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Evaluation of Economic and Environmental Superiority of EV Battery in Power Systems: Development of Multi-objective Optimized Model for V2H

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Summary

Vehicle to Home (V2H) systems are attracting the attention of electric vehicle (EV) owners as a valuable additional benefit of EV technology. In this study, a multi-objective optimization method was developed to derive the operational schedule and optimum capacity of equipment such as photovoltaic (PV), stationary battery (SB), and V2H systems to be installed into the home, using the home energy costs and CO_2 emissions as indices. As a case study, the performance of a V2H system in a Japanese household living in a detached house and possessing a non-commuting EV was evaluated.

Keywords: Electric vehicle, Vehicle to home, Multi-objective Optimization, energy cost, CO_2 emission

1 Introduction

In response to the 2° C scenario, Japan has set the ambitious goal of raising the total percentage of electric vehicle (EV) and plug-in hybrid vehicle (PHV) stock to 16% by 2030. Improving the value of EVs and PHVs by using them to contribute to the supply-and-demand balance of electric power systems, including variable renewable energy sources, is one solution proposed as a means of accelerating their spread. Representative technological examples of this approach are vehicle to grid (V2G) and vehicle to home (V2H) systems. Since V2H is a case in which the EV can contribute directly to the owner's personal electric power system, clarification of this additional benefit of V2H technology may be an important motivating factor for personal EV ownership. An evaluation of the economics of V2H systems was performed in some recent studies. Some studies [1, 2] focused on the combination of residential photovoltaic (PV), stationary battery (SB), and V2H technology, and performed an economical evaluation by optimizing the associated operational schedules. The optimal sizing in terms of the capacity of a residential PV and SB has been considered [3, 4]. However, consumer tastes are diversifying. A multi optimization method, targeting both environmental and economic issues, is necessary in order to develop an optimum plan for environmentally-oriented owners. Some studies [5, 6] have proposed a multi-objective scheduling method to minimize the total operational costs and emissions in a distribution network. However, the multi-objective optimization methods used in these studies did not focus on energy management of the EV owner's home in conjunction with an installed V2H system. In this study, a multi-objective optimization method was developed to derive the operational schedule and optimum capacity of equipment such as PV, SB, and V2H to be installed in the home, using the home energy costs and CO_2

emissions as indices. Using this method, the economic and environmental performance of a V2H was then evaluated.

2 Method

2.1 Overview of optimized V2H model

The energy flow considered in this study assumed the presence of PV, a stationary battery, and V2H for a home already in possession of an EV as shown in Fig. 1. In Fig. 1, x, y, and *z* are the endogenous variables of the power flow and represent the amount of electric power, the capacity of the PV or stationary battery, and the necessity of the V2H equipment, respectively. This model was a multi-objective optimization problem with the objective function (1) involving the minimization of the cost and CO_2 emissions over a period of one year, taking onto account EV power demand and residential power demand was satisfied on an hourly basis. Given that *z* is a binary variable, the calculation method was categorized as mixed integer linear programming (MILP). The annual energy cost (2) was the sum of the grid purchase costs, the income from selling power to the grid, the equipment maintenance costs, and the initial costs, i.e., the initial investment divided by the product life in years. The annual CO_2 emission (3) was calculated from the product of the power supply from the grid and the environmental coefficient. The main constraint was formula (4), where $x_i(t)$ had to satisfy the upper limit $ub_i(t)$ and the lower limit $lb_i(t)$ as specified in Table 1, and the state of charge (SoC) equation (5) of the batteries, which was dependent on the battery's charging or discharging history. In addition, the EV charging or discharging as part of the V2H system could not be performed while the EV was absent. It should be noted that numerical values other than x, y, and *z* are exogenous variables. Further details on these variables are presented in the Variables section.

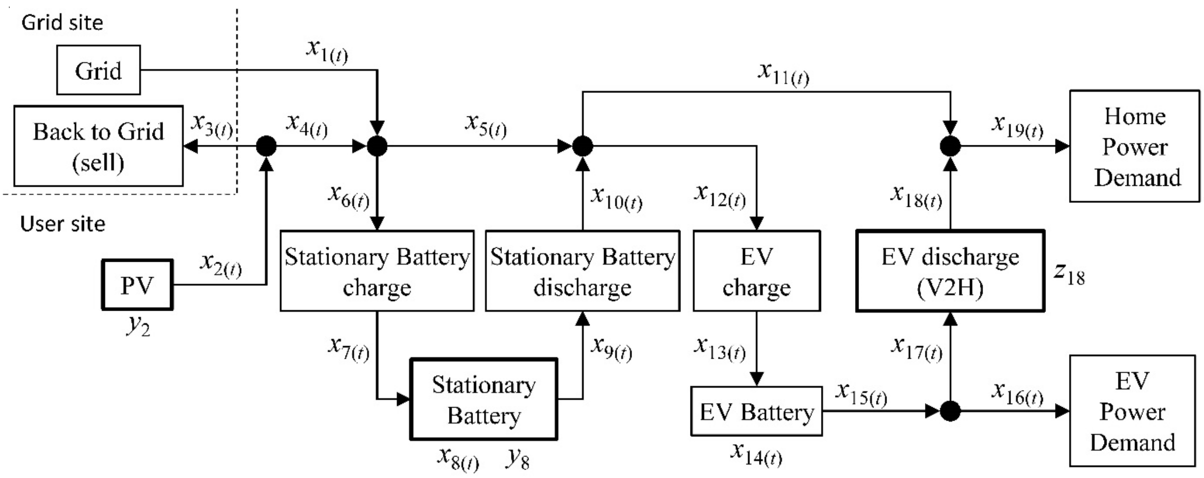

Figure 1: Energy flow and endogenous variables (*x*, *y*, and *z*).

Minimize: $$F(x,y,z) = w\frac{f_{cost}(x,y,z)}{\min\{f_{cost}(x,y,z)\}} + (1-w)\frac{f_{co_2}(x)}{\min\{f_{co_2}(x)\}} \quad , x,y \in R \ , \ \ z \in \{0,1\} \ , \ \ 0 \le w \le 1 \qquad (1)$$

subject to

$$f_{cost} = \sum_{t=1}^{8760} \{p_1(t)\cdot x_1(t) - p_3(t)\cdot x_3(t)\} + (M_{pv} + I_{pv})\cdot y_2 + (M_{SB} + I_{SB})\cdot y_8 + (M_{V2H} + I_{V2H})\cdot z_{18} \quad , \ \ t \in N \qquad (2)$$

$$f_{co_2} = \sum_{t=1}^{8760} e_1(t)\cdot x_1(t) \qquad , \qquad t \in N \qquad (3)$$

$$lb_i(t) \le x_i(t) \le ub_i(t) \quad , \quad i = 1, \ldots, 19 \quad , \quad t = 1, \ldots, 8760 \tag{4}$$

$$x_i(t) = \sum_{\tau=1}^{t} x_{i-1}(\tau) - x_{i+1}(\tau) \quad , \quad i = 8, 14 \quad , \quad t = 1, \ldots, 8760 \tag{5}$$

$$0 \le y_i \le y_i^{max} \quad , \quad i = 2, 8 \tag{6}$$

Table 1: Upper and lower bounds.

i	$lb_i(t)$	$ub_i(t)$	i	$lb_i(t)$	$ub_i(t)$
1	0	-	11	$x_5(t)+x_{10}(t)-x_{12}(t)$	$x_5(t)+x_{10}(t)-x_{12}(t)$
2	$pv_{unit}(t)y_2$	$pv_{unit}(t)y_2$	12	$x_5(t)+x_{10}(t)-x_{11}(t)$	$EVch_{cap}$
3	0	-	13	$\eta_{12,13}x_{12}(t)$	$\eta_{12,13}x_{12}(t)$
4	$x_2(t)-x_3(t)$	$x_2(t)-x_3(t)$	14	EV_{SoClb}	EV_{SoCub}
5	$x_1(t)+x_4(t)-x_6(t)$	$x_1(t)+x_4(t)-x_6(t)$	15	0	$x_{14}(t)$
6	$x_1(t)+x_4(t)-x_5(t)$	$x_1(t)+x_4(t)-x_5(t)$	16	$D_{EV}(t)$	$D_{EV}(t)$
7	$\eta_{6,7}x_6(t)$	$\eta_{6,7}x_6(t)$	17	$x_{15}(t)-x_{16}(t)$	$x_{15}(t)-x_{16}(t)$
8	0	y_8	18	$\eta_{17,18}x_{17}(t)$	$V2H_{cap}z_{18}$
9	0	$x_8(t)$	19	$D_H(t)$	$D_H(t)$
10	$\eta_{9,10}x_9(t)$	$\eta_{9,10}x_9(t)$			

2.2 Sample system

A Japanese household living in a detached house possessing a non-commuting EV was chosen as a typical case study. The yearly power demand of the house was approximated as 5311 kWh/year based on the average yearly demand of detached houses [7]. The time variation $D_H(t)$ was estimated based on information presented in reference [8]. The power demand of the EV $D_{EV}(t)$ was assumed to be typical for that of a non-commuter vehicle and was based on data presented as part of a country-wide survey [9]. Then, the annual mileage of the EV was estimated to be 4881 km/year. The probability of having the EV parked at home is shown in Fig 2. The PV power generation curve per unit capacity $pv_{unit}(t)$ was estimated from solar radiation data [10] for Nagoya city. Then, the capacity factor of the PV was estimated to be 13.98%. The energy cost, the CO_2 emission rate of the grid, and the equipment cost were set as shown in Table 2, assuming that the case study took place in the year 2030. The electricity price $p_1(t)$ was assumed to be the sum of the minimum unit price for domestic customers offered by the Chubu Electric Power company (20.68 JPY/kWh) [11] and the current feed-in tariff payment (2.90 JPY/kWh). The electricity price was assumed to be constant, and the economic impact of the storage system due to differences in hourly electricity prices was not considered. In this paper, the efficiency of SB and V2H was evaluated, focusing on self-consumption of generated PV power. The adopted CO_2 emission rate for grid power was assumed to be the Japanese target value for the year 2030 [12]. The capacity unit cost of PV was assumed with reference to information presented by the Power Generation Cost Verification Working Group [13]. The capacity unit cost of the SB was assumed based on information presented in reference [14]. Th SB cost was approximately 1/4 of the current market price in Japan [15]. The cost of the V2H system was set independently to a sample value for the purposes of this simulation. The charging and discharging maximum power of the EV ($EVch_{cap}$ and $V2H_{cap}$) was assumed to be identical to the typical domestic power for a dwelling of this nature. The vehicle efficiency and the battery capacity of the EV were based on the Nissan Leaf vehicle characteristics: 7 km/kWh and 40 kWh, respectively. The cost of the charging facility, the purchase cost of the EV, and the maintenance cost of the EV were not considered in this study because they were considered to be independent investments in personal mobility.

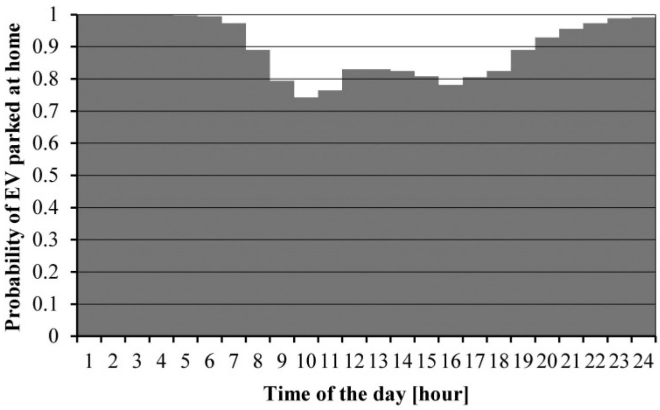

Figure 2: Probability of non-commuting EV parked at home.

Table 2: System parameters.

Equipment	Parameter			Notes
	Variable	Value	Unit	
Grid	$p_1(t)$	23.58	JPY/kWh	Constant
	$p_3(t)$	5.0	JPY/kWh	Constant
	e_1	0.37	kg/kWh	
PV	I_{pv}	8,600	JPY/kW	the initial investment: 258,000 JPY/kW, the product life: 30 years
	M_{pv}	2,580	JPY/kW	1% of the initial investment
	y_2^{max}	10	kW	assuming a rooftop PV
SB	I_{SB}	3,000	JPY/kWh	the initial investment: 30,000 JPY/kW, the product life: 10 years
	M_{SB}	600	JPY/kWh	2% of the initial investment
	y_8^{max}	15	kWh	
	$\eta_{6,7}$	1.0		
	$\eta_{9,10}$	0.86		
V2H	I_{V2H}	15,000	JPY/unit	the initial investment: 300,000 JPY/kW, the product life: 20 years
	M_{V2H}	6,000	JPY/unit	2% of the initial investment
	$V2H_{cap}$	3.3	kW	
	$\eta_{17,18}$	0.9		
EV	$EVch_{cap}$	3.3	kW	
	EV_{SoClb}	8	kWh	20% of battery capacity (40 kWh)
	EV_{SoCub}	32	kWh	80% of battery capacity (40 kWh)
	$\eta_{12,13}$	0.9		

3 Results & discussion

The five introductory combinations of PV, SB, and V2H in Table 3 were evaluated using the multi-objective optimization method. Figure 3 shows the Pareto solution of the cost and amount of CO_2 emission. The conditions applied in this study ensured that the Pareto curves of PV-SB and PV-V2H did not intersect. It was found that introduction of V2H equipment could reduce CO_2 emissions while maintaining equivalent energy costs. In addition, the results of the PV-SB-V2H combination showed that CO_2 emissions could be reduced without significantly increasing costs by using a combination of V2H and SB. For each curve in Fig. 3, the left ends were the results of cost minimization (w = 1) and the right ends were the results of CO_2 emission minimization (w = 0). Table 4 shows the minimum value of the energy cost and the CO_2 emissions, the optimum capacities of PV and SB, and the necessity of V2H. When focusing on cost minimization, the optimum capacity of the PV increased when introducing SB or V2H. It was found that V2H was always adopted under conditions that included V2H as an optimization target (PV-V2H and PV-SB-V2H). When the conditions permitted cooperation between SB and V2H systems, the SB system was not adopted during cost minimization. When focusing on CO_2 minimization, PV and SB capacity reached the installation upper limits in order to reduce the use of grid power as far as possible. Although the battery capacity of the EV was larger than that of SB, the minimum CO_2 emission in the PV-V2H combination was larger than that in PV-SB. In this case study, we found that the EV could not charge excess PV power more than SB having the capacity of 15 kWh due to the probability of EV parked at home.

Table 3: The Combinations to be optimized.

Identifier	Grid	PV	SB	V2H
Grid only	○			
PV	○	○		
PV-SB	○	○	○	
PV-V2H	○	○		○
PV-SB-V2H	○	○	○	○

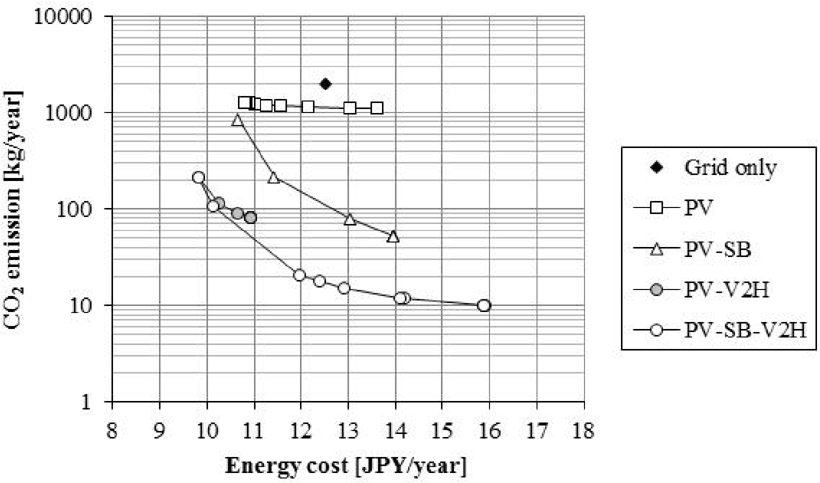

Figure 3: Pareto solution.

Table 4: Results of cost minimization and CO_2 emission minimization.

	Identifier	Energy cost f_{cost} [JPY/year]	CO_2 emission f_{co2} [kg/year]	Cap. of PV y_2 [kW]	Cap. of SB y_8 [kWh]	Necessity of EV z_{18}
Cost minimization	Grid only	12.53	1964.98	0	0	0
	PV	10.81	1279.60	2.65	0	0
	PV-SB	10.67	838.62	3.70	4.08	0
	PV-V2H	9.82	214.26	6.55	0	1
	PV-SB-V2H	9.82	214.26	6.55	0	1
CO_2 minimization	Grid only	12.53	1964.98	0	0	0
	PV	13.60	1095.78	10	0	0
	PV-SB	13.98	51.33	10	15	0
	PV-V2H	10.92	81.54	10	0	1
	PV-SB-V2H	15.91	10.16	10	15	1

4 Conclusion

A multi-objective optimization method was developed to evaluate the environmental and economic characteristics of an EV owner's home incorporating V2H technology. As a case study, the efficiency of V2H technology in a Japanese household possessing a non-commuting EV was evaluated. It was confirmed that this method could be used to derive the operational schedule and optimum capacity of equipment (PV, SB, and V2H) and to evaluate the home energy costs and CO_2 emissions using the Pareto solution. The relationship between the probability of the EV being parked at home and the performance of the V2H system remained an interesting, outstanding question that could possibly be clarified through further parameter studies. In addition, a scenario study analysing the cost and life of SB and V2H equipment could also be considered.

Variables

$x_i(t)$	Electrical energy [kWh]	M_{V2H}	V2H equipment maintenance cost per unit capacity [JPY/unit]
y_2	Capacity of PV [kW]	I_{pv}	Initial cost of PV per unit capacity [JPY/kW]
y_8	Capacity of stationary battery [kWh]	I_{SB}	Initial cost of stationary battery per unit capacity [JPY/kWh]
z_{18}	Binary variable	I_{V2H}	Initial cost of the V2H equipment [JPY/unit]
T	Time step [hour]	$D_H(t)$	Power demand of the house [kWh]
F	Target function	$D_{EV}(t)$	Power demand of the EV [kWh]
f_{cost}	Total cost of energy flow [JPY]	$\eta_{i,j}$	Lost efficiency from x_i to x_j
f_{co2}	Amount of CO_2 emission [kg-CO_2]	$EVch_{cap}$	Capacity of the EV charger [kW]
W	Weight	EV_{SoClb}	EV battery's minimal SoC [kWh]
$p_1(t)$	Electricity purchase price [JPY/kWh]	EV_{SoCub}	EV battery's maximum SoC [kWh]
$p_3(t)$	Electricity sales price [JPY/kWh]	$V2H_{cap}$	Capacity of the V2H equipment [kW]
M_{pv}	PV maintenance cost per unit capacity [JPY/kW]	$pv_{unit}(t)$	PV power generation per unit capacity [kWh/kW]
M_{SB}	SB maintenance cost per unit capacity [JPY/kWh]	e_1	Environmental coefficient [kg-CO_2/kWh]

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