally, the waste from house demolition is treated as industrial waste. Although the exact amount of CO_2 emitted by industrial waste treatment differs by waste specification, this study approximates residential waste using the assumed gross floor area of 132.3 [m2] assumed in section 3.1.1 and the data included in IDEA as follows:

- According to the house construction data used to produce IDEA datasets, approximately 0.8 [t/m2] of materials are required for constructing a house, the majority of which are treated as industrial waste at its end-of-life stage.
- The IDEA provides the embodied CO_2 emissions of 3.893 [g-CO2/Japanese yen (JPY)] (466 [g-CO2/USD] using the currency conversion rate of 1 USD = 119.8 JPY, 7 January 2015) for industrial waste treatment.

Industrial waste is traded in the market at a price of several thousand JPY per ton. The default case in this study assumes 5,000 [JPY/ton]. Although the CO_2 emissions from this stage may change according to the price of industrial waste, it is calculated [14] that the emissions from this stage only account for approximately 1% of the total residential house emissions, and therefore its $LCCO_2$ emission contribution is small (Fig. 3).

3.2 Solar PV panel system

Among the various studies that calculate the solar PV panel system $LCCO_2$ emissions, Japan's Central Research Institute of Electric Power Industry (CRIEPI) [15] and Mizuho [16] reflect the state-of-the-art solar PV technology. Table 3 shows the specifications of the assumed solar PV systems and their system boundaries. While CRIEPI provides the detailed material and energy inputs required for producing a solar PV system, its end-of-life stage is outside its system boundary. In contrast, Mizuho includes the end-of-life stage but does not provide the production stage material and energy data. This study uses both reports to estimate the solar PV system $LCCO_2$ emissions.

3.2.1 Production stage

Fig. 4 represents the CO_2 emissions from the solar PV system production stage as calculated from CRIEPI and IDEA data. In the production stage, 80% of the emissions are attributed to the materials required for solar PV components.

Table 3. CRIEPI [15] and Mizuho [16] solar PV specifications and system boundaries.

		CRIEPI [15]	Mizuho [16]
Solar PV type		Polycrystalline silicon	
Cell	Size [mm]	155x155	
	Thickness [mm]	0.2	
Module	Size	900×1165	1326×1008
	No. of cells	42	48
	Capacity [W]	160	186
	Efficiency [%]	13.9	
System	No. of modules	24	21
	Capacity [W]	3.84	3.9
	Weight [kg]	574	579
	Annual power generation [kWh]	5046	3863
	Lifetime [years]	30	20
System boundary	Cell and module production	✓	✓
	Mounting production	✓	✓
	Control devices production	✓	✓
	Products transport	✓	✓
	Spare parts production	✓	✓
	End-of-life	-	✓

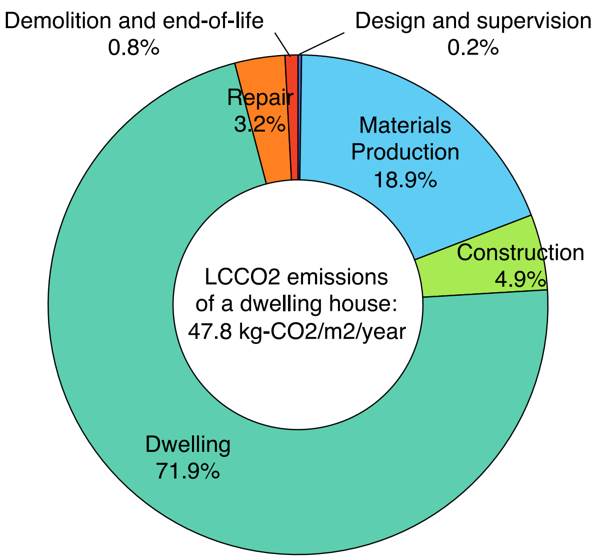

Figure 3. LCCO2 emissions from a dwelling house [14].

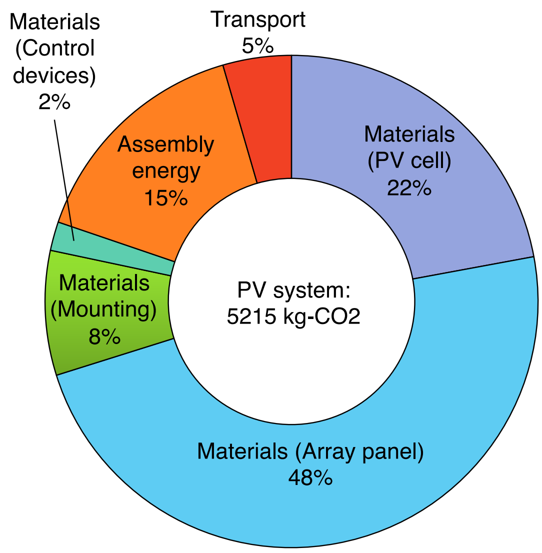

Figure 4. Solar PV system production: CO_2 emissions.

3.2.2 End-of-life stage

Japan's New Energy and Industrial Technology Development Organization (NEDO) estimates CO_2 emissions of 972.7 [kg-CO_2/kW-system] from the production stage and 2.1 [kg-CO_2/kW-system] from the end-of-life stage for a solar PV system whose specifications are shown in Table 3. Since the assumed system power generation capacities of both [15] and [16] are almost identical, the emissions from this stage are approximated as 9.6 [kg-CO_2/system]. This result arises by multiplying the CO_2 emissions ratio of the production stage vs. the end-of-life stage by the production stage estimate shown in Fig. 4.

3.2.3 Life cycle CO2 emissions

The assumed annual power generation and lifetime of the solar PV system significantly differ in [15] and [16] as confirmed by Table 3, although both reports assume approximately the same power generation capacity. This indicates that a variety of assumptions can be made relating to the solar insolation and other conditions that strongly affect the $LCCO_2$ estimates of a solar PV system. Therefore this study assumes a default average from the CRIEPI and Mizuho annual power generation and lifetime of parameters in Table 3: this gives the $LCCO_2$ emissions of 46.9 [g-CO_2/kWh].

3.3 Power control system

The PCS is the key component of the V2G system; however, detailed PCS input data is unavailable. Therefore the study assumes that the PCS inventory can be approximated by the solar PV system power conditioner with an emission of 98.6 [kg-CO_2] as calculated from Fig. 3, where the direct solar PV current is converted to the alternate current used by households. Since the lifetime of a PCS is approximately 10 years, it is assumed that four PCSs are required during the 35-year lifetime of a dwelling house.

3.4 Petrol station

The gasoline and electricity CO_2 emissions shown in Table 2 are equivalent to the well-to-wheel CO_2 emissions intensity. Well-to-wheel analysis generally only considers the energy flow to produce automotive energy over the life cycle and the emissions attributed to the construction of infrastructures are not included. Various well-to-wheel studies and petroleum refinery LCAs were evaluated in the attempt to calculate the CO_2 emissions associated with the construction and the end-of-life stages of the infrastructures required; however, none provided a detailed petrol station material component analysis. Although petrol station emissions should vary according to the size and specification of its components (such as the operator's premises, the shed area, the tank container and the fuel dispenser), this study approximates its construction and end-of-life stage emissions in the same manner as the residential house estimates described in sections 3.1.1 and 3.1.3. The data for the default case calculation are as follows:

- Assuming a petrol station with a steel-reinforced concrete (SRC) structure, the IDEA gives the embodied CO_2 emissions for a SRC office construction of 1,551.6 [kg-CO_2/m^2].
- The IDEA datasets consider that approximately 2.5 [t/m^2] of materials are required to construct a SRC office and most of the materials are treated as industrial waste at their end-of-life stage.
- Industrial waste is traded in the market at several thousand JPY per ton. This study assumes a default of 5,000 [JPY/ton].
- The IDEA provides the embodied CO_2 emissions of 3.893 [g-CO_2/JPY] for industrial waste treatment.

A petrol station's construction and end-of-life stages CO_2 emissions ($\mathrm{CO2}_p$ [kg-CO_2/year]) can be approximated using equation (1). This assumes that the total construction and end-of-life stage emissions of every Japanese petrol station are attributed to and shared with the entire fleet of passenger vehicles owned in Japan.

$$\mathrm{CO2}_p = (\mathrm{E}_c \mathrm{A}_p + \mathrm{E}_w \mathrm{W}_p \mathrm{P}_w \mathrm{A}_p) \times \mathrm{N}_p / \mathrm{N}_v / \mathrm{t} \quad (1)$$

where E_c is the embodied SRC office construction CO_2 emissions [CO2/m2], A_p is the ground area of a petrol station [m2], E_w is the embodied industrial waste treatment CO_2 emissions [CO_2/JPY], W_p is the amount of industrial waste from a petrol station demolition [t/m2], P_w is the price of industrial waste [JPY/t], N_p is the number of petrol stations, N_v is the number of vehicles owned, and t is the lifetime of the petrol station [years] (assumed as 30 years by default in this study).

3.5 GV and BEV

This study assumes that the GV and BEV lifetimes are both 11 years, which is the average for Japanese passenger vehicles. It further assumes that every single household owns one vehicle (either a GV or a BEV).

Fig. 5 illustrates the $LCCO_2$ emissions for both GVs and BEVs assumed in this study. The assumptions made for these calculations follow.

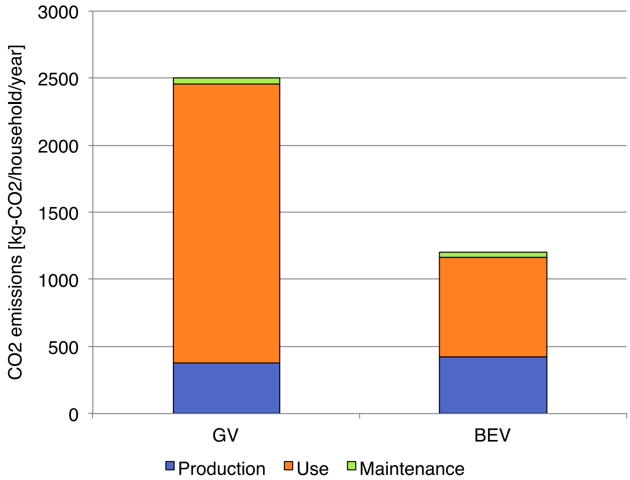

Figure 5. GV and BEV: CO_2 emissions.

3.5.1 Vehicle cycle

This study uses Kudoh's [5] production stage CO_2 emission estimates of 4.12 [t-CO_2] for GVs and 4.65 [t-CO_2] for BEVs.

3.5.2 Fuel cycle

The CO_2 emissions attributed to GV use can be calculated as shown in Fig. 6 using data from Table 2 and from [17] that provides the annual amount of gasoline used for passenger vehicles by households (for private use).

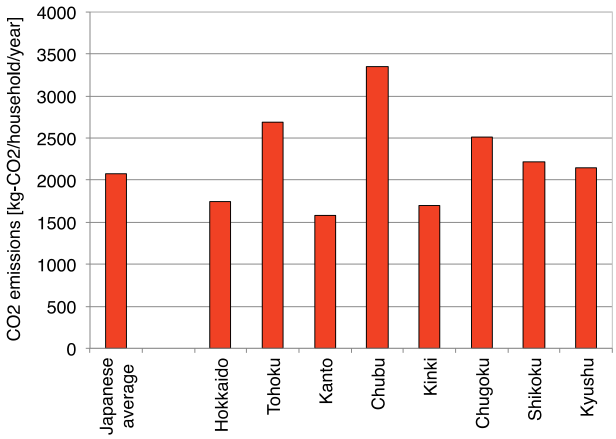

Figure 6. GV fuel cycle: CO_2 emissions.

This study assumes a BEV with a battery capacity of 24 [kWh], a vehicle range of 160 [km] and a charging efficiency of 0.85. The transport volume of passenger vehicles in Japan is 368,919 [thousand vehicle-km] and the total number of passenger vehicles is 40,528 [thousand vehicles], from which the Japanese average annual driving distance is estimated to be 9,100 [km] for a passenger vehicle [17-18]. Using these parameters and data from Table 2, the default CO_2 emissions for a BEV per household can be estimated.

3.5.3 Vehicle maintenance stage

The study follows Kudoh's [5] assumptions for vehicle maintenance stage emissions.

- The vehicle tires should be replaced every 30,000 km. Each of the four tires is replaced three times over the 11-year lifetime with an annual driving distance of 9,100 km. The tire production generates CO_2 emissions of 206 [kg-CO_2/4 tires].
- A GV's engine oil should be replaced every 5,000 km: it is replaced 19 times in the vehicle's lifetime. Each replacement requires 3.5 kg (3.9 liters) of engine oil and its CO_2 emissions are 5.72 [kg-CO_2/3.5kg-engine oil].
- A GV's lead acid battery should be replaced every 25,000 km: it is replaced three times in the vehicle's lifetime. The CO_2 emissions from such lead acid battery production are 18 [kg-CO_2].
- No replacement is required for the lithium ion battery mounted on the assumed BEV during its lifetime.

3.6 LCCO$_2$ emissions of the target systems

The potential LCCO$_2$ emissions of the target system can be estimated by summing all of the CO_2 emissions from the components and their life cycle stages as shown in Table 1. The emissions vary by the assumptions made; therefore this study conducts a sensitivity analysis to capture the minimum and maximum LCCO$_2$ emissions to indicate potential variation. Three cases are assumed for the calculation whose parameter settings are shown in Table 4.

Fig. 7 depicts the potential LCCO$_2$ emissions of the target systems. The estimated emissions from the V2G system are 5.7 [t-CO_2/household/year]: this is a 36% reduction compared with the baseline conventional system of 8.9 [t-CO_2/household/year] for the default case. The minimum case CO_2 emissions are 4.1 [t-CO_2/household/year] for the V2G system and 7.2 [t-CO_2/household/year] for the conventional systems (a 42% emissions reduction). These emission figures are 7.6 and 12 [t-CO_2/household/year], respectively, for the maximum CO_2 case (a 35% emissions reduction). The following findings can also be made from Fig. 7 regarding the V2G system CO_2 emissions:

Table 4. Assumed parameters for sensitivity analysis.

Cases	Parameters
Default case	Gross floor area of a detached owned house: 132.3 [m^2] (3.1.1); Target area for dwelling stage: Japanese average of Fig. 2 (3.1.2); Amount of industrial waste from a house demolition: 0.8 [t/m^2] (3.1.3); Price of industrial waste: 5,000 [JPY/t] (3.1.3 and 3.4); Solar PV annual power generation: 4,455 [kWh] (3.2); Solar PV lifetime: 25 [years] (3.2); Amount of industrial waste from a petrol station demolition: 2.5 [t/m^2] (3.4); Ground area of a petrol station: 1,000 [m^2] (3.4); Target area for fuel cycle: Japanese average of Fig. 6 (3.5); Annual driving distance of vehicles: 9,100 [m] – Japanese average (3.5.2); Tire replacements: three times (3.5.3); Engine oil replacements: 19 times (3.5.3); Lead acid battery replacements: three times (3.5.3).
Minimum CO_2 case	Gross floor area of a detached owned house: 99 [m^2] (3.1.1); Target area for dwelling stage: Kyushu area of Fig. 2 (3.1.2); Amount of industrial waste from a house demolition: 0.6 [t/m^2] (3.1.3); Price of industrial waste: 1,000 [JPY/t] (3.1.3 and 3.4); Solar PV annual power generation: 5,046 [kWh] (3.2); Solar PV lifetime: 30 [years] (3.2); Amount of industrial waste from a petrol station demolition: 1.9 [t/m2] (3.4); Ground area of a petrol station: 500 [m^2] (3.4); Target area for fuel cycle: Kanto area of Fig. 6 (3.5); Annual driving distance of vehicles: 8,400 [m] – Kanto area (3.5.2); Tire replacements: three times (3.5.3); Engine oil replacements: 18 times (3.5.3); Lead acid battery replacements: three times (3.5.3).
Maximum CO_2 case	Gross floor area of a detached owned house: 165 [m^2] (3.1.1); Target area for dwelling stage: Tohoku area of Fig. 1 (3.1.2); Amount of industrial waste from a house demolition: 1 [t/m^2] (3.1.3); Price of industrial waste: 10,000 [JPY/t] (3.1.3 and 3.4); Solar PV annual power generation: 3,863 [kWh] (3.2); Solar PV lifetime: 20 [years] (3.2); Amount of industrial waste from a petrol station demolition: 3.1 [t/m^2] (3.4); Ground area of a petrol station: 1,500 [m^2] (3.4); Target area for fuel cycle: Chubu area of Fig. 6 (3.5); Annual driving distance of vehicles: 9,400 [m] – Chubu area (3.5.2); Tire replacements: three times (3.5.3); Engine oil replacements: 19 times (3.5.3); Lead acid battery replacements: three times (3.5.3).

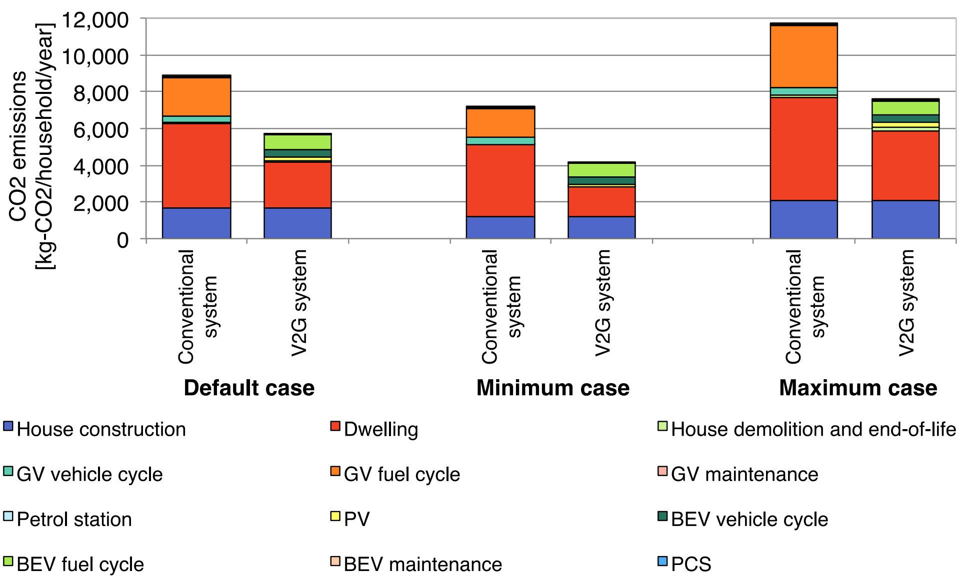

Figure 7. Conventional and V2G systems: LCCO$_2$ emissions.

• The largest carbon hotspot is the residential energy use that accounts for 38%–55% of the total emissions.

• The emissions from the residential house construction stage account for 17%–30% of the total CO_2 emissions.

• The BEV fuel and vehicle cycles account for 10%–17% and 6%–10%, respectively, of the total CO_2 emissions and those of the GVs account for 22%–29% and 3%–5%, respectively.

• The solar PV production and end-of-life stages account for 4% of the V2G system emissions.

• The emissions from other stages (house demolition, vehicle maintenance stage, petrol station construction and demolition and PCS production) are smaller than 2% of those from the target system in any case in Fig. 6. This indicates that they can be excluded from the system boundary.

4. Discussions

This study undertakes a LCI analysis for a V2G system and its conventional counterpart in terms of CO_2 emissions to identify the carbon hotspots in a V2G system. The results indicate that a V2G system that uses a solar PV system and a BEV can achieve a CO_2 reduction of 35%–42% over the conventional residential house that has a GV. The main CO_2 emission contributors of both systems are the dwelling, residential house construction, vehicle cycle and fuel cycle stages. Hence, these components and their life cycle stages should be included in the V2G system boundary when conducting LCAs. It is also important to select and design the appropriate components of these stages to assure the environmental merits of the V2G system.

Fig. 8 shows a system boundary example for a LCA of a V2G system and its potential CO_2 emissions. If a household substitutes a BEV for a GV (comparison of “Conventional house + BEV” with “Conventional house + GV” in Fig. 8), the dwelling energy use will not change and the only difference between the targets is either using a GV or a BEV, whose differential is almost equivalent to conventional LCA studies comparing GV and BEV $LCCO_2$ emissions. The comparison made in this study corresponds to extending the system boundary that includes all of the CO_2 emissions from the potential life cycle stages of a V2G with a solar PV system and its counterpart conventional system (comparison of “V2G + PV and BEV” with “Conventional house + GV” in Fig. 8).

It should be reiterated that data restrictions mean that this study uses data obtained from statistics and literature surveys rather than from actual V2G and conventional systems. A more detailed V2G system analysis requires raw data obtained from actual systems for the calculations. This is particularly relevant for the residential house in a V2G system: its heat insulation and air tightness properties are usually better than in a conventional house. This may lead to more CO_2 emissions from the house construction stage but fewer emissions from the dwelling stage.

Moreover, it is likely that those who live in high value-added houses with V2G systems may have a higher energy saving awareness than normal and there may be a resultant reduction in both their energy use for living and their vehicle use according to their lifestyle change. As shown in the “High performance V2G + PV and BEV + lifestyle change” column of Fig. 8, the study recommends conducting a subsequent LCA study. The environmental merit of an actual V2G system should be discussed that considers the entire causal effect induced by the introduction of a V2G system and that includes the indirect effects in its estimation.

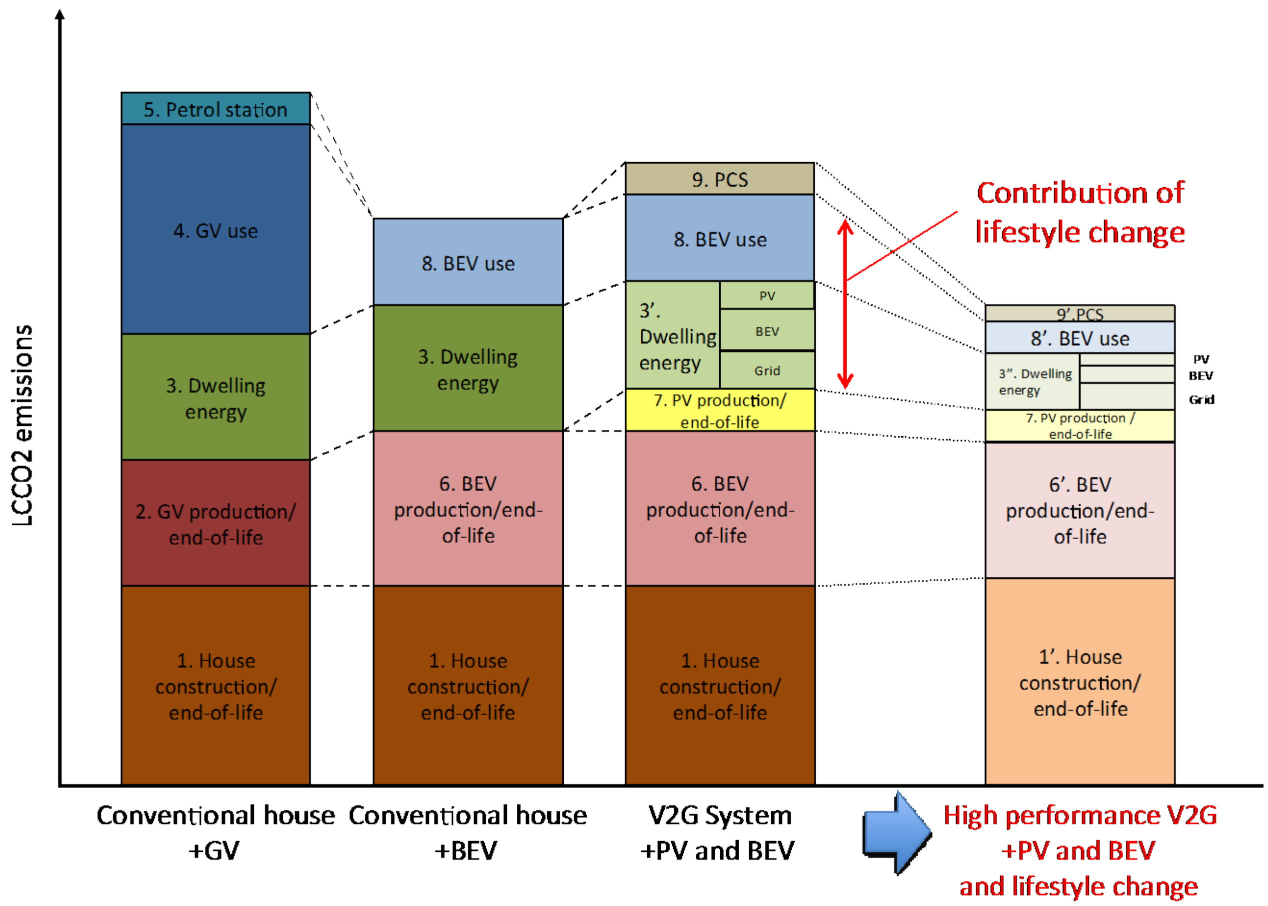

Figure 8. System boundary framework and CO_2 emissions for V2G system evaluation.

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