Optimal Charging Station Investment Strategy for Eco-Friendly Vehicle Manufacturers: An Empirical Study of the Korean Market

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1 Introduction

Background | Global Eco-friendly vehicle policy trend

Global Eco-friendly vehicle policies [1]

1. USA (Multi-State ZEV Action Plan, Nov '19)
- Aim: 3.3 million cumulative Eco-friendly vehicles in 10 states by 2025
- California to ban ICEV sales after 2025

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2. Japan (Strategies for Green Growth, Nov '20)
- Goal: Achieve 100% share of Eco-friendly vehicle sales in new passenger vehicles by 2030

3. China (New Energy Vehicle Industry Development Plan, Nov '20)
- Target: Achieve 100% share of Eco-friendly vehicle sales by 2035

4. EU (Fit for 55, Jun '22)
- Plan: Ban sales of internal combustion engine vehicles starting from 2035.

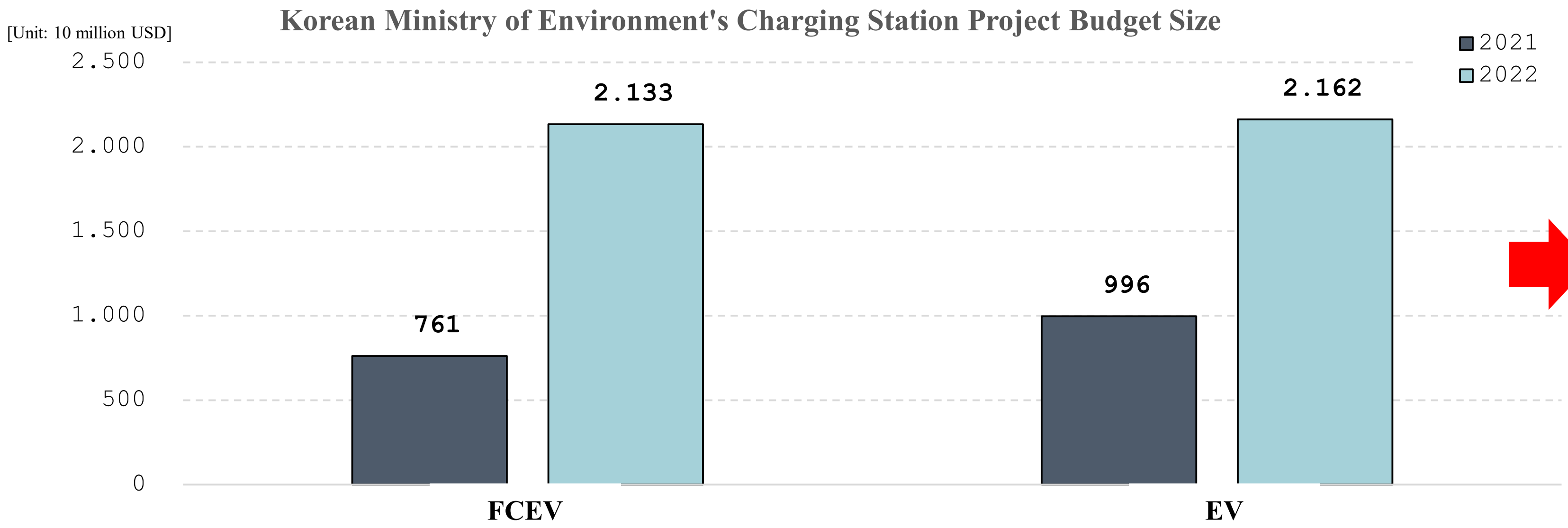
The Eco-friendly vehicle policy of Korea

- The 4th Eco-Friendly Vehicle Basic Plan (2021-2025)[1]
  - In February 2021, South Korea announced the 4th Eco-Friendly Vehicle Basic Plan.
  - The Basic Plan outlines the fundamental strategies for promoting eco-friendly vehicles from 2021 to 2025.
  - Objective: Achieve 83% of new car sales as eco-friendly vehicles by 2030

1) Korean Government Interagency Joint (2021), The 4th Eco-Friendly Vehicle Promotion Plan
2) European Council, Fit for 55, URL: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/, Access date: 2022. 7. 30.

Problem | Limited Private Investment in Charging Stations

- Insufficient Economic Viability Resulting in Low Private Investment in Charging Stations
  - In 2020, South Korea had a private charging station ratio of 26% for EV and 22% for FCEV[4]
  - The Korean government implemented policies to support charging stations, including a 50% installation cost subsidy for fast-chargers and reductions in operational expenses and lease fees for FCEV stations[2]
  - However, A 2021 survey on the subsidy program for hydrogen refueling stations found that about 94% of the surveyed stations were operating at a deficit due to insufficient economic viability [1]

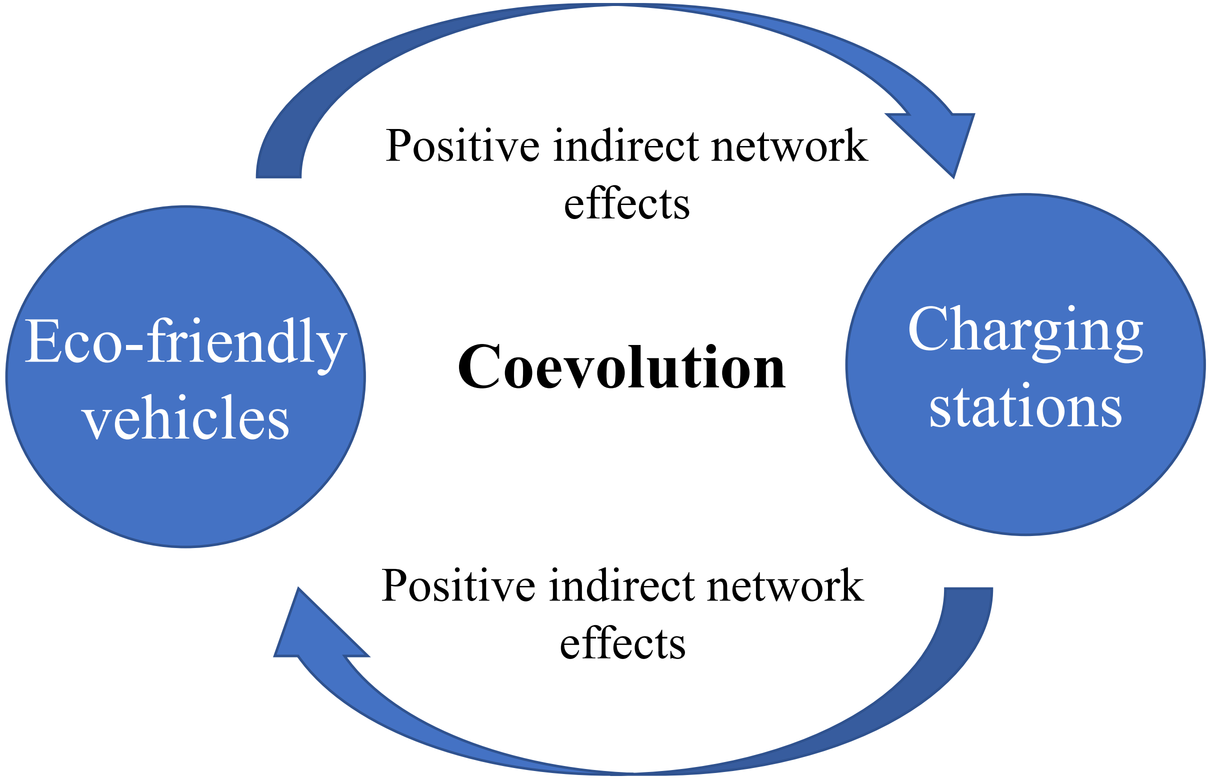


Facing Government Budget Shortage

1) Ministry of Environment, Apr. 28, 2022, Selection and Notification of 2021 Hydrogen Refueling Station Fuel Purchase Subsidy Recipients (Press Release)
2) Government Interagency Joint, 2021, 4th Eco-Friendly Vehicle Promotion Plan
3) Interagency Cooperation, Feb. 21, 2021, Priority Projects by BIG3 Industries
4) Ministry of Environment, Electric Vehicle Statistics Portal, URL: https://www.ev.or.kr/portal/main, Accessed: Jul. 28, 2022

Background | Coevolution between Eco-friendly vehicle and charging stations

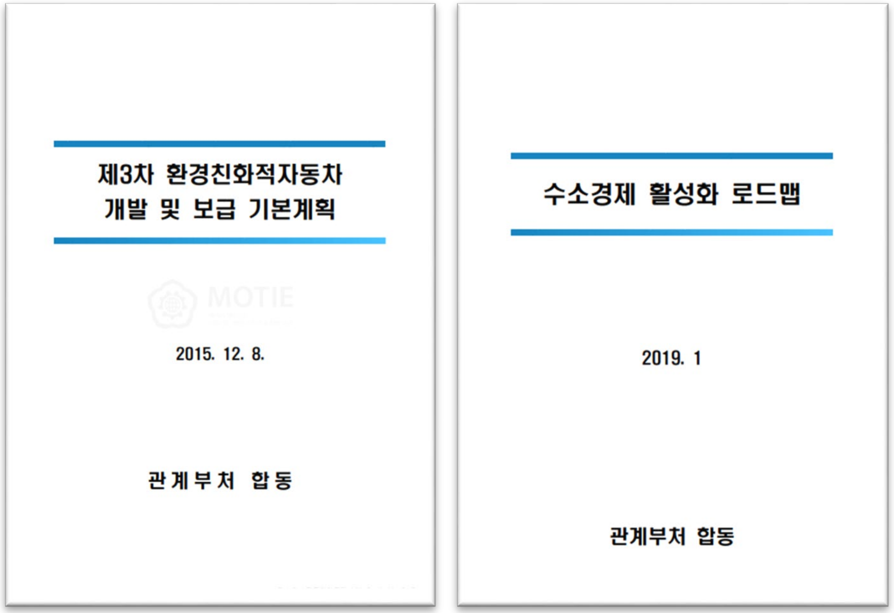
Increased Charging Demand Leading to Higher Profitability



Enhanced Eco-Friendly Vehicle Utility through Reduced Driving Anxiety and Increased Charging Convenience

Background | Hydrogen policy in Korea

- Market and Policy Characteristics of Hydrogen vehicle in Korea
  - High availability of secondary hydrogen in Korea
  - In 2019, global FCEV sales were 7,574 units, with Korea accounting for 63.6%.[1]
  - Secondary hydrogen for automotive use in Korea: 100,000 tons annually (equivalent to 500,000 NEXO vehicles).[2]


제3차 환경친화적자동차
개발 및 보급 기본계획
2015. 12. 8.
관계부처 합동

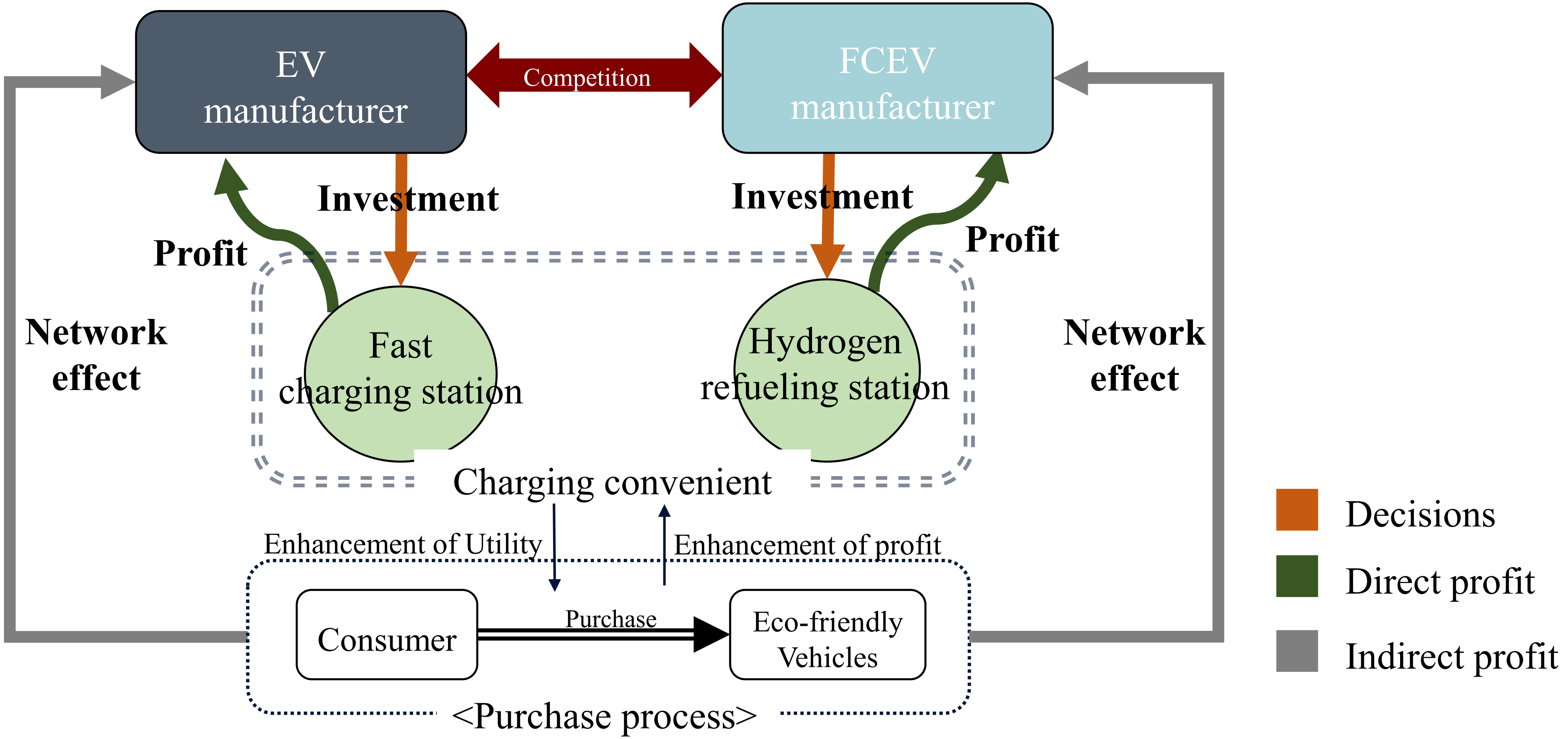
수소경제 활성화 로드맵
2019. 1
관계부처 합동

Main Policies for Hydrogen Vehicles in Korea

1) Frost & Sullivan(2020), Strategic Collaborations Towards Technology Development Transforming The Global Fuel Cell Vehicles Market(2020-2030)
2) Gas Safety Research Institute (2017), Study on Hydrogen Industry Safety Management Policies.

Research framework | Optimal charging station investment strategy

- ✓ Network effects considered
- ✓ The situation after the implementation of the ICEV ban policy is also modeled



Literature reviews

- Indirect network
  - **Pioneering Study on Indirect Network Effects:**
    : Katz&Shapiro (1985) classified positive feedback as direct/indirect network effects, presenting the concept of network effects.
  - **Research on Winner-Takes-All Phenomenon due to Indirect Network Effects**
    : Rochet & Tirole (2002, 2003, 2006) introduced the concept of two-sided markets, highlighting the likelihood of a winner-takes-all phenomenon due to indirect network effects. Their work was recognized with the Nobel Prize in 2014
- Quantifying Indirect Network Effects in Eco-friendly Vehicles
  - **Analysis of Indirect Network Effects through Discrete Choice Theory**
    : In various studies, including Kim et al. (2020), the effects of indirect networks were estimated based on choice games
- Main contributions

1. Empirical analysis of indirect network effects considering companies supplying two interconnected products (e.g., hardware and software).
2. Utilizing practical discrete choice theory for empirical analysis on the level of indirect networks instead of parameter assumptions in previous studies.
3. Previous studies have focused on pricing problems. But we focused on optimal strategies for essential charging station investments in the eco-friendly vehicle market.
4. Conducting the first empirical analysis on optimal charging station investment strategies in the Korean market.

2

Model

Model | Consumer Decision Model in Vehicle Market

- Assumptions
  - There are only two vehicle types in the vehicle market.
- Utility function of vehicle

$$U_i(CS_i) = V_i(CS_i) + \varepsilon_i$$
$$\text{where}$$
$$V_i(CS_i) = \alpha \cdot \frac{CS_i}{GS} + \boldsymbol{\beta}^{\mathrm{T}} \mathbf{x}_i$$

- U_i: *The utility of consumer for vehicle type i*
- α: *The coefficient of refuel station accessibility*
- $\boldsymbol{\beta}, \boldsymbol{x}$: *The coefficient and value vector of other attributes*
- CS: *The number of charging stations of the firm*
- GS: *The number of gas stations*

- Market share

$$P_i(CS_i, CS_{-i}) = S_i(CS_i, CS_{-i}) = P(U_i(CS_i) > U_{-i}(CS_{-i}))$$
$$= P(V_i(CS_i) + \varepsilon_i > V_{-i}(CS_{-i}) + \varepsilon_{-i}) = \frac{e^{V_i}}{e^{V_{-i}} + e^{V_i}}$$

- P_i: *The probability of purchasing vehicle type i*
- S_i: *The market share of vehicle type i*

Model | Profit Model for Eco-friendly Vehicle Manufacturer

- Assumptions
  - There are only two firms in the market, one for Electric Vehicles (EV) and one for Fuel Cell Electric Vehicles (FCEV).
  - Only these two firms provide charging stations.
  - All parameters are constant and not subject to change (Static model).

- Profit model for Eco-friendly vehicle manufacturers

$$\pi_i(CS_i, CS_{-i}) = Q_i(CS_i, CS_{-i})(PC_i \cdot m_i + AL \cdot CR_i) - IC_i \cdot CS_i$$

where

$$Q_i(CS_i, CS_{-i}) = MS \cdot P_i\left(CS_i, CS_{-i}\right)$$

$$CR_i = FE_i \cdot DD \cdot FP_i$$

$$IC_i = \left(CC_i + ISC_i\right)\left(\frac{r(1+r)^{L_i}}{(1+r)^{L_i} - 1}\right) + OC_i$$

$$CS_i^{Min} \leq CS_i$$

- *PC : The price of alternative fuel vehicle*
- *m : The margin rate of Eco-friendly vehicle*
- *AL : The average length of vehicle ownership*
- *FE : Fuel economy*
- *FC : Fuel price*
- *DD : Annual Average Driving Distance*
- *CC: The cost of charger*
- *ISC: The cost of charger installation*
- *OC: The operation cost of charging station*

Model | Market potential size and fundamental condition

- ***Definition 1***

Market potential size: $$MS \cdot (PC_i \cdot m_i + AL \cdot CR_i)$$

- The maximum profit that Eco-friendly vehicle type I can obtain

- ***Proposition 1***

The optimal charging station investment level for a company always exists. Furthermore, charging station investment is not economically viable if the marginal revenue is not greater than four times the investment cost ($\alpha / GS \cdot K < 4 \cdot IC$).

- If the profit in the optimal investment strategy is negative, the market cannot form, rendering the analysis of the optimal strategy meaningless. Therefore, we assume that the profit in the optimal investment strategy is positive.

- Proposition 1 represents the fundamental condition for charging station investments to be economically viable.

Model | Market potential size and fundamental condition

- ***Proposition 2.***

If the competitor's charging station investment level remains constant and the investment in charging stations is economically viable, the optimal level of charging station investment is unique and expressed as below. Additionally, at the optimal investment level, the Eco-friendly vehicle dominate the market.

$$CS_i^*(CS_{-i}) = CS_{-i} + \frac{GS}{\alpha}\ln\left(\frac{\frac{\alpha}{GS}\cdot K_i - 2IC_i + \sqrt{\left(\frac{\alpha}{GS}\cdot K_i - 4IC_i\right)\frac{\alpha}{GS}\cdot K_i}}{2IC_i}\right) - \frac{GS}{\alpha}\boldsymbol{\beta}^{\mathbf{T}}(\mathbf{x}_i - \mathbf{x}_{-i})$$

- The optimal investment strategy can be either the minimum or the dominant level.

- The dominant level can be interpreted based on the number of competitor's charging stations, adjusted to compensate for insufficient utility compared to competitors, and invest to achieve market dominance.

Model | Market potential size and fundamental condition

- ***Proposition 3.***

The revenue at the dominant level remains the same regardless of the investment level of competitor, and its value is as follows:

$$K_i - \frac{2IC_i \cdot K_i}{\frac{\alpha}{GS} \cdot K_i + \sqrt{\left(\frac{\alpha}{GS} \cdot K_i - 4IC_i\right)\frac{\alpha}{GS} \cdot K_i}}$$

- Proposition 3 indicates that at the dominant level, the market share and revenue remain constant regardless of the investment levels of competitor, determined by distinct vehicle characteristics, including charging station costs, market potential, and indirect network coefficients.

Model | Market potential size and fundamental condition

- ***Definition 2.***

The profit difference function, $\mathbf{DF}\left(\mathbf{CS_i} \middle| \mathbf{CS_{-i}}\right)$, between the minimum investment strategy and the maximum investment strategy for the given competitor's investment levels, is defined as the decision function, and its form is as follows.

$$DF(CS_i \,|\, CS_{-i}) = \pi_i(CS_i^* \,|\, CS_{-i}) - \pi_i(CS_i^{Min} \,|\, CS_{-i})$$

- If the decision function is positive, it indicates that the dominant level is optimal, and vice versa.
- The best-response function can be expressed using the decision function.

$$BS(CS_i \,|\, CS_{-i}) = \begin{matrix} CS_i^* & \left\{CS_{-i} \,|\, F(CS_i \,|\, CS_{-i}) \geq 0\right\} \\ CS_i^{Min} & \left\{CS_{-i} \,|\, F(CS_i \,|\, CS_{-i}) < 0\right\} \end{matrix}$$

Model | Market potential size and fundamental condition

- ***Proposition 4.***

> ***The decision function has one local minimum and one local maximum. Both values are constants regardless of $\mathbf{CS_{-i}}$, with the value at the local minimum being 0. Consequently, the optimal strategy transitions to the minimum investment from the dominant level with a single switch as CS_(-i) increases.***

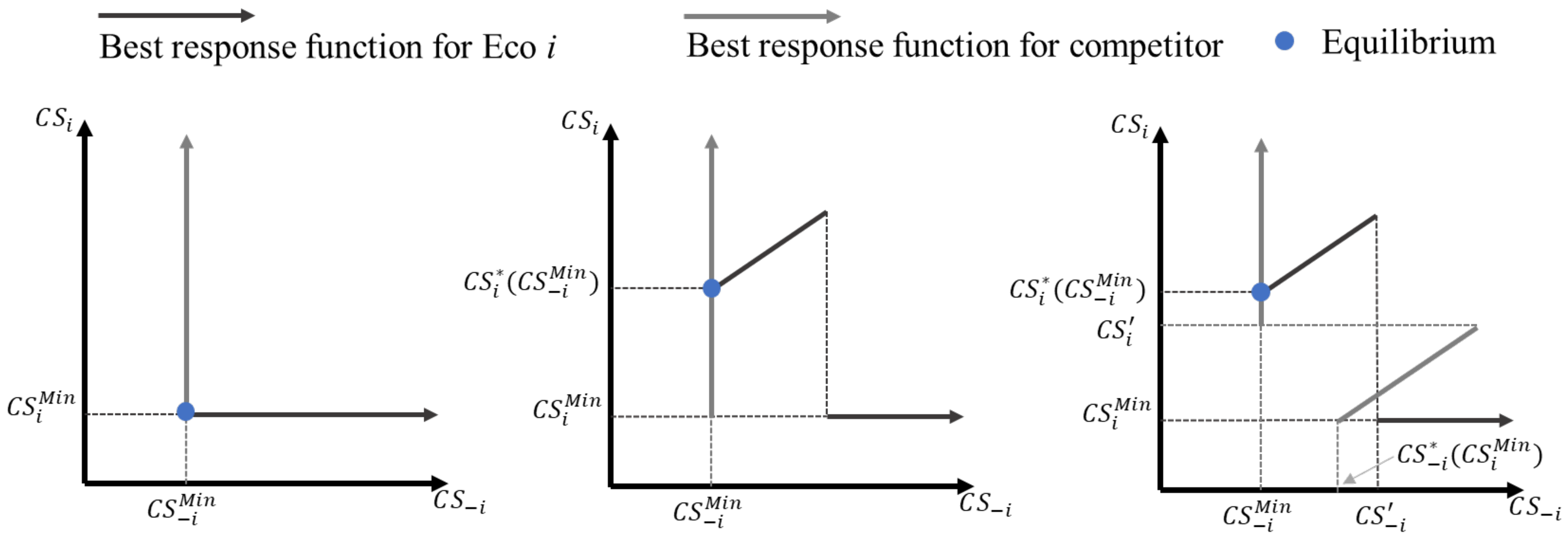
- The best-response function is determined by a specific transition point (CS'_{-i}). If $\mathrm{CS_{-i}} \leq CS'_{-i}$, the dominant level is the optimal, otherwise the minimum investment becomes the optimal response.

- The transition point (CS'_{-i}) can not be express as closed form.

Model | Market potential size and fundamental condition

- ***Theorem***

If the economic viability of charging station investments exists, the equilibrium of competition takes the form of a winner-takes-all market, where the winner dominates the market.



3 Empirical analysis

Empirical Analysis | Vehicle cost data

- Vehicle models

Hyundai NEXO

Hyundai KONA EV, Gasoline

Models	Price (KRW)	Fuel economy (Km/Unit)	Fuel margin (KRW/Unit)	Subsidy (KRW)
NEXO	67,650,000 (USD 48,000)	96.2	1,478 (USD 1.06/Kg)	33,500,000 (USD 24,000)
KONA EV	46,900,000 (USD 33,500)	5.6	177.4 (USD 0.127/KWh)	12,000,000 (USD 8,600)
KONA G	22,440,000 (USD 16,000)	13.6	-	

Empirical Analysis | Data

- Charging station costs

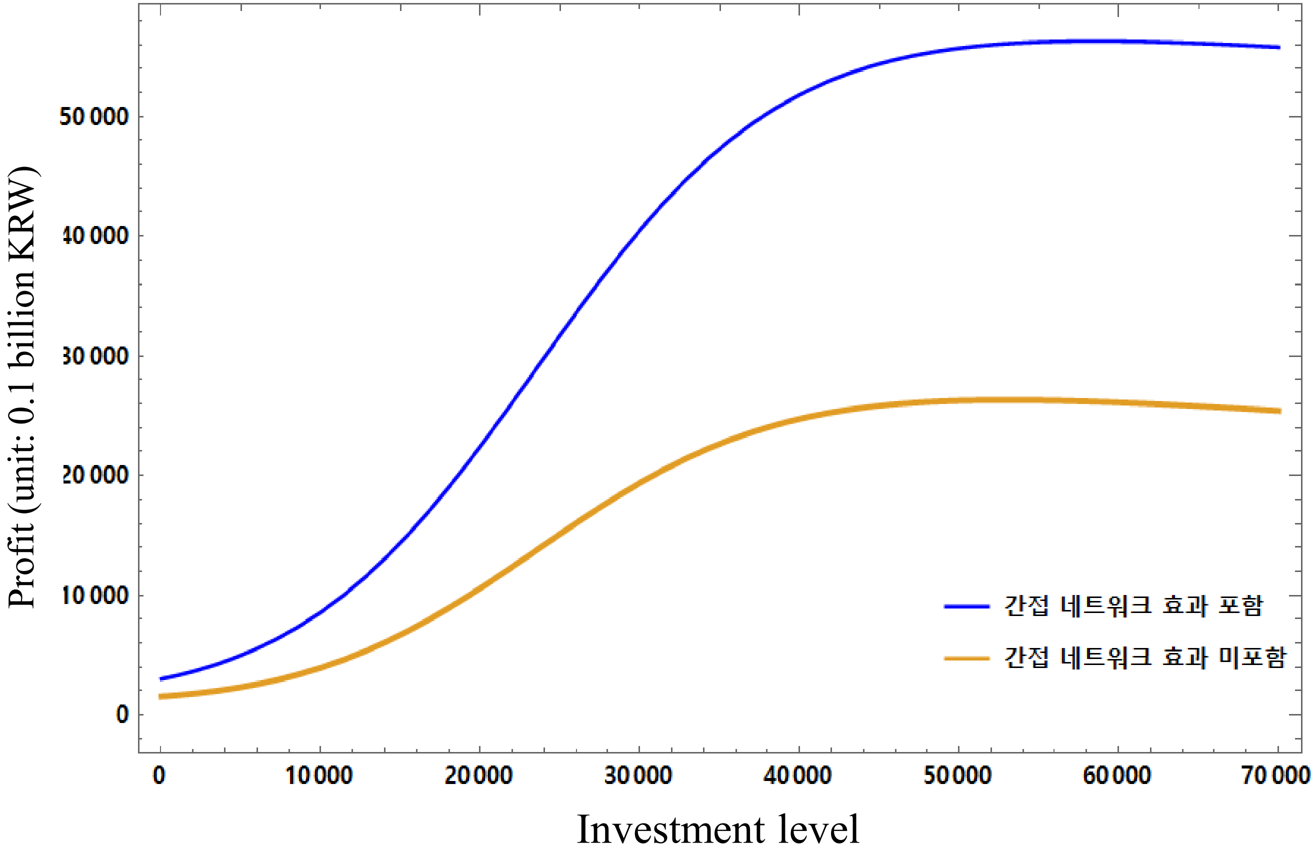
Type	Charging station	Charger costs (1,000 KRW)	Installation Cost (1,000 KRW)	Operation Cost (1,000 KRW)	Life
FCEV	Naphtha cracking- tube trailer	180,000[1]	900,000[1]	273,052[2]	20[7]
BEV	Fast-Charging	40,000[4]		4,225[5]	10[8]

1) Ministry of Related Agencies (2019), Hydrogen Economy Activation Roadmap
2) Korea Energy Economics Institute (2020), Strategic Study for the Early Establishment of a Market-Led Hydrogen Economy
3) Seoul Metropolitan Government, Evaluation Report for the Operation of Sangam Hydrogen Station Production Facilities
4) Gyeonggi Research Institute (2017), Study on Appropriate Installation Standards for Electric Vehicle Charging Infrastructure in Gyeonggi Province
5) Korea Economic Research Institute (2017), Study on the Activation of Electric Vehicle Charging Business
6) Ministry of Related Agencies, 4th Basic Plan for Eco-friendly Vehicles
7) Viktorsson et al. (2017)
8) Ministry of Trade, Industry, and Energy (2016), Business Feasibility Analysis Based on Market Acceptance of New Energy Industries

- Coefficients of utility function (Kim et al. (2020))

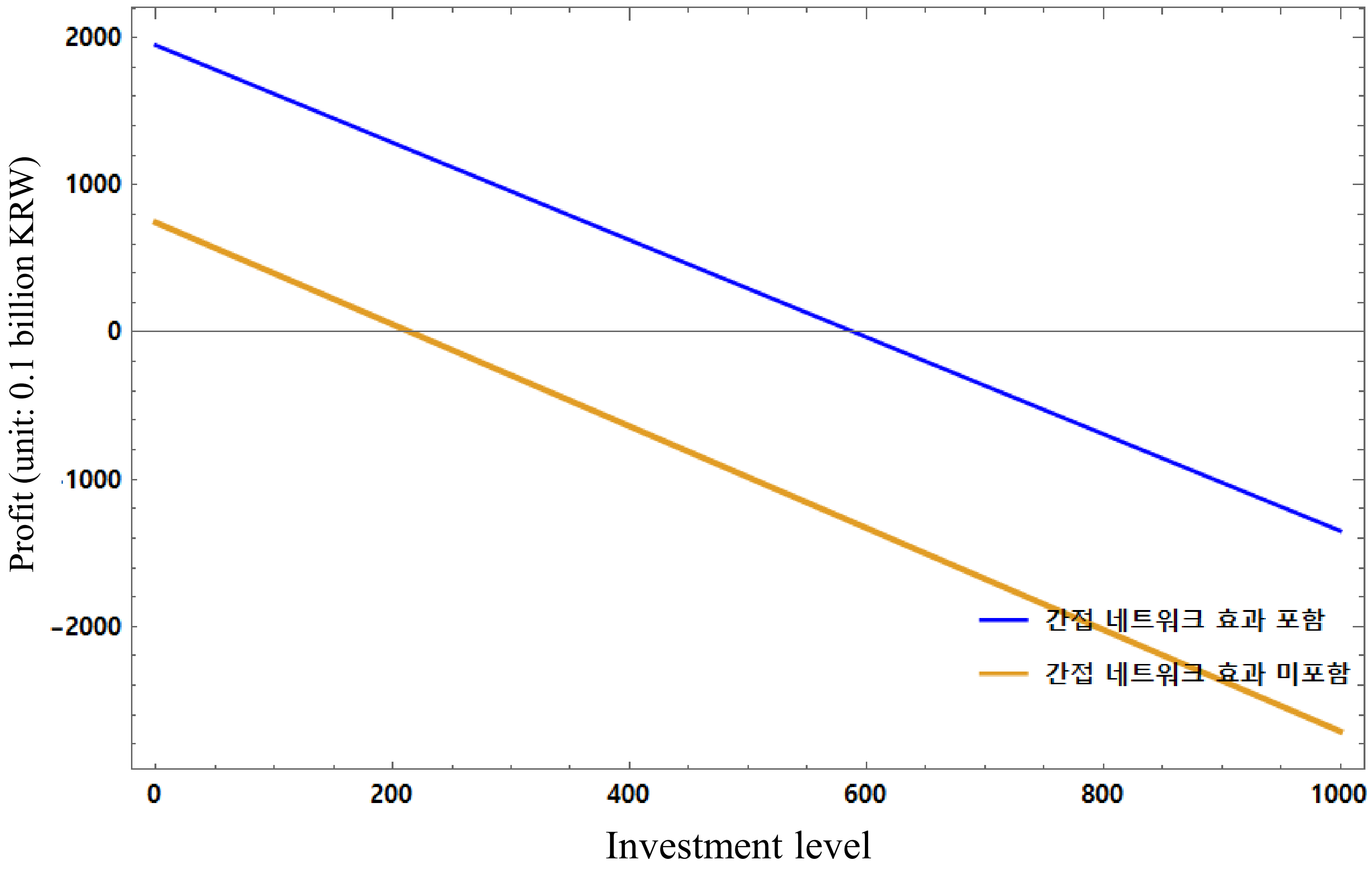
intrinsic utility	Fuel Economy (USD/10Km)	Charging station (% compared to gas stations)	Purchase costs (10,000 USD)
FCEV:-0.625, BEV: -0.505, ICEV: 0	-1.321	0.0144	-1.742

Result | The optimal strategy for BEV in competition with ICEVs



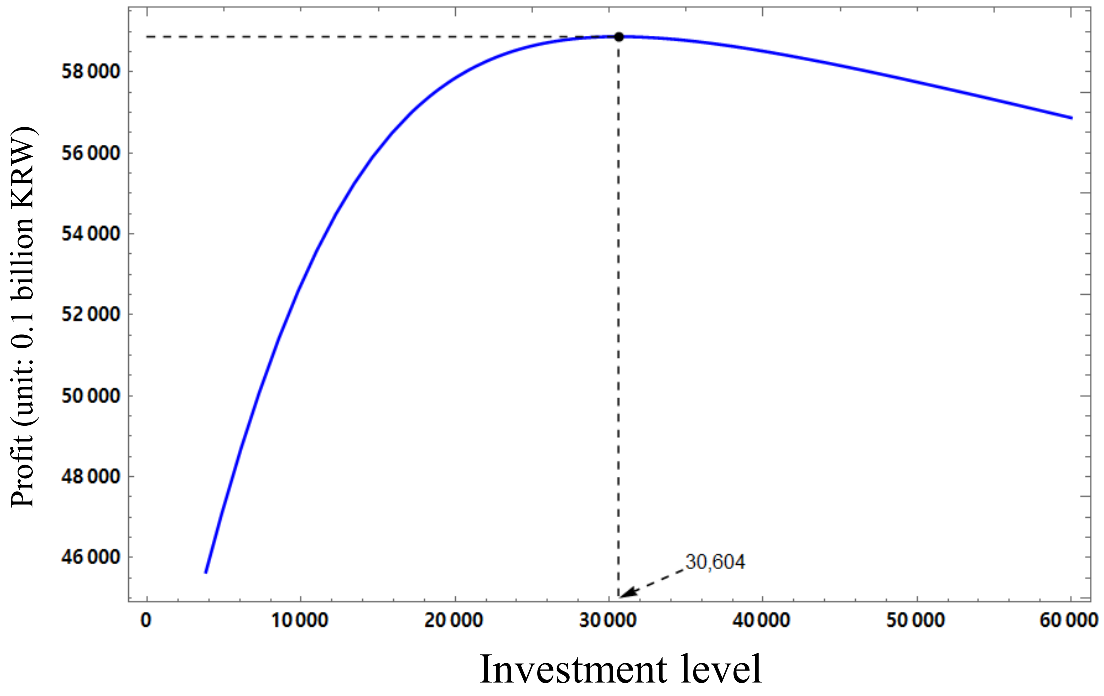
- The optimal fast-charging station investment strategy is approximately 58,492 stations (market share of 98.8%).
- The maximum investment always leads to the optimal outcome.

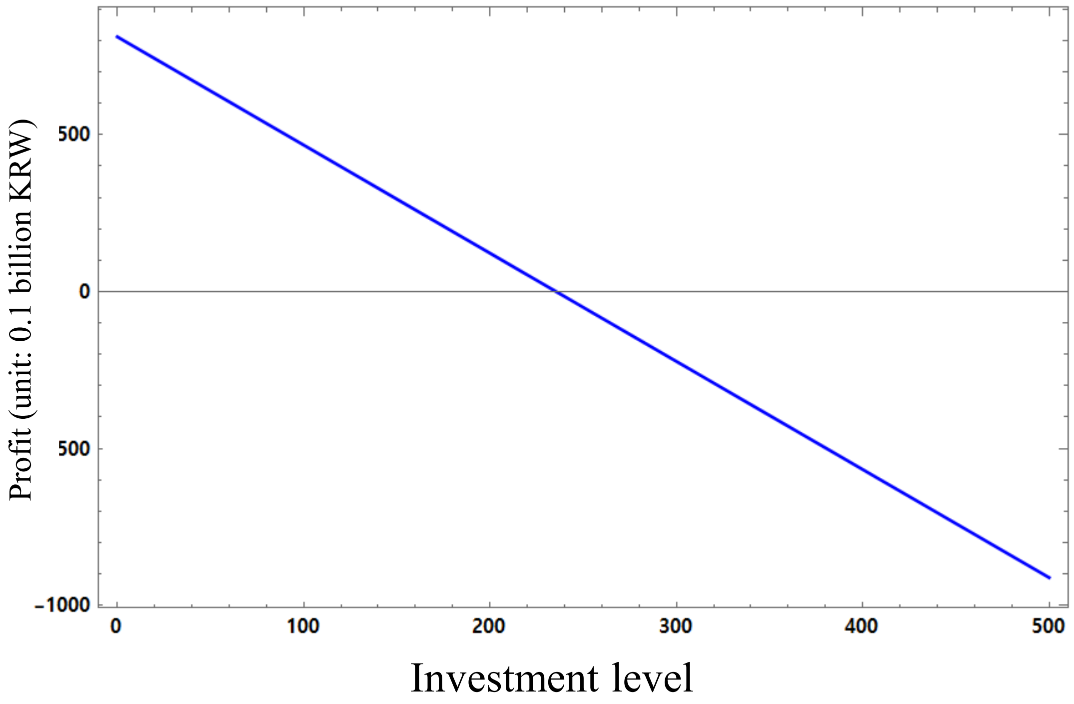
Result | The optimal strategy for FCEV in competition with ICEVs



- FCEV cannot satisfy the fundamental condition

Result | Equilibrium in competition between FCEV and BEV



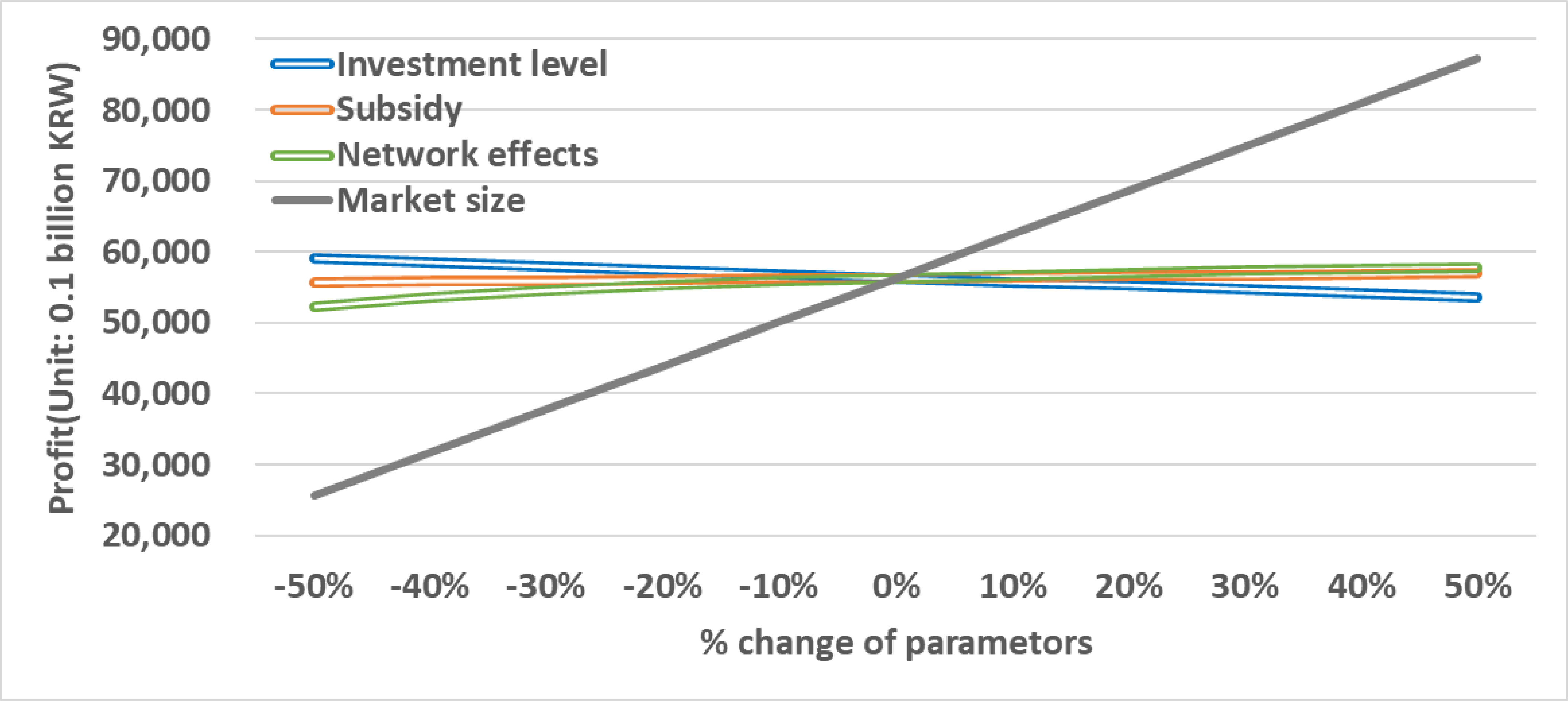


[Equilibrium of charging station investments in the competition between FCEV and EV in South Korea]

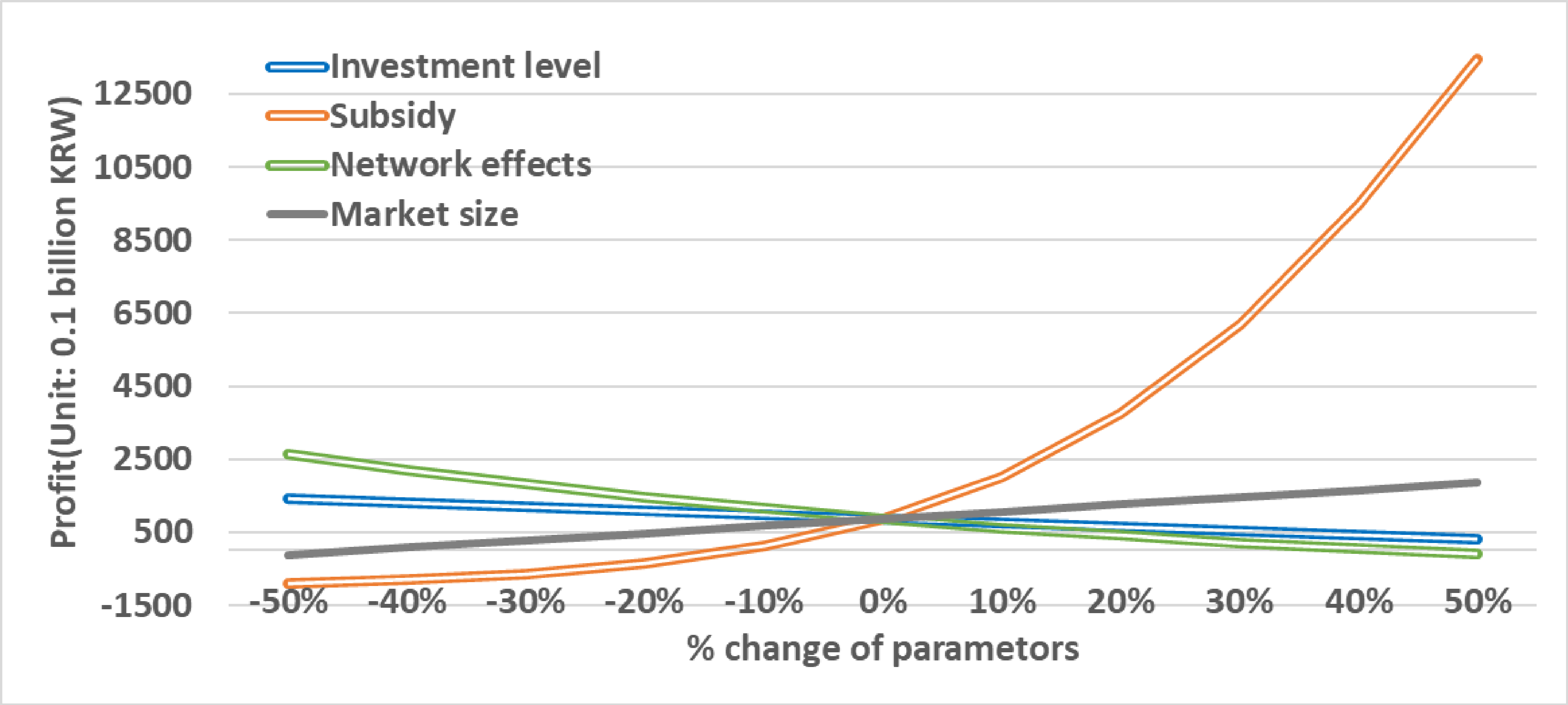
- The equilibrium investment levels for fast-charging and hydrogen fueling stations are 30,604 and 310 stations (the minimum investment level), respectively.
  - FCEVs can not satisfy the fundamental condition for profitability
  - EVs will dominate the market with 98.8%

1) 환경부(2021), 수소 충전소 전략적 배치

Sensitivity analysis | The profit of BEV manufacturer



Sensitivity analysis | The profit of FCEV manufacturer



- The hydrogen fueling station investment strategy results in **the minimum investment being optimal even at a 50% increase or decrease in all four influencing factors**.

Conclusion

- In competition with ICEVs, the optimal strategy is either the minimum or dominant level. If the optimal is minimum, subsidies for transitioning to the dominant level can be considered.
- In the case of FCEVs, the fundamental condition is not satisfied in Korea. Therefore, further technological advancement is necessary.
- In the competition between FCEVs and BEVs, BEVs will dominate the market as the preferred design. This result remains consistent even if each parameter is changed by 50%.
- This model is a static model only. The results of this research may change if dynamic processes are considered. Hence, dynamic analysis should be taken into account.

Thank you

Q&A