Optimal Investment Strategies for Hydrogen Refueling Stations Considering On-Site Conversion Option

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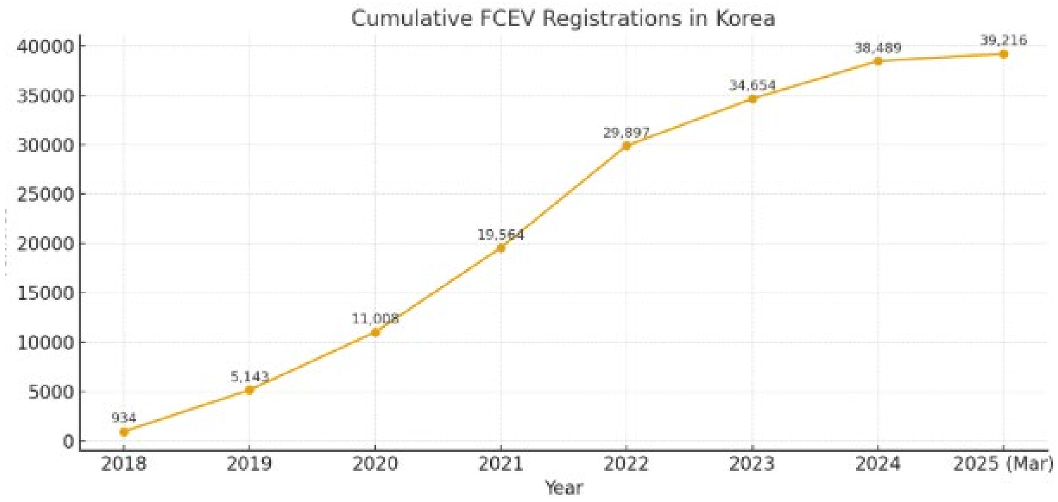
I. Research Motivation and Objectives

"Korea is approaching **50,000 FCEVs**, yet refueling capacity is lagging—calling for strong national support to close the gap." (Industry reports, 2025)

- Thanks to steady FCEV roll-outs and expanded purchase subsidies from the Ministry of Environment, Korea is on track to surpass **50,000 vehicles this year**, maintaining the **world's highest market share**.

- **Yet infrastructure has stalled for years**— Seoul has **only nine HRS** in operation.

- **Investment remains hard to mobilize** due to high upfront CAPEX, uncertain profitability, safety regulations, and local community opposition



Source: Korea Automobile Manufacturers Association (KAMA). Unit: vehicles. As of March 2025.

I. Research Motivation and Objectives

"On-site HRS can cut logistics and improve operational efficiency; **early-stage build support** is still crucial." (Industry reports, 2025)

- **Off-site HRS**: Receives hydrogen produced at external plants and delivered by tube trailers or pipelines.
- **On-site HRS**: Produces hydrogen on site (e.g., electrolysis/SMR) and dispenses it directly to vehicles; higher CAPEX but lower hydrogen cost.

Category	Off-site (Centralized) Supply	On-site Hydrogen Production
Principle	Central plant → delivered	Produced on site → dispensed directly
CAPEX / OPEX	**Low CAPEX**, high H_2 purchase & delivery cost	**High CAPEX**, **lower unit H_2 cost** at scale

I. Research Motivation and Objectives

❖ Research Objectives

- **To select** candidate HRS sites in Seoul by objectively evaluating social, technical, and economic factors using a multi-criteria decision-making (MCDM) approach.
- **To quantify** the economic value and optimal investment timing at each site by explicitly modeling the option to convert from off-site supply to on-site production.

I. Research Motivation and Objectives

❖ Key Prior Studies

Study	Core Methodology / Focus	Key Findings or Contribution	Implication / Gap Addressed in This Study
Li (2023) — *Hydrogen Energy Infrastructure Location Selection Model: A Hybrid Fuzzy Decision-Making Approach*	Fuzzy MCDM integrating 18 indicators across policy, economy, society, and environment	Provides a structured approach to quantify relative importance among heterogeneous siting criteria	Inspired our use of **objective weighting (CRITIC)** and **multi-criteria evaluation** for urban HRS site selection
Kim, Eom & Kim (2020) — *Development of a strategic HRS deployment plan for Korea*	Nationwide spatial optimization using FCEV registration and daily mobility data	Derived national-scale optimal HRS distribution	Highlighted the need to **focus on micro-scale (urban district-level)** decisions, which our study extends to **Seoul-specific candidate sites**
Zhao (2024) — *Investment of hydrogen refueling station based on compound real options*	Two-stage compound real-options model for HRS investment	Determined optimal investment timing under uncertainty	Provided the **methodological basis** for our **two-stage (off-site → on-site) real-options framework**
Li, Kool & Engelen (2020) — *Analyzing the business case for hydrogen-fuel infrastructure investments in the Netherlands: A real options approach*	Real-options approach with endogenous demand and multi-stage investment	Suggested **phase-wise investment strategy** reflecting demand growth	Motivated our integration of **demand uncertainty and conversion flexibility (on-site upgrade option)** in the investment model

Ⅱ. Selection of Candidate HRS Sites

❖ Multi-Criteria Evaluation System

- Urban HRS siting must reflect diverse social and economic factors. We therefore build a **multi-criteria evaluation system** for Seoul's 423 administrative districts, with four factor blocks: **Safety, Population, Demand, and Geography.**

- We apply **CRITIC** to derive objective weights and **TOPSIS** to obtain the final composite ranking and shortlist candidate sites.

Ⅱ. Selection of Candidate HRS Sites

❖ Multi-Criteria Evaluation System

Seoul's 423 administrative districts

Factor blocks*

- Safety
- Population
- Demand
- Geography

Objective weights via **CRITIC**

Final ordering via **TOPSIS**

* Factor blocks follow commonly used criteria in HRS siting studies: safety buffers and sensitive receptors, population exposure, refueling demand, and land-price constraints (e.g., Li, 2023; Kim, Eom, & Kim, 2020; Zhao, 2024)

2.1 Factor Selection Criteria

- **Safety factor**:
  - Anticipated **public opposition** and **accident risk** near hazardous facilities.
  - Count of **Type-1 protective facilities** (hospitals + schools) within each administrative district.
- **Population factor:**
  - **Resident population ratio** by administrative district (monthly average, 2024).
- **Demand factor:**
  - **Registered hydrogen vehicles** by district (as of Dec 2024).
- **Geography factor:**
  - **Average land price** by district (Seoul Open Data Plaza, Official Land Price).

Ⅱ. Selection of Candidate HRS Sites

2.2 Factor Weighting

CRITIC (Criteria Importance Through Intercriteria Correlation)

- Computes objective weights from (i) standard deviation of each criterion and (ii) its correlation with other criteria. Criteria with **high dispersion** and **low redundancy** receive larger weights.

Standard deviation + **Inter-criterion correlation** ⇒ **Information content** for criterion

$$S_j = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_{ij}-\bar{x}_j\right)^2}$$

$$r_{jk} = \frac{\sum_{i=1}^{n}\left(x_{ij}-\bar{x}_j\right)\left(x_{ik}-\bar{x}_k\right)}{\sqrt{\sum_{i=1}^{n}\left(x_{ij}-\bar{x}_j\right)^2}\sqrt{\sum_{i=1}^{n}\left(x_{ik}-\bar{x}_k\right)^2}}$$

	Population	Geography	Demand	Safety
Contrast (std. dev.)	0.1276	0.0982	0.0992	0.0723
Inter-criterion correlation	1.8738	2.6304	2.2971	2.0964
Information content	0.2390	0.2583	0.2279	0.1515
Weight	**0.2726**	**0.2946**	**0.2600**	**0.1728**

Ⅱ. Selection of Candidate HRS Sites

2.3 Ranking by Suitability

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution)

- Ranks each district by its **closeness to the positive-ideal solution** and **distance from the negative-ideal solution**, using the CRITIC-weighted criteria.

Step 1. Normalization

Step 2. Determine the Positive-Ideal and Negative-Ideal

Step 3. Compute Separation Measures

Step 4. Compute Relative Closeness and Rank

Euclidean distance of alternative i from the ideals:

Positive-Ideal distance: $d_i^+ = \sqrt{\sum_{j=1}^{p} (v_{ij} - v_j^+)^2}$

Negative-Ideal distance: $d_i^- = \sqrt{\sum_{j=1}^{p} (v_{ij} - v_j^-)^2}$

Relative closeness: $\psi_i = \frac{d_i^-}{d_i^+ + d_i^-} \quad (i = 1, \ldots, n)$ $\quad 0 \leq \psi_i \leq 1$

Larger ψ ⇒ **closer to Positive-Ideal** and **farther from Negative-Ideal** ⇒ **higher rank**.

2.4 Final Candidate Set

- Prior work suggests roughly **1 HRS per 100–150 FCEVs** (Kim, Eom & Kim, 2020). With ≈2,200 FCEVs in Seoul, about **14 stations** are needed as a planning benchmark.
- We **exclude** candidates within **2.5 km** of existing HRS or of top-ranked newly sited stations (to avoid spatial clustering).
- **Final five candidates** selected:

Guro 3-dong, **Gayang 1-dong**, **Jingwan-dong**, **Gangil-dong**, **Gil-dong**.

No.	Administrative District	Existing HRS	Excluded (Proximity)
1	Yangjae 1-dong	✓	
2	Yeoui-dong	✓	
3	Samsung-dong	✓	
4	**Guro 3-dong**		
5	**Gayang 1-dong**		
6	**Jingwan-dong**		
7	**Gangil-dong**		
8	**Gil-dong**		
9	Gaehwa-dong		✓
10	Banghwa 1-dong		✓

❖ Compound Real Option

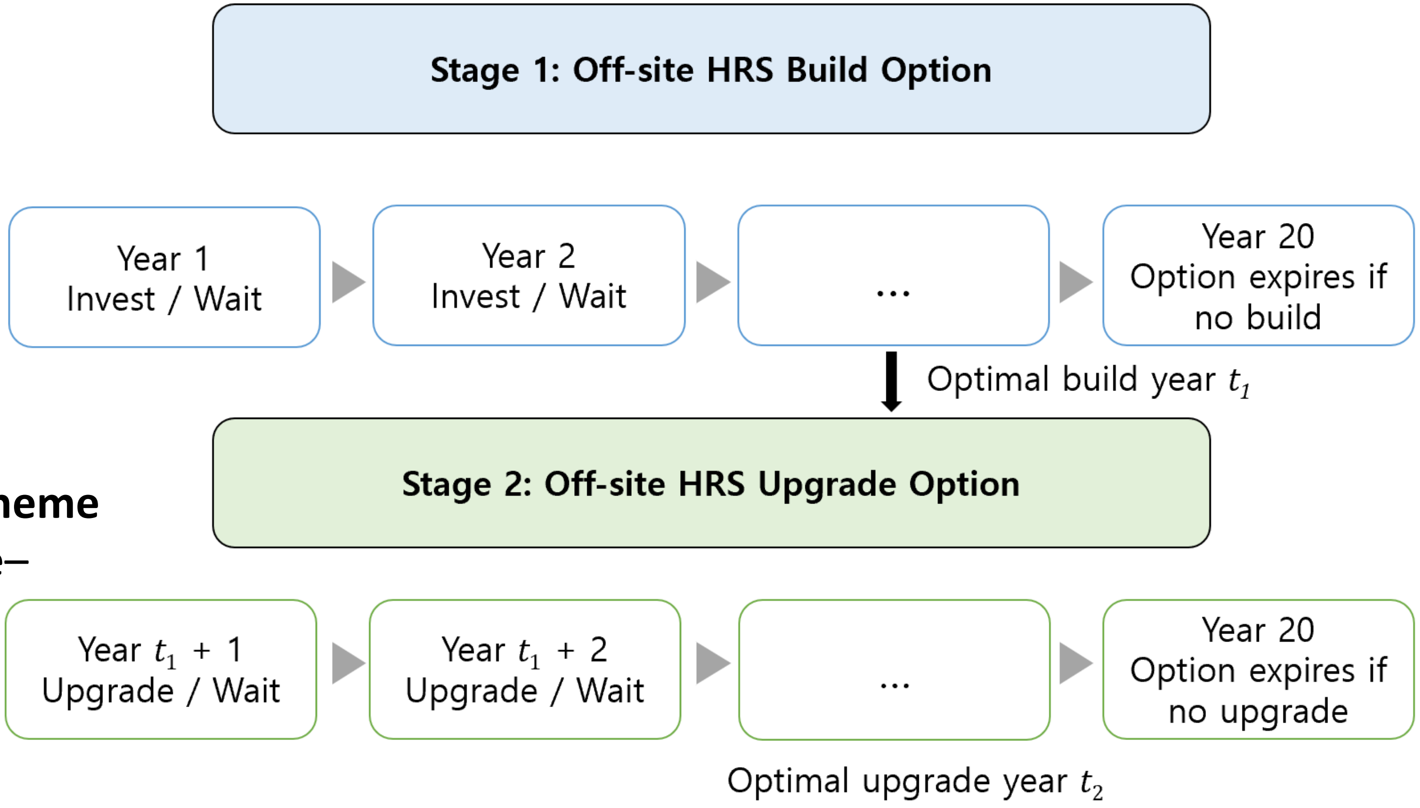
- Under uncertain future cash flows, determine **when and how** to invest to **maximize economic value**, leading to **staged decisions**.

In this study: two embedded options

Stage 1 — Off-site HRS Build Option

Stage 2 — On-site Production Upgrade Option

- Dynamic decisions are solved by **an LSMC scheme with backward induction** along 20-year price–demand paths.



Ⅲ. Optimal Investment Strategy by Site

1. Basic assumptions

1-1. Hydrogen Market Price

$$P_h(0) = P_{h0}, \quad dP_h(t) = \mu_p P_h(t)\,dt + \sigma_p P_h(t)\,dW_t$$

- $P_h(t)$: market price of hydrogen at year t (KRW/kg).
- μ_p, σ_p: drift of price growth (e.g., 3%) and volatility (e.g., 20%).

1-2. Station Throughput (Demand)

$$Q(0) = Q_0, \quad dQ(t) = \mu_q Q(t)\,dt + \sigma_q Q(t)\,dW_t$$

- $Q(t)$: annual dispensed volume at the HRS actually operating at year t (kg/yr).
- μ_q, σ_q: demand growth (e.g., 5%) and volatility (e.g., 30%).

1-3. Investment Costs with Technological Progress

$$I^{(1)}(t) = I_{1,0}\exp(-\delta_1 t), \quad I^{(2)}(t) = I_{2,0}\exp(-\delta_2 t)$$

2. Annual Cash-Flow (CF) Definitions

2-1. Off-site Cash Flow

$$CF^{(1)}(t) = [P_h(t) - c_1] \times Q(t)$$

- c_1: unit cost when **purchasing hydrogen from external suppliers** and reselling.

2-2. On-site Cash Flow

$$CF^{(2)}(t) = P_{\max}[P_h(t) - c_2] + \max\{Q(t) - P_{\max}, 0\}[P_h(t) - c_1] \qquad Q(t) \geq P_{\max} \quad \forall t$$

$$\Delta CF^{(2)}(t) = P_{\max}[P_h(t) - c_2] + (Q(t) - P_{\max})[P_h(t) - c_1] - Q(t)[P_h(t) - c_1]$$
$$= P_{\max}[P_h(t) - c_2] - P_{\max}[P_h(t) - c_1] = P_{\max}(c_1 - c_2)$$

- c_2: unit cost of **on-site production** (e.g., 3,000 KRW/kg).
- $P_{\max}$: annual on-site **production capacity** (e.g., 91,250 kg/yr).

Ⅲ. Optimal Investment Timing by Candidate Site

Value Function

NPV of On-site Upgrade

$$\mathrm{NPV}^{(2)}(t_2) = \mathrm{E}\left[\sum_{m=t_2}^{t_1+T_\ell-1} e^{-r\,(m-t_2)}\,\Delta CF^{(2)}(m) \;-\; I^{(2)}(t_2) \;+\; S^{(2)}(t_2)\right]$$

- t_1: off-site (stage-1) **investment timing**.
- t_2: on-site **upgrade decision** timing (stage-2).
- T_ℓ: **station service life** (years).
- r: **annual discount rate**.
- $\Delta CF^{(2)}(m)$: **incremental cash flow** from upgrading to on-site on top of off-site.
- $I^{(2)}(t_2)$: upgrade CAPEX at t_2 (with learning).
- $S^{(2)}(t_2)$: **subsidy** received at t_2 (if any).
- $\mathrm{NPV}^{(2)}(t_2)$: present value **when "upgrade now"** at t_2.

Value of the Second-Stage Option

$$F_2(t_2) = \max\left\{\mathrm{NPV}^{(2)}(t_2),\; e^{-r}\,\mathrm{E}\left[F_2(t_2+1)\right]\right\}, \quad F_2(t_1+T_\ell) = 0$$

Upgrade now — Next year's expected F_2 (wait-and-see value)

- By backward induction, we start from the second-stage upgrade option F_2 and then feed this value into the first-stage build option F_1.

Ⅲ. Optimal Investment Timing by Candidate Site

NPV of Off-site Entry

$$\mathrm{NPV}^{(1)}(t_1) = \mathrm{E}\left[\sum_{n=t_1}^{t_1+T_\ell-1} e^{-r\,(n-t_1)}\, CF^{(1)}(n) \;-\; I^{(1)}(t_1) \;+\; S^{(1)}(t_1) \right]$$

$$\mathrm{NPV}_{\mathrm{HRS}}(t_1) = \mathrm{NPV}^{(1)}(t_1) + F_2(t_1)$$

- $\mathrm{NPV}^{(1)}(t_1)$: **present value** if we build **off-site now** and operate to the end of life.
- $\mathrm{NPV}_{\mathrm{HRS}}(t_1)$: off-site NPV **plus** the continuation value of the **upgrade option**.
- $F_2(t_1)$: continuation value (at t_1) of the on-site upgrade option

Value of the First-Stage Option

$$F_1(t_1) = e^{-r\,(t_1-t_0)}\ \max\big(\mathrm{NPV}_{\mathrm{hrs}}(t_1), 0\big), \quad F_1(t_0) = 0$$

$F_1(t_1)$: the value, as of t_0, of starting construction in year t_1 while retaining the upgrade option.

$$F_1(t) = \max\left\{e^{-r}\mathbb{E}[F_1(t+1)],\ \max_{\tau=t+1,...,t_1+T_\ell-1} \mathrm{NPV}_{\mathrm{hrs}}(\tau)\right\}$$

Ⅲ. Optimal Investment Timing by Candidate Site

Case Analysis

A. Hydrogen price & demand process parameters

Symbol	Short description	Baseline value	Short data source / note
μ_p	Annual drift of hydrogen retail price	**3% / year**	KEPCO retail electricity price trend, 2015–2024
σ_p	Price volatility	**20% / year**	Hydrogen price variability in KR literature
$P_H(0)$	Initial hydrogen retail price	**7,500 KRW/kg**	KOGAS quotations & market reports (2025)
μ_q	Annual drift of station throughput $Q(t)$	**5% / year**	Living-population & FCEV registrations by dong
σ_q	Throughput volatility	**30% / year**	Early-stage station demand volatility (H_2 / CNG refs)

Ⅲ. Optimal Investment Timing by Candidate Site

Case Analysis

B. Throughput & unit-cost parameters by candidate site

Symbol	Short description	Baseline value	Short data source / note
$Q_i(0)$	Initial annual throughput, site i (kg/yr)	**Guro-3: 3,950; Gayang-1: 3,600; Jingwan: 3,800; Gangil: 3,350; Gil: 3,050**	From living-population & FCEV density by dong; scaled to early utilization
$c_1(t)$	Unit cost, off-site hydrogen (delivered)	$c_1(t) = 0.90 \times P_H(t)$ **KRW/kg**	~10% delivery premium over wholesale price
$c_2(t)$	Unit cost, on-site hydrogen production	$c_2(t) = 0.70 \times P_H(t)$ **KRW/kg**	On-site OPEX assumptions from electrolyzer cases
$P_{\max}$	Rated annual on-site production capacity	**3,000 kg/yr**	Small urban HRS size (~5–9% utilization)
δ_1	Stage-1 (off-site) investment learning factor	**10%**	Learning/scale effects for early off-site HRS

Ⅲ. Optimal Investment Timing by Candidate Site

Case Analysis

C. Investment-cost & policy parameters

Symbol	Short description	Baseline value (KRW)	Short data source / note
δ_2	Stage-2 (on-site) investment learning factor	**8%**	Electrolyzer CAPEX learning curve (Zhao, 2024)
$I_1(i)$	Stage-1 CAPEX for off-site HRS, site i	**Guro-3:** 1.20×10^9; **Gayang-1:** 1.15×10^9; **Jingwan:** 1.10×10^9; **Gangil:** 1.25×10^9; **Gil:** 1.18×10^9	Baseline ≈ 1.1 bn KRW adjusted by land price & permitting constraints
$I_2(i)$	Stage-2 CAPEX for on-site upgrade, site i	**Guro-3:** 5.0×10^8; **Gayang-1:** 4.8×10^8; **Jingwan:** 4.5×10^8; **Gangil:** 5.2×10^8; **Gil:** 4.9×10^8	Baseline ≈ 0.5 bn KRW adjusted by land-use & safety spacing
T_L	Economic service life of HRS (project horizon)	**20 years**	HRS planning horizon & equipment lifetime
r	Real annual discount rate	**8% / year**	Weighted average cost of capital for HRS projects
S_1	Off-site build subsidy per project	5.0×10^8 **KRW** (≈ 0.5 bn)	Central/local HRS deployment guidelines (draft, 2025)
S_2	On-site upgrade subsidy per project	3.0×10^8 **KRW** (≈ 0.3 bn)	Same as above, illustrative level

Ⅲ. Optimal Investment Timing by Candidate Site

Result

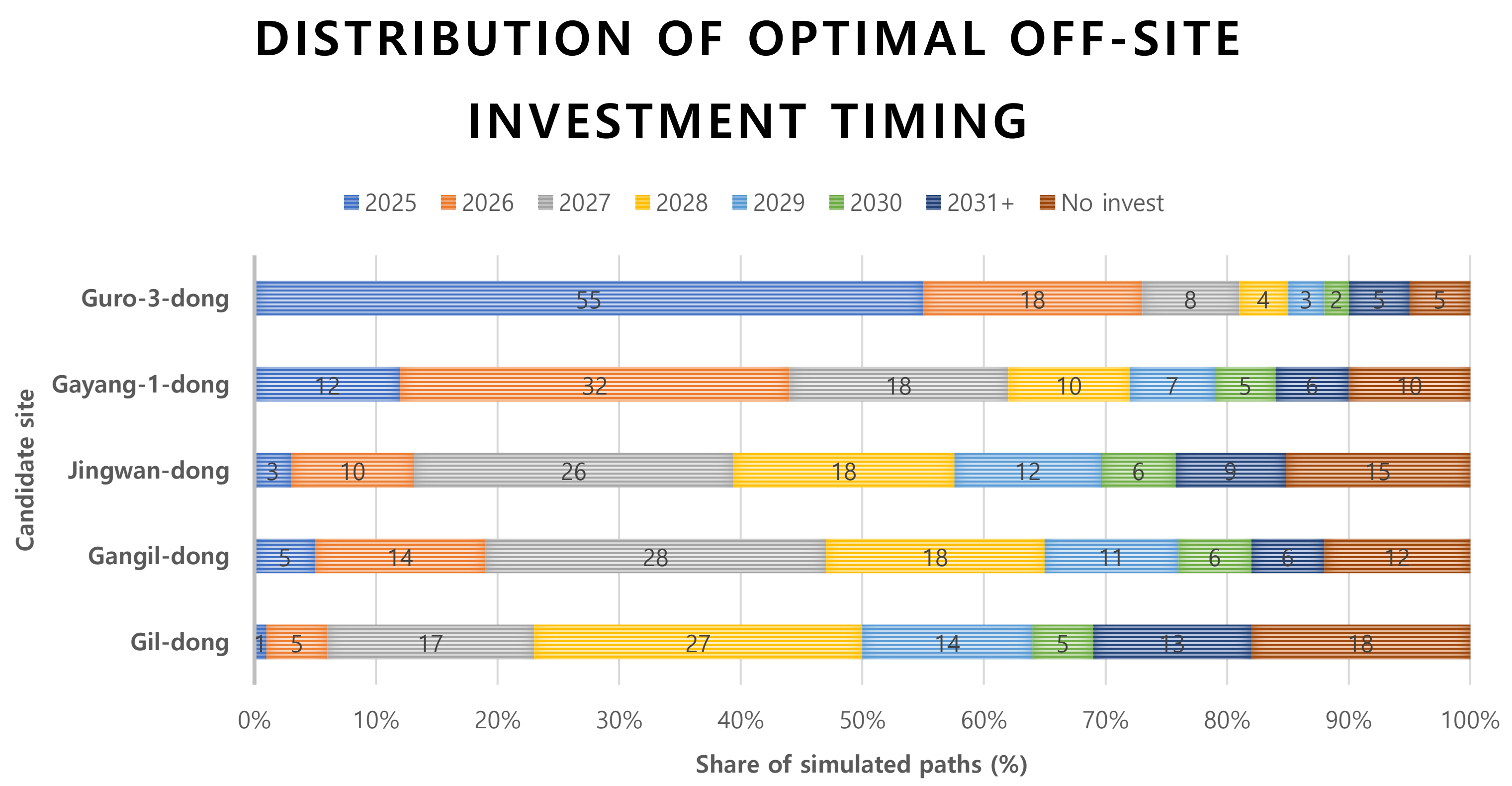
- **Compute the present expected compound option value** $E[F_1(0)]$ for each candidate site using an LSMC Monte Carlo scheme. $$\mathbb{E}[F_1(0)] \approx \frac{1}{N}\sum_{i=1}^{N} F_1^i(0)$$

- Apply backward induction along simulated price–demand paths to obtain the optimal exercise policy (Invest/wait).

- Define **investment timing** as the **modal exercise year** across 10,000 paths: off-site start year and, if exercised, on-site upgrade year.

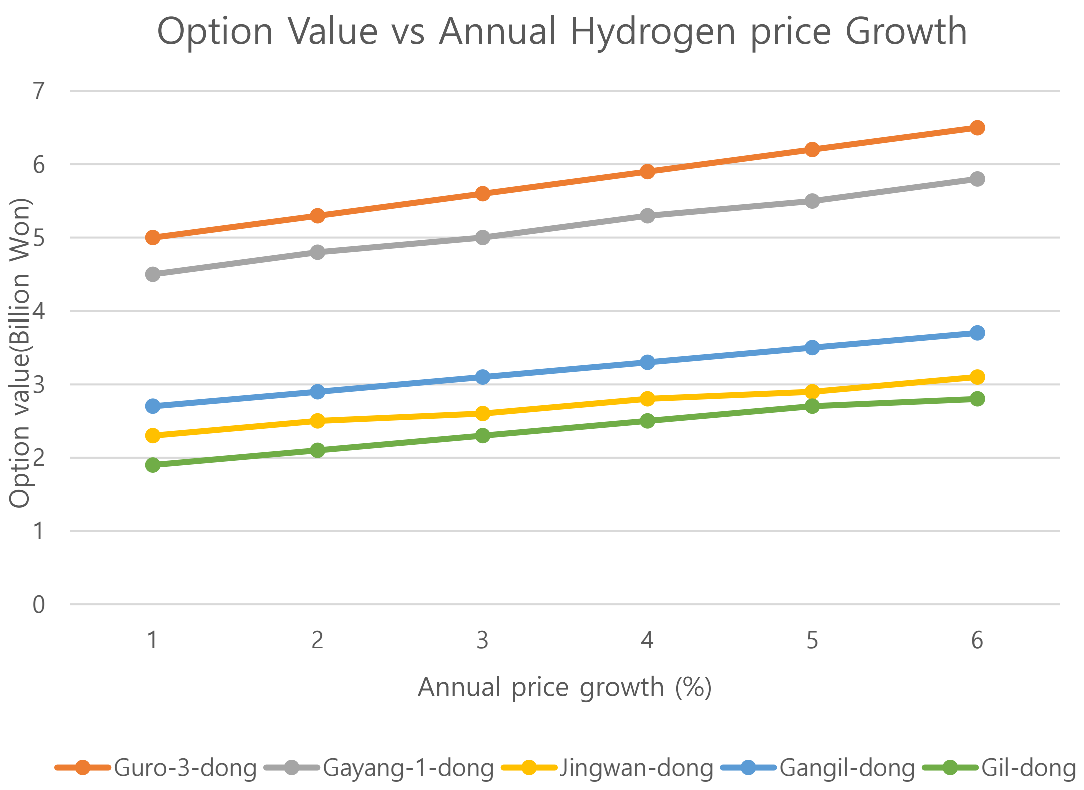
	Option value if on-site upgrade considered	Off-site start year (mode)	Year of on-site upgrade (mode)	Option value if upgrade ignored	Optimal start year w/o upgrade
Guro-3-dong	5.6	2025	2031	3.1	2026
Gayang-1-dong	5	2026	2032	2.3	2027
Jingwan-dong	2.6	2027	2034	1.6	2029
Gangil-dong	3.1	2027	2033	2	2029
Gil-dong	2.3	2028	2035	1.8	2031

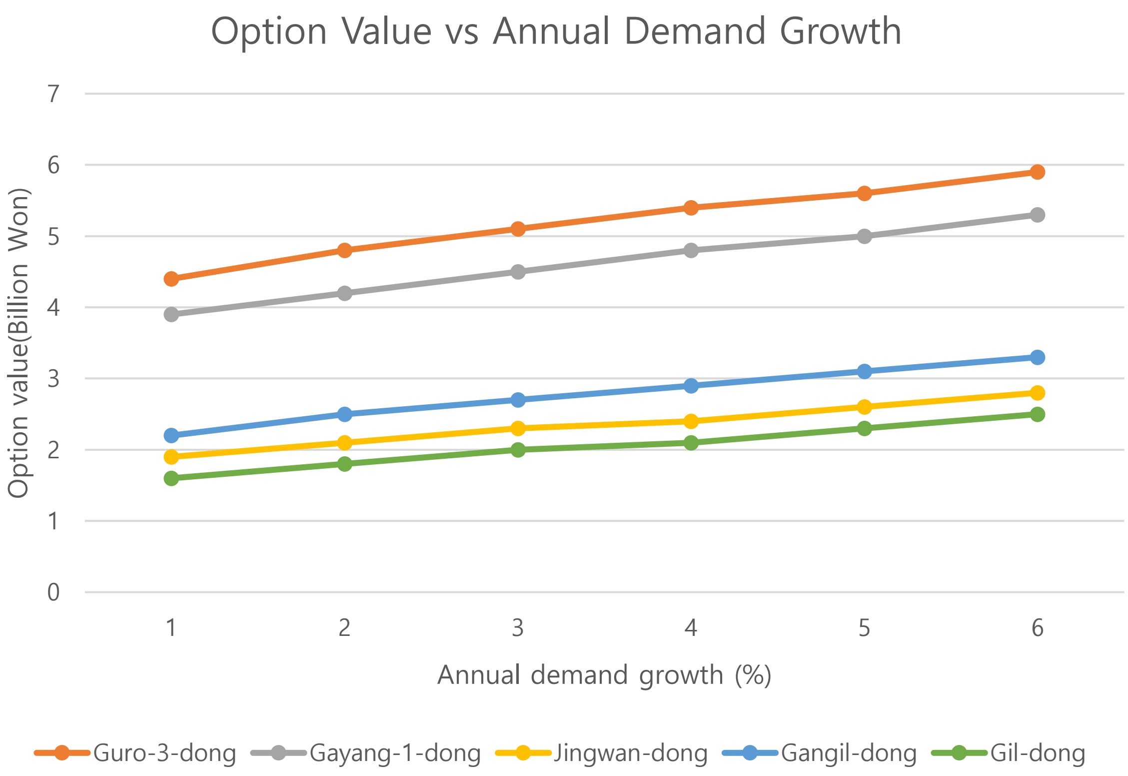
Ⅲ. Optimal Investment Timing by Candidate Site



Ⅲ. Optimal Investment Timing by Candidate Site

Sensitivity Analysis: Hydrogen Price & Demand Growth





- Higher price/demand growth increases option value at all sites, with larger marginal gains at lower-ranked sites (Jingwan-dong, Gil-dong).

Ⅲ. Optimal Investment Timing by Candidate Site

Sensitivity Analysis: Subsidy

S_1 (bn KRW)	Guro-3-dong	Gayang-1-dong	Jingwan-dong	Gangil-dong	Gil-dong
0.0	2026	2027	2029	2029	2030
0.2	2025	2026	2028	2028	2029
0.4 (baseline)	**2025**	**2026**	**2027**	**2027**	**2028**
0.6	2025	2025	2026	2026	2027
0.8	2025	2025	2026	2026	2026

S_2 (bn KRW)	Guro-3-dong	Gayang-1-dong	Jingwan-dong	Gangil-dong	Gil-dong
0.0	2025	2026	2028	2028	2029
0.2 (baseline)	**2025**	**2026**	**2027**	**2027**	**2028**
0.4	2025	2026	2027	2027	2027
0.6	2025	2026	2026	2026	2027
0.8	2025	2025	2026	2026	2027

- The off-site build subsidy $\boldsymbol{S_1}$ shifts the optimal start year more strongly than the on-site upgrade subsidy $\boldsymbol{S_2}$.
- Subsidies mainly **accelerate investment** at **marginal sites** (Jingwan-dong, Gil-dong), while top-ranked sites (Guro-3, Gayang-1) are built early even without strong subsidies

Ⅳ. Conclusion

Key findings

- **Candidate screening:** Using a CRITIC–TOPSIS MCDM system with four factor blocks (Safety, Population, Demand, Geography), we ranked Seoul's 423 administrative dongs and identified **five** economically and socially balanced candidate sites.

- **Compound real-options framework:** For each candidate, a **two-stage option (off-site build → on-site upgrade)** was valued via **LSMC Monte Carlo with backward induction**, yielding implementable decision rules for build and upgrade timing

- **Value of flexibility:** Relative to a one-stage off-site investment, the compound option delivers **higher expected value** and **earlier optimal start/upgrade years**, illustrating the economic benefit of retaining on-site upgrade flexibility under price and demand uncertainty.

Future work

- **Scenario extensions:** Fuel/price shocks, alternative tariff and demand-growth regimes.
- **Network effects:** Competition and spillovers among multiple HRSs in the same corridor.
- **Policy and acceptance:** Learning-curve-based subsidies and explicit treatment of siting risk and local opposition.

Q&A