Diffusion of Electric Vehicles and Public and Home Charging Stations in a Two-sided Market

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***Abstract*—The diffusion of electric vehicles (EVs) is affected by the spread of EV public charging stations (PCSs) and vice versa. Their interactions are often referred to as "indirect network effects" and analyzed with a two-sided market model. However, the consumer adoption of home charging stations (HCSs), which are considered key drivers of EV deployment, is often ignored. By modeling a two-sided market of EVs and PCSs (i.e., indirect network effects) under the adoption of HCSs, this study explores the EV diffusion process and considers effective strategies for its spread. We examine two cases: in the first, consumer adoption is determined exogenously; in the second, it is determined endogenously. In each case, we vary the strength of the indirect network effects, which correspond to the drivers' concern referred to as "range anxiety." Through numerical simulations, we evaluate the market shares of EVs, HCSs, and PCSs, as well as social welfare. Our findings have strategic implications for policymakers seeking to increase the market share of EVs in the presence of different types of charging stations without negative social impacts.**

***Index Terms*—Electric vehicles, home charging stations, public charging stations, indirect network effects, two-sided market, simulation**

I. Introduction

Electric vehicles (EVs) are expected to be used for decarbonation under the conditions of global warming. For example, the European Union aims to shift all vehicles to EVs and reduce 100% of CO_2 emissions from vehicles by 2035 [1]. The Japanese government has also declared that by 2035, 100% of new vehicles sold will be electric [2]. Therefore, given the according likelihood of increased demand for EVs, it is necessary to understand the diffusion process of EVs.

The EV diffusion process is significantly affected by the availability of charging stations. Owing to the current limited driving range of EVs, people worry that they will run out of energy on their way to their destinations. This concern is referred to as "range anxiety." The presence of adequate charging infrastructure, that is, public charging stations (PCSs) capable of addressing this anxiety, is crucial for EV adoption [3] [4] [5] [6]. Accordingly, limited infrastructure is a barrier to EV adoption. However, investments in charging networks depend on the number of EVs on the road.

This chicken-and-egg relationship between the diffusion processes of EVs and PCSs can be analyzed using a two-sided market model. In a two-sided market, which involves two groups, one group's benefit from joining a platform depends on the size of the other group that joins the platform [7]. Examples of two-sided markets include compact disk (CD) players and CD titles [8]; credit cards [9]; and video games and game consoles [10] [11].

The effect wherein the utility of participants in a group (e.g., consumers) depends on the number of participants in another group (e.g., suppliers), is often referred to as an "indirect network effect" or "indirect effect." Regarding previous studies on the EV diffusion process, Yu et al. (2016) [12] introduced a sequential game with EV consumers and PCS investors and provided an EV-PCS market equilibrium at a given EV price. Meanwhile, Jang et al. (2018) [13] proposed two-sided market platform competition, including the profit maximization problems of manufacturers, where the EV price is endogenous, and analyzed the EV diffusion process. They show that the market share of EVs is affected differently by energy costs (i.e., gasoline and electricity prices) according to the strength of the indirect network effect. They also show that some policies achieve EV diffusion while also increasing social welfare.

Most previous studies with two-sided market models for EVs exclusively focused on PCSs. Meanwhile, we focus on another type of charging station: home charging stations (HCSs). HCSs enable EV users to charge EVs at home. In particular, some residential homes have installed photovoltaic and battery energy systems [15] [16] [17] that can charge EVs at a low cost. HCSs can enhance consumers' preference for EVs by increasing the availability of charging facilities, which could, in turn, lead to higher levels of EV deployment—Jang et al. (2018) refer to this as a "direct effect" [13][1]. However, HCSs can be substitutes for PCSs. A reduction in PCS may prevent people from adopting EVs through the indirect network effect. The complex interactions between EVs, PCSs, and HCSs, that is, both the direct and indirect effects, should be considered when investigating EV diffusion process. The prevalence of

[1]It should be noted that "direct effect" here does not mean "direct network effects," which are generally used in the two-sided market model. Direct network effects occur when the value of a product depends on other consumers purchasing or using the same product [14].

different types of charging stations is also important in the design of power grids.

Therefore, this study explores the diffusion process and considers effective strategies for spreading EVs by modeling a two-sided market for the EV diffusion process using HCSs (i.e., a direct effect) and PCSs (i.e., an indirect effect). Specifically, we extend the model proposed by Jang et al. (2018) [13] to include the consumer adoption process for HCSs. We analyze two cases: one in which consumer adoption is determined exogenously and one in which it is determined endogenously. In each case, we examine how the diffusion process changes as range anxiety relaxes, which is likely to occur in the future due to improvements in EV storage capacity.

This study contributes policymakers' comprehension of the effects of the HCSs adoption. The findings from the simulations give strategic implications to policymakers seeking to accelerate the market share of EVs. In the case where the adoption of HCSs is controlled at a designated ratio, policymakers should monitor the range anxiety and take some countermeasures in order to prevent the decline of the market share of EVs and the social welfare. In the case where the adoption ratio of HCSs is determined by consumers' behavior, they should take into consideration the enhancement of the energy-saving performance and base utility of HCSs in addition to the change of the range anxiety.

The remainder of this paper is organized as follows. Section II presents our two-sided market model that depicts the relationship between EVs, PCSs, and HCSs. Section III focuses on the case in which the adoption of HCSs is exogenously determined. We show the simulation results for the market shares of EVs and PCSs by introducing HCSs. Section IV focuses on the case in which adoption is endogenous and presents the results. Section V discusses the results, concludes the paper, and describes future research directions.

II. Basic Model: Exogenous Adoption of Home Charging Stations

An overview of the proposed model is presented in Fig. 1. We describe a two-sided model between consumers who purchase either a conventional gasoline vehicle (GV) or an electric vehicle (EV), and energy suppliers who settle for either a gasoline station (GS) or public charging station (PCS). Three types of manufacturers supply products to consumers: GV manufacturers, EV manufacturers, and HCS manufacturers. Competition between GV and EV platforms is structured in the consumer and energy supplier markets. This model assumes that GVs require only gasoline as an energy source to run and EVs require only electricity; thus, GV consumers use GSs, and EV consumers use either PCSs or HCSs. Some EV consumers are assumed to purchase an HCS, which means that these consumers use an HCS instead of PCSs to obtain energy. The adoption ratio of HCSs by EV consumers is denoted by α. This α is defined as an exogenous value in the basic model, which assumes that the government establishes the target penetration rate of HCSs (e.g., in the Netherlands, one of the world's leading EV markets, the deployment of smart chargers is targeted at 70% of the country's EV drivers [18]). The extended model treats α as endogenous in the extended model, which assumes that the sales quantities of HCSs are determined exclusively by EV consumer behavior.

The model includes two periods. In the first period, the GV, EV, and HCS manufacturers decide prices simultaneously to maximize their profits. In the second period, given the prices, consumers and energy suppliers simultaneously decide which platform to join. The game is solved using backward induction. We first describe the decision-making problems in the second period.

A. Consumer Utilities

Consumers are assumed to be uniformly distributed according to their preferences $x \in [0,1]$ for GV platforms and the size of the consumer market is normalized to 1, as in Hotelling's linear city model (Fig. 1). A consumer at $x = 0$ is on the GV platform side, whereas one at $x = 1$ is on the EV platform side. A consumer at position x has lower preferences for GV and EV by $t_c x$ and $t_c(1-x)$, respectively. The utility functions of a consumer at position x are defined in (1) and (2). The consumer has utility u_{GV} and u_{EV} from purchasing a GV and an EV, respectively.

$$u_{GV}(x) = u_0 - t_c x - p_{GV} - r_{GV} + k_c y_{GV} \tag{1}$$

$$u_{EV}(x) = u_0 - t_c(1-x) - p_{EV} - \alpha p_{HC} - r_{EV}(1-\alpha) + k_c y_{EV} \tag{2}$$

The utilities are depicted using the following five components: First, a consumer obtains the same base utility u_0 by owning a vehicle, regardless of whether it is a GV or EV. Second, consumers' preferences for the GV and EV platforms are described by subtracting $t_c x$ and $t_c(1 - x)$, respectively, from the base utilities. Third, the purchasing costs of a GV, an EV, and an HCS are represented by p_{GV}, p_{EV}, and p_{HC}, respectively. These prices are determined by the manufacturer's profit maximization. The adoption ratio of HCSs among EV consumers is α; thus, the term of the HCS purchase cost in the consumer utility function for an EV is calculated as αp_{HC} as an expectation value.

Fourth, the energy costs for running a GV and EV are represented as r_{GV} and r_{EV}, respectively; however, the costs for EV users depend on whether they have HCSs. Consumers with an HCS are assumed to charge EVs at home at low cost instead of using PCSs, as introduced in Section I; thus, they can reduce energy costs. Here, we assume that they can charge at no cost. Owing to this reduction in energy costs, the expansion of access to charging facilities has a direct effect on EV deployment. Hence, the energy cost for EV users is calculated as an expected value $r_{EV}(1 - \alpha)$.

Finally, the indirect network effects from the energy supplier to the consumer are described in the last term of each utility function as $k_c y_{GV}$ and $k_c y_{EV}$. k_c is the indirect network coefficient, and y_{GV} and y_{EV} represent the market shares of the energy supplier on the GV and EV platforms, respectively.

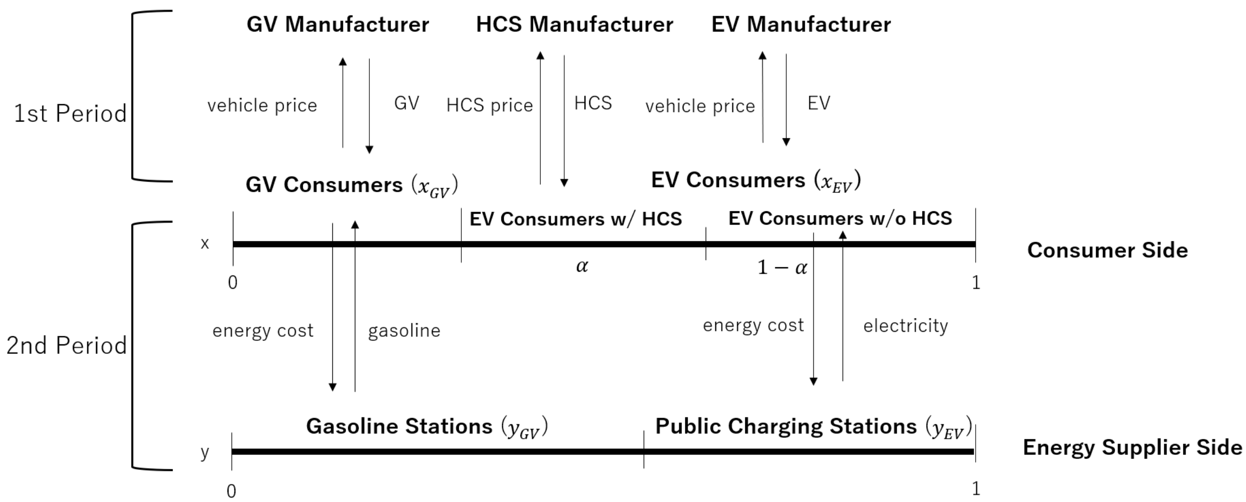


Fig. 1: Overview of the two-sided market model developed based on Jang et al. [13].

The utility of purchasing a GV, u_{GV}, increases as the market share of GSs, y_{GV}, increases, whereas the utility of purchasing an EV, u_{EV}, increases as the market share of PCSs, y_{EV}, increases. The indirect network coefficient from the energy supplier to the consumer, k_c, indicates the degree of range anxiety.

B. Energy Supplier Utilities

In addition to consumers, energy suppliers are assumed to be distributed according to their preferences $y \in [0, 1]$ for the GV platform and their size is normalized to 1 as in Hotelling's linear city model (Fig. 1). The energy supplier at $y = 0$ is on the GV platform side, whereas that at $y = 1$ is on the EV platform side. The energy supplier at position y has a lower preference for GV and EV by $t_s y$ and $t_s(1-y)$, respectively. The energy supplier's utility functions at position y are defined in (3) and (4). The energy supplier has utilities v_{GV} and v_{EV} for setting up a GS and a PCS, respectively.

$$v_{GV}(y) = v_0 - t_s y + r_{GV} + k_s x_{GV} \tag{3}$$

$$v_{EV}(y) = v_0 - t_s(1-y) + r_{EV}(1-\alpha) + k_s x_{EV}(1-\alpha) \tag{4}$$

The utilities have the following four components: First, the base utility v_0 is obtained by setting up the energy station. Second, the energy supplier's preferences for the GV and EV platforms are described by subtracting $t_s y$ and $t_s(1-y)$, respectively, from the base utility. Third, energy suppliers exchange the produced energy for payments made by the consumers. The energy supplier utilities for the GV and EV platforms increase by energy costs r_{GV} and $r_{EV}(1-\alpha)$, respectively. Finally, the indirect network effects from the consumer to the energy supplier are also considered in the last term of the utility functions for the GV platform and EV platform as $k_s x_{GV}$ and $k_s x_{EV}(1-\alpha)$, respectively. The energy cost and indirect network effects on the EV platform are multiplied by $1-\alpha$. This is because we assume that the energy suppliers know the market share of EV consumers, $x_{EV}(1-\alpha)$, who use PCSs instead of HCSs.

C. Manufacturing Profits

The GV, EV, and HCS manufacturers simultaneously determine vehicle and HCS prices to maximize their profits in the first period of the model. The model assumes a monopoly market and each manufacturer produces one type of product. The profits of the GV, EV, and HCS manufacturers are π_{GV}, π_{EV}, and π_{HC}, respectively. The profit maximization problems are formulated as in (5), (6), and (7):

$$\max_{p_{GV}} \pi_{GV} = (p_{GV} - c_{GV}) x_{GV} \tag{5}$$

$$\max_{p_{EV}} \pi_{EV} = (p_{EV} - c_{EV}) x_{EV} \tag{6}$$

$$\max_{p_{HC}} \pi_{HC} = (p_{HC} - c_{HC}) x_{HC} \tag{7}$$

Here, c_{GV}, c_{EV}, and c_{HC} are the unit production costs of GV, EV, and HCS, respectively. The market share of HCS owners among EV consumers is denoted as x_{HC}, which is equivalent to $x_{HC} = \alpha x_{EV}$.

D. Social Welfare

The equilibrium market shares of EVs, x^*_{EV}, and PCSs, y^*_{EV}, are obtained by solving $u_{GV}(x) = u_{EV}(x)$ and $v_{GV}(y) = v_{EV}(y)$ after the prices, p_{GV}, p_{EV}, and p_{HC}, are determined in (5), (6), and (7). The numerical analyses in this study show how the equilibrium market shares of EVs and PCSs change with the introduction of HCSs. Social welfare is also used as an index to investigate the impact of platform competition on society. Social welfare, SW, is defined as the sum of consumer surplus, CS; supplier surplus, SS; and the total profit of the manufacturers, Π, as follows:

$$SW = CS + SS + \Pi \tag{8}$$

Here, consumer surplus, CS; supplier surplus, SS; and total profit, Π are defined as

$$\begin{aligned} CS &= CS_{GV} + CS_{EV} \\ &= \int_{0}^{x^*_{GV}} u_{GV}\, dx + \int_{1-x^*_{EV}}^{1} u_{EV}\, dx \end{aligned} \tag{9}$$

$$\begin{aligned} SS &= SS_{GV} + CS_{EV} \\ &= \int_{0}^{y^*_{GV}} v_{GV}\, dy + \int_{1-y^*_{EV}}^{1} v_{EV}\, dy \end{aligned} \tag{10}$$

$$\Pi = \pi_{GV} + \pi_{EV} + \pi_{HC} \tag{11}$$

Here, CS_{GV} and CS_{EV} represent the consumer surplus of the GV and EV platforms, respectively. Meanwhile, SS_{GV} and SS_{EV} represent the energy-supplier surpluses of the GV and EV platforms, respectively.

E. Parameters

The numerical analyses are conducted by setting the specific parameters listed in Table I. The outcomes show the equilibrium market shares of EVs, x^*_{EV}; PCSs, y^*_{EV}; and social welfare, SW, at each adoption ratio of HCSs, α, according to the indirect network coefficient from the energy suppliers to the consumers, k_c. The shift to an EV society in the future can be depicted as a decrease in k_c because range anxiety will decrease as the battery performance of EVs increases. We change k_c from 0.3 to 0.8. Consequently, we observe the following four different results: as representatives, we demonstrate $k_c = 0.80$ (referred to as "Case I"), $k_c = 0.65$ ("Case II"), $k_c = 0.50$ ("Case III"), and $k_c = 0.30$ ("Case IV").

III. Basic Model Analysis

A. Case I: $k_c = 0.80$

Fig. 2a, Fig. 2b, and Fig. 2c are the results of the equilibrium market shares of EVs and PCSs and social welfare, respectively. The horizontal axes represent the adoption ratios of HCSs. The vertical axes represent market share and social welfare values.

Fig. 2a shows that the equilibrium market share of EVs, x^*_{EV}, decreases when the adoption ratio of HCSs, α, increases. Fig. 2b that shows the equilibrium market share of PCSs, y^*_{EV}, decreases when the adoption ratio increases. The adoption of HCSs decreases the energy cost, r_{EV}, leading to an increase in consumer utility for the EV platform, u_{EV}. However, the indirect network effect from the energy supplier to the consumer decreases utility because of a decrease in the market share of PCSs. The results show that the indirect network effect is stronger than the direct effect (i.e., reduction in energy costs) in (2). The adoption of HCSs also decreases the energy supplier's utility, v_{EV}, because of the reduced expected profit, r_{EV}, and the decreasing market share of EVs (i.e., the indirect network effect from the consumer to the energy supplier). Hence, the equilibrium market share of PCSs decreases owing to adoption.

Fig. 2c shows that social welfare, SW, increases when the adoption ratio of HCSs increases. Social welfare includes the surplus of the GV and EV platforms. The results show that the adoption of HCSs has a positive influence on society, although the market shares of EVs and PCSs decrease.

B. Case II: $k_c = 0.65$

Fig. 3a shows the equilibrium market share of EVs, x^*_{EV}, increases when the adoption ratio of HCSs, α, increases. The indirect network effect from the energy supplier to the consumer affects the consumer's utility u_{EV} more weakly than in Case I. Then, more consumers benefit from energy cost savings, r_{EV}, through the adoption of HCSs. As in Case I, the equilibrium market share of PCSs, y^*_{EV}, decreases (Fig. 3b) and the social welfare, SW, increases (Fig. 3c) by raising the adoption ratio of HCSs, α. The increasing market share of EVs affects the energy supplier's utility, v_{EV}, as an indirect network effect; however, the result shows that the reduction in energy cost, r_{EV}, dominates the indirect network effect in (4).

C. Case III: $k_c = 0.50$

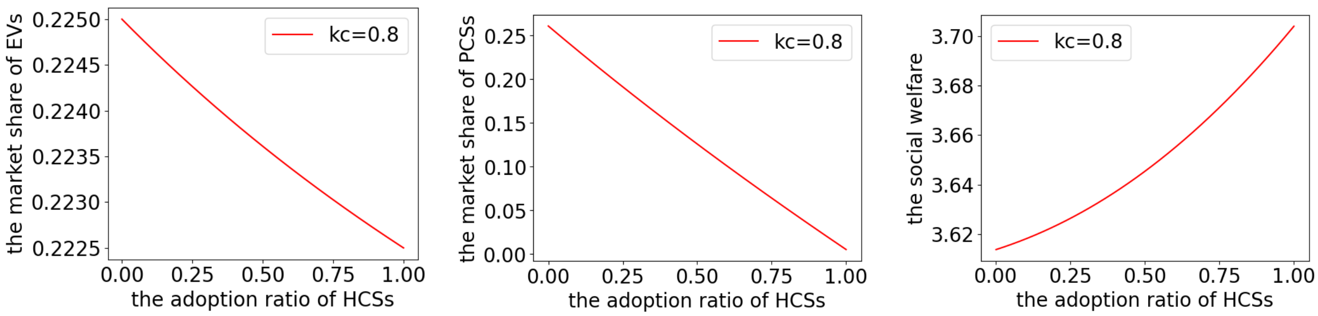
Fig. 4a shows that the equilibrium market share of EVs, x^*_{EV}, increases when the adoption ratio of HCSs, α, increases, as in Case II. Fig. 4b shows that the equilibrium market share of PCSs, y^*_{EV}, decreases when the adoption ratio increases, as in Cases I and II. Compared to previous cases, Fig. 4c shows that social welfare, SW, decreases in the lower adoption ratio of HCSs (until around $\alpha = 0.3$) and increases in the higher adoption ratio (from around $\alpha = 0.3$). The results show that the introduction of a small number of HCSs has adverse effects on the society.

D. Case IV: $k_c = 0.30$

Fig. 5a shows that the equilibrium market share of EVs, x^*_{EV}, increases when the adoption ratio of HCSs, α, increases, as in Cases II and III. Fig. 5b shows that the equilibrium market share of PCSs, y^*_{EV}, also decreases when the ratio increases, as in Cases I, II, and III. Similar to Case III, Fig. 5c shows that social welfare, SW, decreases in the lower adoption ratio (until around $\alpha = 0.5$) and increases in the higher adoption ratio (from around $\alpha = 0.5$). However, even when all EV consumers own HCSs ($\alpha = 1$), social welfare is less than without introducing HCSs.

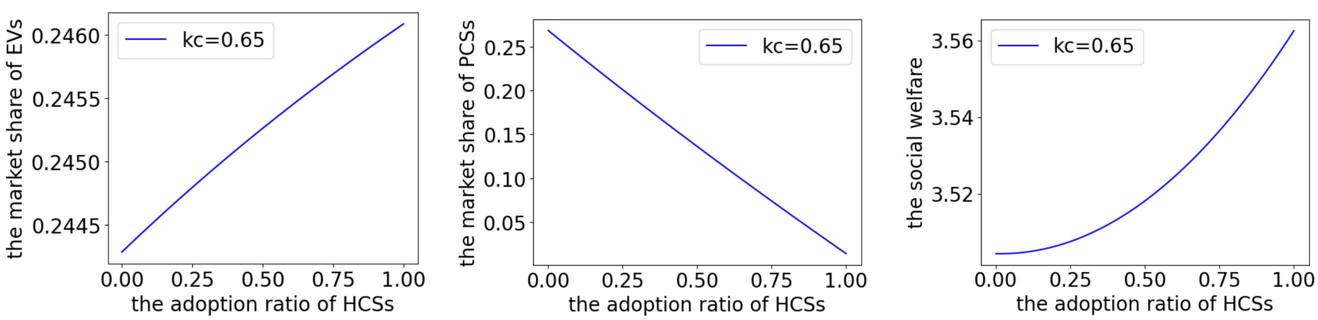
TABLE I: The values of parameters used in the simulation

Param.	Description	Eq.	Value
u_0	Base utility for purchasing a vehicle	(1) (2)	3.40
v_0	Base utility for settling a station	(3) (4)	0.80
t_c	Preference coefficient in consumer side	(1) (2)	1.00
t_s	Preference coefficient in energy supplier side	(3) (4)	1.20
k_s	Indirect network coefficient from consumer to supplier side	(3) (4)	0.50
r_{GV}	Energy cost of GV	(1) (3)	0.75
r_{EV}	Energy cost of EV	(2) (4)	0.45
c_{GV}	Production cost of GV	(5)	0.50
c_{EV}	Production cost of EV	(6)	1.40
c_{HC}	Production cost of HCS	(7)	0.20



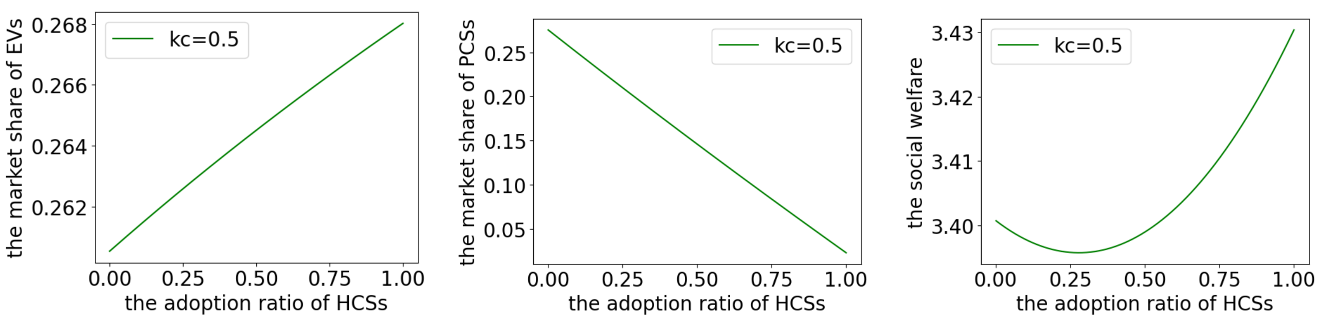
(a) (b) (c)

Fig. 2: Results of Case I: (a) the market share of EVs, (b) that of PCSs, and (c) social welfare, according to the adoption ratio of HCSs.



(a) (b) (c)

Fig. 3: Results of Case II: (a) the market share of EVs, (b) that of PCSs, and (c) social welfare, according to the adoption ratio of HCSs.



(a) (b) (c)

Fig. 4: Results of Case III: (a) the market share of EVs, (b) that of PCSs, and (c) social welfare, according to the adoption ratio of HCSs.

IV. Extended Model: Endogenous Adoption of Home Charging Stations

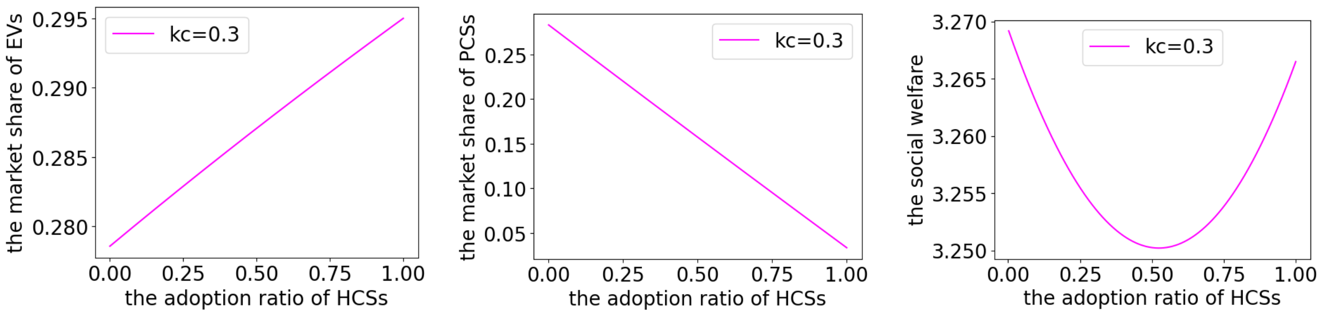
A. Structure of the extended model

Consumers determine whether to purchase an HCS by considering the utility of owning an HCS, u_{HC}, or not owning it, u_{nonHC}. These utilities are formulated as follows:

$$u_{HC} = u_w - p_{HC} - t_h r_{EV} + k_c y_{EV} + \epsilon_1 \tag{12}$$

$$u_{nonHC} = -r_{EV} + k_c y_{EV} + \epsilon_2 \tag{13}$$

Here, u_w is the base utility gained from holding an HCS. The energy-saving performance of HCSs is represented by t_h ($0 < t_h < 1$), and the reduced energy cost is expressed as $t_h r_{EV}$. When t_h is low, the energy-saving performance is high. The terms ϵ_1 and ϵ_2 represent the unobserved preferences for having and not having an HCS, respectively. These terms are assumed to follow a Gumbel distribution. Hence, the discrete choice model is considered by logit model, and the equilibrium adoption ratio of HCS owners among EV consumers, α^*, is



(a)

(b)

(c)

Fig. 5: Results of Case IV: (a) the market share of EVs, (b) that of PCSs, and (c) social welfare, according to the adoption ratio of HCSs.

obtained as

$$\alpha^* = 1 - \frac{1}{\exp(u_w - p_{HC} + (1-t_h)r_{EV}) + 1} \tag{14}$$

Considering this decision process, the utility function of EV consumers can be extended from (2) as follows:

$$u_{EV}(x) = u_0 - t_c(1-x) - p_{EV} + \mathbb{E}[\max(u_{HC}, u_{nonHC})] \tag{15}$$

The term describing the purchasing cost of HCS, energy cost, and indirect network effect is expressed in the expectation form $\mathbb{E}[\max(u_{HC}, u_{nonHC})]$, which can be calculated using the logit model as follows:

$$\begin{aligned} &\mathbb{E}[\max(u_{HC}, u_{nonHC})] \\ &= \ln[\exp(u_w - p_{HC} - t_h r_{EV} + k_c y_{EV}) \\ &\qquad + \exp(-r_{EV} + k_c y_{EV})] \end{aligned} \tag{16}$$

Similar to the previous section, numerical analyses are conducted with different k_c values under the same parameter values as in Table I, with $t_h = 0.50$ and $u_w = 1.20$. We also demonstrate how the base utility of HCS, u_w, and the energy-saving performance of HCS, t_h, change the equilibrium. This analysis is motivated by future improvements in the energy-saving performance, which can be described as lowering the value of t_h. In addition, one particular type of HCS—vehicle-to-home (V2H) devices—are becoming increasingly popular. V2H devices enable EVs to supply power to homes, which saves energy in daily life and maintains quality of life during blackouts [19] [20], thereby increasing the base utility, u_w.

B. Numerical analysis of the extended model

Table II shows the equilibrium results for the adoption ratio of HCSs, α^*; market share of EVs, x^*_{EV}; HCSs, x^*_{HC}; PCSs, y^*_{EV}; and social welfare, SW. When the indirect network coefficient is smaller, the equilibrium adoption ratio, α^*, increases as the purchase price of HCSs increases. Then, the market share of PCSs decreases owing to an increase in the adoption ratio of HCSs or a decrease in the coefficient. Meanwhile, the market share of EVs decreases because of an increase in their purchase price and a decreases in the market share of PCSs and the coefficient. The adoption ratio, α^*, increases, but the market share of EVs, x^*_{EV}, decreases. The market share of HCSs, x^*_{HC}, decreases when the coefficient, k_c, decreases.

However, an improvement in the energy-saving performance of HCSs, t_h, and the base utility, u_w, can cause EV markets to flourish. Table IIIa shows the results of the adoption ratio, α^*; equilibrium market shares, x^*_{EV}, y^*_{EV}, and x^*_{HC}; and social welfare, SW, according to the charging capacity of HCSs, t_h. Here, k_c and u_w are set to 0.45 and 1.20, respectively. The decrease in t_h leads to an increase in the adoption ratio of HCSs, the market shares of EVs and HCSs, and social welfare. Table IIIb shows the results according to the base utility, u_w. Here, k_c and t_h are set to 0.45 and 0.50, respectively. The adoption ratio, α^*; market share of EVs, x^*_{EV}; market share of HCSs, x^*_{HC}; and social welfare, SW increase as the base utility, u_w, increases.

V. Discussion and Conclusion

The diffusion of EVs is crucial for a decarbonized society organized against global warming. This study aims to unveil the diffusion process and consider effective strategies for the spread of EVs by modeling a two-sided market for the EV diffusion process with PCSs (i.e., indirect effects) and HCSs (i.e., direct effects), as a simple extension of Jang et al. (2018) [13]. Numerical analyses clarified the complex interactions among EVs, PCSs, and HCSs.

Section III investigates the case in which the adoption ratio of HCSs (i.e., α in (2)) is exogenously determined. An example of this is when the government instructs car dealerships to sell HCSs together at a designated ratio. The findings of this section can be summarized as follows: (i) the HCSs always substitute for the PCSs; (ii) the HCSs affect the market share of EVs differently according to the strength of indirect network effects (i.e., range anxiety); and, consequently, (iii) the effect of HCSs on social welfare varies according to the strength of the indirect network effects.

(i) Adopting HCSs always decreases the equilibrium market share of PCSs (see Fig. 2b, Fig. 3b, Fig. 4b, and Fig. 5b). This is because the energy suppliers on the EV platform expect to earn less profit owing to the reduction in energy costs even

TABLE II: the adoption ratio of HCSs, the size of the EV platform, and social welfare with different indirect network coefficients

k_c	α^*	x^*_{EV}	x^*_{HC}	y^*_{EV}	SW
0.80	0.45	0.64	0.29	0.29	4.95
0.60	0.46	0.57	0.26	0.26	4.81
0.45	0.48	0.52	0.25	0.24	4.70
0.30	0.49	0.47	0.23	0.22	4.58

TABLE III: the adoption ratio, the size of the EV platform, and social welfare with different (a) charging capacities and (b) base utilities

(a)

t_h	α^*	x^*_{EV}	x^*_{HC}	y^*_{EV}	SW
0.50	0.48	0.52	0.25	0.241	4.70
0.20	0.50	0.53	0.26	0.238	4.76
0.01	0.52	0.54	0.28	0.236	4.80

(b)

u_w	α^*	x^*_{EV}	x^*_{HC}	y^*_{EV}	SW
0.50	0.34	0.46	0.16	0.26	4.45
1.20	0.48	0.52	0.25	0.24	4.70
2.00	0.61	0.59	0.36	0.22	5.11

though the equilibrium market share of EVs increases. This result is consistent with Jang et al. (2018) [13], who showed that the equilibrium market share of PCSs decreased because of the energy cost reduction. However, our model included HCSs; thus, the chargers' market share differs from that in Jang et al. (2018) [13]. This difference encourages further consideration of power grid design.

(ii) In Case I, the equilibrium market share of EVs decreases with the adoption of HCSs (Fig. 2a). This is because a reduction in the market share of PCSs (i.e., a strong indirect effect from suppliers) discourages consumers from purchasing EVs, although HCSs reduce energy costs. In contrast, when the indirect network effect is weaker, the equilibrium market share of EVs increases by adopting HCSs (Fig. 3a, Fig. 4a, and Fig. 5a). This is because the indirect effect becomes weaker and EV consumers benefit more from energy cost reduction owing to HCS adoption. These results imply that policymakers should monitor range anxiety when introducing HCSs.

(iii) The adoption of HCSs increases social welfare in Cases I and II (Fig. 2c and Fig. 3c, respectively). However, when range anxiety is relaxed, social welfare decreases, with a lower adoption ratio of HCSs in Case III (Fig. 4c). In such cases, policymakers should set a higher HCS adoption ratio as a target to increase social welfare. Moreover, in Case IV (i.e., when range anxiety was mostly relieved), social welfare was never greater than that without the HCSs (Fig. 5c). In the future, when EV storage capacity improves (which relaxes users' range anxiety), policymakers interested in accelerating EV penetration should develop countermeasures to resolve this adverse impact. In sum, HCSs have different effects on the EV diffusion process and social welfare, depending on the balance between the direct and indirect effects. Policymakers should comprehend and monitor these effects and set targets to increase the market share of EVs without the negative social impacts.

Section IV extends the model to consider the endogenous adoption ratio of HCSs. Each consumer decides whether to purchase an HCS according to their utility. The equilibrium market shares of EVs, PCSs, and HCSs decrease as range anxiety relaxes (Table II). However, the equilibrium adoption ratio of HCSs among EV consumers (i.e., α^*) increases, indicating that EV consumers cope with a shortage of PCSs by purchasing HCSs. Meanwhile, in this scenario, social welfare decreases, as shown in Table II. This indicates that the relaxation of range anxiety itself has an adverse impact on society.

The decline in the EV market share and social welfare can be prevented by enhancing the energy-saving performance and base utility of HCSs (Tables IIIa and IIIb). In the future, when EV storage capacity improves (which relaxes users' range anxiety), the energy-saving performance of HCSs should also be developed to spread EVs and HCSs and enhance social welfare. As mentioned in Section IV, promoting the benefits of HCSs, including V2H devices, can increase the base utility of HCSs and should thus be encouraged.

Because the above results are fundamental, several issues need to be addressed in future studies. First, this model ignores the load on the electricity grid. Although the risk of overload is low in the early stages of EV diffusion, a peak in demand is no longer negligible if EVs are widely spread [5]. Thus, the model should consider the limited amount of electricity supplied, which may affect the diffusion process of chargers. Second, our results are based on hypothetical simulations; therefore, an empirical analysis is required. In particular, it is important to explore the extent to which people experience range anxiety (i.e., the value of k_c) to implement effective strategies.

ACKNOWLEDGMENT

This study was supported partly by the Japan Society for the Promotion of Science (KAKENHI Grant No. 21K04288). We would like to thank Editage (www.editage.com) for English language editing.

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