High-ambition climate action in all sectors can achieve a 59% greenhouse gas emissions reduction in Korea by 2035

Hyuntae Choi[1,3], **Sangin Park**[1,*], **and Haewon McJeon**[2,3,**]

[1]Graduate School of Public Administration, Seoul National University, Seoul 08826, Korea
[2]Graduate School of Green Growth and Sustainability, Korea Advanced Institute of Science & Technology, Daejeon 34141, Korea
[3]KAIST IAM Group, Korea Advanced Institute of Science and Technology, 34141, Daejeon, Korea
[*]Corresponding author: sanpark@snu.ac.kr
[**]Corresponding author: hmcjeon@kaist.ac.kr

ABSTRACT

Under the Paris Agreement's ratchet mechanism, countries are expected to regularly strengthen their climate commitments, with 2035 emerging as the next critical milestone. For Korea—one of the world's largest emitters of CO_2—the central challenge is not only to meet its 2030 nationally determined contribution (NDC), but to define a credible and substantially more ambitious pathway for 2035. In this study, we employ an integrated assessment model to project Korea's greenhouse-gas emissions trajectory under current policy frameworks, based on the First National Framework Plan for Carbon Neutrality and Green Growth, the Eleventh Basic Plan for Long-term Electricity Supply and Demand, and other officially announced sectoral policies across the economy. We further construct an enhanced policy scenario that reflects highly ambitious yet technically viable and institutionally grounded measures across all major sectors. Our results show that current policies reduce emissions by 35% below net 2018 levels by 2035 (30–41%), even falling short of the 2030 NDC. By contrast, the enhanced scenario achieves a 59% reduction (55-64%) without reliance on international offsets. This deeper reduction is driven by an accelerated coal phase-out, rapid deployment of offshore wind, tighter constraints on lifetime extensions of blast furnace capacity, a ban on new internal combustion engine vehicle sales by 2040, and the gradual replacement of fossil-based heating with heat pumps. These findings provide system-wide evidence that a more ambitious 2035 pathway is feasible when existing policy and institutional constraints are explicitly accounted for, contributing to ongoing discussions on Korea's post-2030 mitigation strategy.

Introduction

To achieve the long-term goals of the Paris Agreement—limiting global temperature rise to well below 2 °C while pursuing efforts to limit it to 1.5 °C—countries are expected to progressively strengthen their near-term climate targets through nationally determined contributions (NDCs), updated every five years[1].

While the second round of NDCs submitted after the 2015 Paris pledges reflected only modest increases in ambition[2,3], a growing body of evidence indicates that substantially stronger mitigation efforts will be required beyond 2030 to keep the 1.5 °C goal within reach[4–7].

Against this backdrop, the next round of NDCs, due in 2025 and extending targets to 2035, has emerged as a critical juncture for aligning near-term policy action with long-term climate objectives. The first Global Stocktake, concluded at COP28 in 2023, reinforced this urgency by highlighting persistent gaps in mitigation progress and calling for accelerated action across energy systems, industry, buildings, transport, and agriculture[8–10].

The Republic of Korea (hereafter Korea), one of the world's largest emitters of CO_2, ranking 9th globally and 13th in total greenhouse gas (GHG) emissions as of 2024[11], began preparing its 2030 NDC shortly after the Paris Agreement was adopted[12]. However, a comprehensive sectoral policy framework to support implementation was only articulated more recently, with the release of the First National Framework Plan for Carbon Neutrality and Green Growth in 2023[13]. Korea has committed to reducing GHG emissions by 40% below *total* 2018 levels by 2030 and has legally enshrined a 2050 net-zero target[14].

Yet questions remain regarding how these commitments translate into an operational, economy-wide mitigation pathway. In particular, it remains unclear whether Korea's current constellation of sectoral policies, when considered together, can credibly deliver an adequate and internally consistent mitigation strategy.

Recent developments have further elevated the importance of defining a credible post-2030 trajectory. In August 2024, Korea's Constitutional Court held that the existing climate framework lacked a sufficiently concrete and scientifically grounded pathway beyond 2030 and required the government to develop a clearer medium-to long-term emissions trajectory[15,16]. This ruling has brought renewed attention to the formulation of Korea's forthcoming 2035 NDC and the need to situate it within a coherent post-2030 mitigation pathway.

In parallel, Korea has signaled strengthened political commitment by reorganizing the former Ministry of Environment into the Ministry of Climate, Energy and Environment in 2024, elevating climate mitigation and energy transition at the center of national governance. The government has subsequently announced a proposed range for Korea's 2035 NDC, targeting a reduction of 53–61% relative to the 2018 *net* emission level[17].

From a quantitative perspective, the scale of the challenge is substantial. Between 1990 and 2018, Korea's net GHG emissions increased by an average of 16.8 $MtCO_2e$ per year[18]. By contrast, achieving net-zero emissions by mid-century would require sustained annual reductions of approximately 23.2 $MtCO_2e$ from 2018 onward. Under a smooth net-zero pathway, this corresponds to reductions of roughly 38% by 2030[1] and 53% by 2035 relative to 2018 net emissions.

While Korea's 2030 and proposed 2035 targets appear broadly aligned with a linear net-zero pathway, it incorporates a substantial contribution from international mitigation. For the 2030 NDC, Korea plans to use 33.5 $MtCO_2e$ of international offsets, accounting for more than 11% of the total required reductions; for the proposed 2035 NDC, the international offsets still represent roughly 9–10% of total reductions (29.8–34.0 $MtCO_2e$)[2] More importantly, despite the apparent ambition of the headline target, a comprehensive and internally consistent domestic policy package specifying how these reductions are to be achieved across sectors has yet to be clearly articulated. This gap has also been noted by the Constitutional Court, which found Korea's mitigation framework insufficient to ensure emissions reductions consistent with scientific evidence and international standards.

In this study, we assess Korea's GHG emissions trajectory through 2035 using an integrated assessment model with detailed representation of the energy and industry systems. We construct a *Current Policies* scenario that reflects existing and officially announced policy measures centered on the First National Framework Plan for Carbon Neutrality and Green Growth, alongside a *High Ambition* scenario that explores the upper bound of mitigation achievable under strengthened but institutionally grounded measures already under discussion

[1] This corresponds to approximately 41% reduction relative to total 2018 emissions, slightly more ambitious than Korea's 2030 NDC target of 40%.

[2] In its 2035 NDC, Korea revised the accounting framework such that the reference for the reduction target shifted from total emissions net of removals to net emissions measured relative to the net emissions of the base year. The Constitutional Court has held that the use of differing emissions accounting bases across target years weakens the statutory mitigation framework by effectively lowering the required level of emissions reduction[16].

within Korea's policy framework. Rather than seeking to identify economically optimal transitions in an abstract sense, the analysis focuses on evaluating the feasibility and system-wide implications of policy-driven mitigation pathways grounded in Korea's current policy and institutional context.

The objective of this study is twofold. First, we evaluate whether Korea's current policy package is sufficient to deliver its 2030 and proposed 2035 NDCs under a consistent accounting framework. Second, we assess the additional emissions reductions that could be achieved by 2035 under an enhanced, policy-driven mitigation pathway. By comparing outcomes across scenarios, we identify key sectors and policy instruments that play a disproportionate role in shaping near- and mid-term emissions trajectories, thereby providing evidence relevant to the design of domestic policy packages for the implementation of Korea's forthcoming 2035 NDC.

While existing studies on Korea have predominantly focused on long-term net-zero pathways[19,20] or on individual sectors[21–24], few have examined the feasibility of near-term NDCs within a comprehensive, sectorally detailed policy framework[25]. In particular, much of the existing literature in the Korean context has approached decarbonization primarily from a techno-economic perspective, often with limited attention to the institutional and policy feasibility that ultimately shapes actual mitigation pathways.

More broadly, in other contexts—particularly for the United States—several integrated assessment (IA) studies have assessed emissions trajectories under multiple policy scenarios that incorporate relatively concrete policy instruments, including regulatory standards and sector-specific measures[26–28]. Beyond the U.S. context, comparable IA studies have been conducted at the global scale—for example, for the transport sector[29], for economy-wide decarbonization toward temperature targets[30], and through multi-model assessments of long-term mitigation pathways[31,32]. However, most of these analyses adopt harmonized or stylized policy representations—such as uniform carbon prices, generic technology subsidies, or broad efficiency standards— rather than embedding the detailed configuration of legislated and planned instruments within a specific national policy context.

As a result, IAs that combine sector-specific policy frameworks to evaluate the feasibility of near- and mid-term NDCs remain largely absent for Korea. By explicitly embedding detailed, sector-level policy instruments across electricity, industry, buildings, transport, agriculture, waste, and hydrogen into an IA modeling framework, this study provides a policy-grounded, system-wide assessment of near- and mid-term mitigation feasibility and clarifies how institutional and policy configurations shape feasible emissions trajectories toward Korea's 2035 NDC.

Methods

We construct two core policy scenarios to assess Korea's greenhouse gas mitigation pathway through 2035 and evaluate these scenarios using *GCAM-ROK*, a nationally customized version of the Global Change Analysis Model (GCAM) (see Supplementary Information SI2)[3]: (1) a *Current Policies* scenario, representing the policy landscape as of 2025, and (2) a *High Ambition* scenario, designed to explore a highly ambitious yet technically and institutionally feasible mitigation pathway. The former reflects policies that are currently implemented or legally enacted, while the latter builds on top of existing policies by strengthening key instruments and selectively expanding the policy space, informed by international mitigation policy trends and constrained by Korea's domestic feasibility.

Both scenarios are developed through a systematic, sector-by-sector mapping of climate-related policies compiled from national planning documents, legislative texts, administrative guidelines, technical reports, nd

[3]In sensitivity analyses, selected components of these core scenarios—such as GDP and population trajectories, fuel prices, exogenous electricity demand shocks associated with AI data centers, and the coal phase-out timeline—are systematically varied. See Supplementary Information SI11-13.

relevant academic literature. To ensure internal consistency and analytical credibility, all policies were screened and operationalized according to five guiding principles:

1. **Implementability**—policy targets lacking enforceable mechanisms or legal authority were excluded from the *Current Policies* scenario.

2. **Temporal consistency**—policies were assumed to persist over time unless an explicit sunset clause was specified.

3. **Quantification discipline**—policy instruments were implemented directly in the model wherever feasible; where quantification of policy impacts was required, estimates were drawn from government-assessed policy effects where available, supplemented by peer-reviewed studies, and, in the absence of both, based on relevant empirical data.

4. **Feasibility filtering**—enhanced measures in the High Ambition scenario were restricted to options assessed as feasible within the Korean policy context, reflecting a holistic consideration of technological readiness, institutional capacity, and implementation constraints.

5. **Methodological alignment**—parameterizations were selected to ensure consistency with established approaches in the modeling literature.

The *Current Policies* scenario is anchored in Korea's overarching mitigation framework, the 1st National Framework Plan for Carbon Neutrality and Green Growth[13,14], and incorporates the comprehensive set of sectoral mitigation frameworks specified in the plan. These include the 11th Basic Plan for Long-Term Electricity Supply and Demand (BPESD)[33,34] [4], the Core Technology Development Program for Carbon Neutrality[37], the *Act on the Promotion of Development and Distribution of Environment-Friendly Automobiles*, the *Green Buildings Construction Support Act*, the *First Master Plan for Implementing the Hydrogen Economy*[38], and the *2050 Carbon Neutrality Strategy for the Agri-Food Sector*[39], among others. At a more granular level, the scenario further reflects the legislative and regulatory instruments that underpin the implementation of these frameworks.

The *High Ambition* scenario preserves this underlying policy structure but systematically intensifies and selectively expands key instruments to represent a policy-driven upper bound of near- to mid-term mitigation. Importantly, these measures are not hypothetical constructs but extensions of existing policy trajectories, informed by international climate agreements, foreign policy experience, domestic policy proposals, and recent modeling studies. Further details on the modeling framework and approach are provided in Supplementary Information Sections SI2–SI3.

Results

Assessing the Impact of Current and Enhanced Policies toward Korea's 2035 NDC

We evaluate Korea's economy-wide greenhouse gas (GHG) emissions trajectory through 2035 under two policy scenarios using the *GCAM-ROK* integrated assessment model: the *Current Policies* scenario and the *High Ambition* scenario. These scenarios, described in detail in the Methods section, represent two alternative policy environments—one reflecting legislated and implemented policies as of 2025, and the other representing

[4] Electricity generation mix in the *Current Policies* scenario is calibrated to the officially approved 11th BPESD. Historical generation mix values for 2020 and 2025 reported in the Plan, consistent with KEPCO electricity statistics[35,36], are used to calibrate the model's 2020 and 2025 generation mix, while projections for 2030 and 2035 are directly adopted from the BPESD targets. A comparison between BPESD values and model outputs is provided in Supplementary Information Table SI2.

a plausible expansion and reinforcement of those measures, which results in a mitigation pathway broadly consistent with linear net-zero 2050 pathway of Korea.

Each scenario includes a comprehensive set of sector-specific policies that influence emissions across power, industry, transportation, buildings, and other sectors including agriculture, waste, hydrogen, and refrigerant. The *Current Policies* scenario captures Korea's baseline mitigation framework, while the *High Ambition* scenario represents a more aggressive pathway toward deep decarbonization, designed to remain within plausible technical and institutional bounds.

Table 1 summarizes the major policy instruments applied across sectors in each scenario. The results presented below illustrate the implications of these different policy pathways for Korea's capacity to meet its 2030 target and to inform a credible and enhanced 2035 NDC

Under the *Current Policies* scenario, moderate mitigation is achieved primarily through a gradual shift from coal to renewables in power generation, existing regulatory instruments, an economy-wide carbon price implemented through the Korean Emissions Trading System (K-ETS), and targeted subsidy programs for clean technologies.

The power sector reflects a gradual transition driven by LNG co-firing, moderate renewable energy expansion, and progressive coal retirement, with coal-based generation declining from 185 TWh in 2023 to 89 TWh in 2035. Nuclear power output rises substantially, consistent with the capacity expansion outlined in the 11th Basic Plan for Long-Term Electricity Supply and Demand[5].

In the industrial sector, mitigation relies on incremental technological measures rather than structural transformation. These include R&D investments in hydrogen-based direct reduced iron (H_2–DRI) steelmaking, limited uptake of limestone calcined clay cement (LC^3), and the substitution of perfluorocarbon (CF_4) and sulfur hexafluoroethane (C_2F_6) gases in semiconductor manufacturing processes.

In the transport sector, mitigation reflects existing promotional and regulatory measures, including subsidies for zero-emission vehicle (ZEV) purchases and compliance with manufacturer-average fuel economy standards, corresponding to an average improvement of approximately 32% over nine years[6]. In the buildings sector, Zero-Energy Building (ZEB) requirements are applied to new public buildings.

Shares of intermittent drainage (ID) and continuous flooding with water saving (CF+WS) in rice cultivation are assumed to reach the levels targeted in the current agri-food sector mitigation strategy, while regulation of hydrofluorocarbons (HFCs) in refrigerants remains limited in scope.

By contrast, the *High Ambition* scenario represents an accelerated decarbonization pathway enabled by stronger regulatory signals, expanded investment support, and the introduction of additional sector-specific measures.

In the power sector, coal generation is fully phased out by 2035, accompanied by a rapid scale-up of renewable energy capacity. Offshore wind expands at an average rate of 4 GW per year, while installed solar PV capacity triples by 2030 relative to 2023 levels, consistent with Korea's international commitments. The effective carbon price under the Korea Emissions Trading System rises to 40 constant 2020 US$/t$CO_2$, supported by strengthened

[5]The implied expansion from 24.1 GW to 32.4 GW over 12 years corresponds to approximately 0.69 GW/yr, closely matching Korea's historical expansion rate of about 0.64 GW/yr during 1997–2016. Moreover, both capacity and generation assumptions strictly follow the 11th Basic Plan, which has historically served as Korea's primary planning instrument for nuclear development and has been implemented with relatively high fidelity. This interpretation is reinforced by a recent government statement confirming that new nuclear construction under the 11th Basic Plan is being pursued as scheduled[40].

[6]The assumed improvement in vehicle efficiency is grounded in Korea's Administrative Notice on Vehicle GHG and Fuel Economy Standards (2021–2030), which regulates fuel economy on a manufacturer-average basis by vehicle class rather than through technology-specific performance requirements. This implies that compliance can be achieved through a combination of modest efficiency improvements in internal combustion engine vehicles (ICEVs) and increasing penetration of electric vehicles (EVs), rather than through drastic efficiency gains in ICEVs alone. Reflecting this policy design, under the *Current Policies* scenario we assume only modest improvements (0.7% per year) in ICEV fuel economy, while compliance with the overall standard is primarily achieved through rising EV shares.

allowance allocation and auctioning rules.

In transport, fuel economy standards tighten for both passenger vehicles (approximately 1.5% per year) and freight vehicles (about 1.3% per year), while zero-emission vehicle (ZEV) purchase and infrastructure subsidies are maintained at peak levels. In parallel, progressively stricter regulations on internal combustion engine vehicle sales culminate in a complete ban on new passenger ICE vehicle sales by 2040.

In buildings, Zero-Energy Building (ZEB) mandates are expanded to cover all new buildings regardless of size, and fossil-based heating systems are gradually replaced by electric heat pumps.

In the waste and refrigerants sectors, nationwide landfill bans are implemented, and hydrofluorocarbon (HFC) emissions are reduced through the accelerated substitution of high-GWP refrigerants with low-GWP or natural alternatives.

In agriculture, mitigation is strengthened through higher adoption of continuous flooding with water-saving (CF+WS) practices in rice paddies, reductions in nitrogen fertilizer application, and the deployment of low-methane livestock feed. Finally, negative emissions are scaled up through the deployment of direct air capture (DAC), with capacity reaching levels roughly twice those envisioned under Option B of Korea's 2050 Carbon Neutrality Scenario[41].

Table 1. **Summary of Modeled Policies under the Current Policies and Enhanced Ambition scenarios**

Sector	*Current Policies* Scenario	*Enhanced Ambition* Scenario
Power	• Generation trajectories for all major energy sources follow the approved 11th Basic Plan for Long-Term Electricity Supply and Demand (MOTIE, March 2025)[33]; although the Plan provides projections through 2038, this study reflects values through 2035 to match the temporal scope of the analysis.[7] • Coal generation declines from 184.9 TWh (2023) to 110.5 TWh (2030) and 88.9 TWh (2035). • Co-firing (clean H_2 + NH_3) increases from 15.5 TWh (2030) to 32.8 TWh (2035); see SI5 for the H_2/NH_3 disaggregation. • LNG generation increases from 157.7 TWh (2023) to 161.0 TWh (2030), then declines to 101.1 TWh (2035). • Nuclear generation increases from 180.5 TWh (2023) to 204.2 TWh (2030) and 236.0 TWh (2035). • Solar generation increases from 29.3 TWh (2023) to 67.1 TWh (2030) and 88.7 TWh (2035). • Wind generation increases from 3.4 TWh (2023) to 38.8 TWh (2030) and 76.2 TWh (2035); see SI5 for capacity factor and onshore/offshore disaggregation. • The RPS is maintained along its current trajectory[8].	• Complete coal phase-out by 2035; NH_3 co-firing is replaced by CCS-equipped generation in a limited extent. • Offshore wind capacity expands at a rate of 4 GW per year through 2035. • Solar PV capacity triples by 2030 (71.7 GW) relative to 2023 levels, with continued capacity expansion through 2035. • The RPS target is raised to 36% by 2035, supporting higher renewable penetration.

(Continued on next page)

[7]Electricity generation values for 2030 and 2035 are adopted directly from the 11th BPESD, while historical generation values for 2020 and 2025 are taken from the Plan, consistent with KEPCO electricity statistics. Full traceability of Plan and statistical values to model inputs is provided in Supplementary Information Section SI5. A detailed comparison between the modeled *Current Policies* power-sector outcomes and the 11th Basic Plan targets is presented in Supplementary Information Table S2.

[8]The effective renewable share implied by Korea's RPS differs from its nominal targets because the RPS applies only to generators with 500 MW or greater capacity and employs differentiated REC weights. We compute the ratio of the mandatory supply volume (GWh) to total electricity generation and extrapolate to model periods, yielding an effective renewable share of approximately 27% by 2035 under the *Current Policies* scenario. In the *High Ambition* scenario, institutional constraints are progressively relaxed—through expanded coverage, higher obligation rates, and REC reform—leading to effective renewable shares of 25% in 2030 and 36% in 2035, consistent with Korea's emerging 2035 NDC range.

Sector	*Current Policies* Scenario	*Enhanced Ambition* Scenario
Industry	• DRI-H_2-EAF is commercialized from 2035. • Lifetime extensions of BFs are prohibited after 2040. • The ETS price remains at its 2016–2022 average level. • LC3 is introduced after 2030 in the cement industry. • CF_4 and C_2F_6 are phased out after 2030 in semiconductor manufacturing. • Structural demand contraction in emissions-intensive manufacturing is incorporated to reflect declining competitiveness.	• BF extensions are fully banned by 2035. • H_2-DRI is adopted from 2030, with its production share increasing linearly to 55% by 2050. • Scrap-based steel increases by 30% every five years. • The ETS price increases by 4.5% annually. • Feedstock substitution reaches 5% by 2030 and 22% by 2035 in the chemical industry. • HFC-23 and SF_6 are also substituted from 2035 in semiconductor manufacturing. • Effective CO_2 storage costs decline to 50 US$/t$CO_2$ by 2030 through government subsidies.
Transportation	• ZEV purchase subsidies sunset after 2025, while infrastructure subsidies remain at their 2021–2024 average levels through 2035. • Early retirement of diesel ICE vehicles (Grade 4–5, $\geq$20 years) is subsidized. • Fuel efficiency improvements apply only to small passenger ICE vehicles (0.7% per year). • Low-emission vessel construction is supported via capital subsidies averaging 15% of shipbuilding costs.	• ZEV purchase and infrastructure subsidies are extended at peak-year levels through 2035. • Fuel efficiency improves by 1.5% per year for passenger vehicles and 1.3% for large cars and trucks. • A ban on new ICE passenger vehicle sales takes effect from 2040, with tightening regulations beforehand. • Passenger transport demand is reduced via mobility demand management, lowering VKT by 0.6% annually. • Capital subsidies covering 30% of shipbuilding costs apply to all low-emission vessels.

(Continued on next page)

Sector	*Current Policies* Scenario	*Enhanced Ambition* Scenario
Buildings	• ZEB mandates follow the current roadmap, applying only to new buildings (public ≥1,000 m^2 at Grade 4; private ≥1,000 m^2 at Grade 5). • Annual efficiency improvements follow historical EERS trends, reaching 1.96% for electricity/heat and 0.50% for gas by 2030. • Installation subsidies for building-level solar PV and fuel cells remain at their 2021–2024 average levels. • Concessional financing covers 35% of renewable energy investment costs. • No explicit green remodeling or fossil heating phase-out is assumed.	• ZEB requirements are extended to all new buildings, maintaining current grade stringency. • Post-2030 efficiency improvement rates double relative to baseline EERS trends. • Installation subsidies for building-level solar PV and fuel cells remain at peak 2021–2024 levels. • Financing support is strengthened, covering 55% of renewable energy investment costs. • Mandatory green remodeling reduces average building energy use by at least 16% by 2030 and 20–22% by 2035, prioritizing poorly performing commercial buildings. • Fossil-based heating systems are mandatorily phased out in favor of heat pumps or fully electric alternatives by 2035.

(Continued on next page)

Sector	*Current Policies* Scenario	*Enhanced Ambition* Scenario
Other sectors	• Clean hydrogen certification exists but lacks an operational incentive mechanism and is therefore not implemented in the model. • A direct landfill ban applies in the Seoul Metropolitan Area from 2025 and expands nationwide after 2030. • Water-saving irrigation in rice paddies remains at current targets (ID 61.1%, CF+WS 10%). • The Kigali Amendment is ratified but not explicitly implemented due to the absence of domestic enforcement instruments. • Smart farming diffuses gradually, reaching 35% coverage by 2035 with 10–20% productivity gains. • No explicit economy-wide methane policy or DAC deployment is assumed.	• Clean hydrogen targets are met exclusively with Grade 1–2 hydrogen (green and pink), reaching 51.6% by 2030 and 63.7% by 2035. • A direct landfill ban is implemented nationwide from 2025, yielding larger methane reductions in the waste sector. • Ratification and implementation of the UN Plastic Treaty reduce plastic waste by 25% by 2040. • Adoption of CF+WS irrigation rises to 30% by 2035, while nitrogen fertilizer use and manure inputs decline through precision agriculture. • Low-methane feed standards and expanded smart farming reduce enteric fermentation emissions and improve productivity. • The Global Methane Pledge is operationalized across agriculture, waste, and energy sectors. • The Kigali Amendment is actively implemented via low-GWP refrigerants and process substitution. • DAC deployment increases linearly from zero in 2025 to 14.8 $MtCO_2$ by 2050.

Under the *Current Policies* scenario, total GHG emissions are projected to decrease by 22.5% in 2030 and 34.8% in 2035 relative to 2018 net levels (Figure 1). This represents an average annual reduction of approximately 13.9 $MtCO_2e$ from 2018 to 2030, and 18.4 $MtCO_2e$ between 2030 and 2035. Despite steadily accelerating reductions, this scenario falls short of meeting Korea's 2030 nationally determined contribution (NDC), which calls for a 40% reduction relative to total 2018 emissions, even under optimistic assumptions regarding the availability of international offset mechanisms.

By contrast, the *High Ambition* scenario achieves substantially deeper decarbonization, with emissions declining by 36.0% (39.4% under total–net accounting) in 2030 and 58.9% in 2035 relative to 2018 net levels. These reductions correspond to average annual declines of 22.3 $MtCO_2e$ during 2018–2030 and 34.0 $MtCO_2e$ during 2030–2035. Importantly, this enhanced policy package brings Korea close to meeting its 2030 NDC without reliance on international offsets, while placing emissions reductions on a trajectory broadly consistent with a linear pathway toward net-zero emissions by 2050.

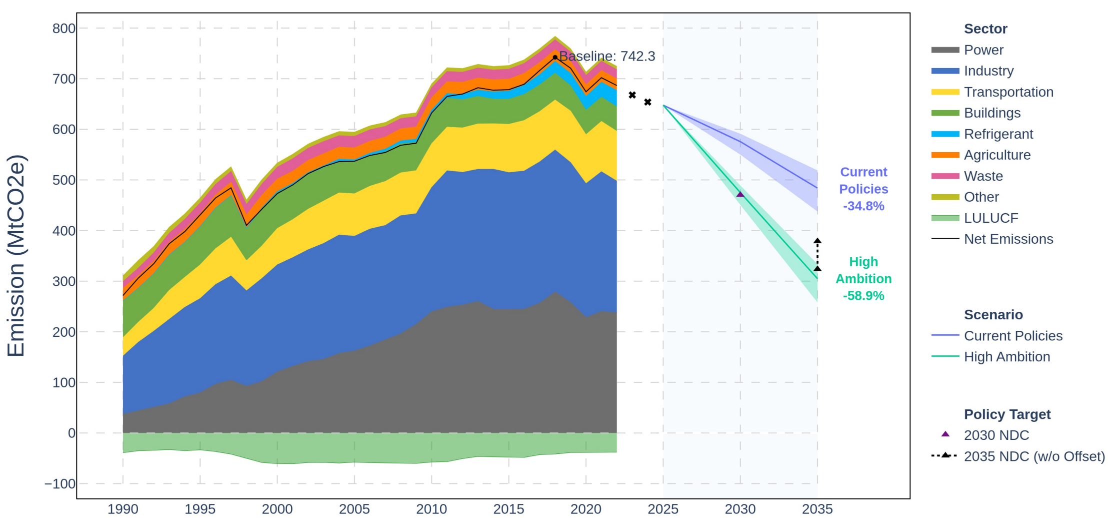


Figure 1. GHG emissions trajectories for Korea from 1990 to 2035. Emissions from 1990 to 2022 are based on historical data provided by the Greenhouse Gas Inventory and Research Center of Korea (GIR, 2025), disaggregated by sector. Emissions trajectories from 2025 onward are driven by scenario assumptions. Policies implemented in 2025 are held constant across both scenarios to isolate the effects of policy divergence thereafter. Both scenarios does not include international offset measures. Cross markers (×) show provisional net emissions for 2023–2024.

Recent discussions surrounding Korea's forthcoming 2035 NDC have proposed a headline target range of a 53–61% reduction in net GHG emissions relative to 2018. While this range appears highly ambitious at face value, it is predicated on the inclusion of 29.8–34.0 $MtCO_2e$ of international mitigation, implying an effective domestic reduction of only 49.0–56.4%. When evaluated on a purely domestic basis, this ambition level falls below the emissions reductions achieved in the *High Ambition* scenario presented in this study. Although the policy package underlying the *High Ambition* scenario represents a challenging transformation from a technical and institutional perspective, the results indicate that Korea's upper-bound 2035 NDC target is achievable under a strengthened domestic policy framework. Moreover, reliance on international offsets can be substantially reduced—from roughly 34 $MtCO_2e$ in current planning assumptions to about 15.3 $MtCO_2e$—even under a scenario consistent with the upper bound of Korea's proposed 2035 NDC, thereby enhancing the credibility and robustness of the mid-term mitigation pathway.

To account for uncertainties in key economic and technical drivers, we further explored sensitivity cases that vary assumptions regarding GDP[42] and population growth[43], technological progress, fossil fuel price trajectories. In particular, reflecting recent debates on the feasibility of "green growth" under deep decarbonization[44–48], we explicitly differentiate alternative growth pathways spanning optimistic, conservative, and structurally low-growth trajectories, rather than relying on a single growth-oriented baseline. Under these alternative assumptions, emissions reductions in the *Current Policies* scenario range from 30.1% to 41.1% by 2035, whereas the *High Ambition* scenario yields reductions between 55.1% and 65.3%. Across this uncertainty range, the *High Ambition* scenario remains consistent with Korea's proposed 2035 NDC, approaching the lower bound of the target range under conservative assumptions and reaching its upper end under optimistic assumptions (see Supplementary Information SI11).

Figure 2 shows that the power sector accounts for the largest share of total emissions reductions under both scenarios, contributing approximately 234.0 $MtCO_2e$—about 81.9% of total reductions—in the *High Ambition* scenario. Industry contributes the second-largest absolute reduction (98.4 $MtCO_2e$, 35.1%, followed by transport (31.3 $MtCO_2e$, 31.7%), buildings (30.4 $MtCO_2e$, 57.4%), and refrigerants (13.3 $MtCO_2e$, 57.7%). Absolute reductions and sectoral reduction rates are calculated against 2018 sectoral emission levels[18].

The incremental mitigation achieved when moving from the *Current Policies* to the *High Ambition* scenario is largest in the power sector (66.0 $MtCO_2e$), followed by industry (39.9 $MtCO_2e$), which contributes the second-largest increment and underscores the critical role of strengthened industrial policies in achieving higher ambition beyond the power sector alone.

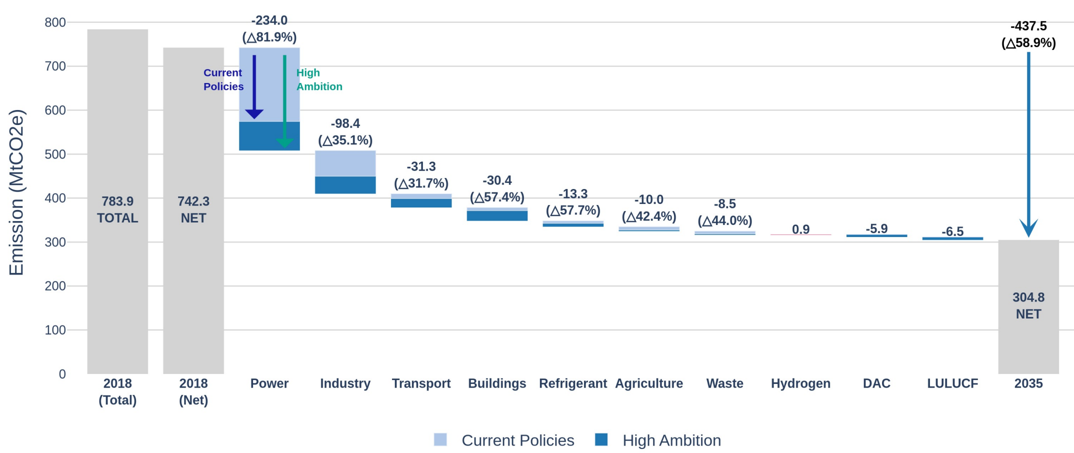


Figure 2. Sectoral contributions to GHG emissions reductions from 2018 to 2035 under the *Current Policies* and *High Ambition* scenarios. Light blue bars indicate reductions under the *Current Policies* scenario, while dark blue bars represent additional reductions under the *High Ambition* scenario. The total reductions are calculated against 2018 net emissions (742.3 $MtCO_2e$).

Under the *Current Policies* scenario, industrial emissions decline by 11.9% in 2030 and 20.9% by 2035, closely representing the sectoral target in 2030 NDC (11.4%) and falls below the lower range of sectoral mitigation target of 2035 NDC (24.3%). By contrast, the *High Ambition* scenario delivers a 35.1% reduction in industrial emissions by 2035 slightly above the upper sectoral target of 2035 NDC (31.0%). This highlights industry as one of the most consequential sectors for closing Korea's post-2030 ambition gap.

In the transport sector, the difference between the two scenarios amounts to 20.4 $MtCO_2e$ in sectoral reduction, driven by a combination of strengthened fuel economy standards, extended zero-emission vehicle support, and progressively tighter regulation of internal combustion engine vehicle sales.

The buildings sector exhibits an even larger divergence between scenarios, with a 23.2 $MtCO_2e$ difference in sectoral reduction rates by 2035. This gap is primarily attributable to the introduction of mandatory green remodeling for existing buildings and the accelerated substitution of fossil-based heating systems with electric heat pumps—measures that remain absent under the *Current Policies* scenario.

Hydrogen-related emissions increase in both scenarios, reflecting rising hydrogen use across sectors. However, the magnitude of this increase under the *High Ambition* scenario (0.9 $MtCO_2e$) remains below the +6.5–8.1 $MtCO_2e$ range projected in Korea's 2035 NDC, owing to the mandatory application of theclean hydrogen certification scheme. Finally, refrigerant-related emissions decline by 13.3 $MtCO_2e$ relative to 2018 levels under the *High Ambition* scenario, a qualitatively different outcome from the 10–18% increase projected in the NDC. This reversal reflects the effective substitution of high-GWP fluorinated gases with alternative process gases and natural refrigerants under strengthened regulatory measures.

Decarbonizing the Electricity Sector

The power sector delivers the largest contribution to Korea's total greenhouse gas (GHG) emissions reductions by 2035 under both modeled scenarios. As shown in Figure 3, electricity generation from fossil fuels— particularly coal—declines substantially, while carbon-free technologies, including renewables and nuclear power, account for an increasing share of the generation mix.

In the *Current Policies* scenario, total electricity generation closely follows the demand trajectory projected in the 11th Basic Plan for Long-Term Electricity Supply and Demand, reaching 642.3 TWh in 2030 and 691.6 TWh in 2035. In contrast, the *High Ambition* scenario exhibits a pronounced increase in electricity generation, reaching 787.5 TWh by 2035, reflecting higher electrification across end-use sectors. Despite the higher absolute generation level, the renewable energy share in the *High Ambition* scenario is approximately 14 percentage points higher than under *Current Policies*.

Under the *Current Policies* scenario, power-sector emissions decline by approximately 167.9 $MtCO_2e$ by 2035, corresponding to a 58.8% reduction relative to 2018 levels. This outcome falls short of the lower bound of the power-sector reduction range implied by Korea's 2035 NDC (68.8%). Moreover, because the national target relies partly on international offsets—whose availability and credibility remain uncertain—this apparent alignment does not necessarily imply a robust domestic mitigation outcome. Given that the power sector is generally regarded as the most flexible and scalable source of near-term emissions reductions, its relatively modest performance under *Current Policies* raises concerns about Korea's ability to compensate for mitigation shortfalls in other sectors and to securely achieve its overall climate targets.

The share of carbon-free electricity rises from 34% in 2020 to 65% by 2035 under the *Current Policies* scenario, with renewables accounting for 26%. This transition is driven by moderate expansion of solar and wind capacity and continued reliance on nuclear power. Nevertheless, a non-negligible share of electricity generation remains reliant on insufficiently abated fossil fuels, particularly coal and natural gas, including configurations with co-firing.

The *High Ambition* scenario accelerates the phase-out of unabated coal, including ammonia co-firing, and enables large-scale deployment of renewable energy. By 2035, the share of carbon-free electricity reaches 75%, with renewables alone accounting for 44%. These gains are primarily achieved through rapid expansion of wind and solar capacity, complemented by limited deployment of CCS-equipped fossil generation (26.1 TWh in 2035) to address residual system-balancing needs.

By 2035, CCS-equipped electricity generation reaches 26.1 TWh, corresponding to an economy-wide CCUS deployment of approximately 27.0 $MtCO_2e$. Of this total, about 5.9 $MtCO_2e$ is attributable to direct air capture (DAC), while the remaining 21.4 $MtCO_2e$ comes from conventional point-source CCS. Despite this expansion, CCS remains a supplementary mitigation option in Korea's decarbonization portfolio rather than a dominant pathway. The scale of CCUS deployment under the *High Ambition* scenario is broadly consistent with the upper-range CCUS projections in Korea's proposed 2035 NDC, which envisage approximately 20.3 $MtCO_2e$ by that year.

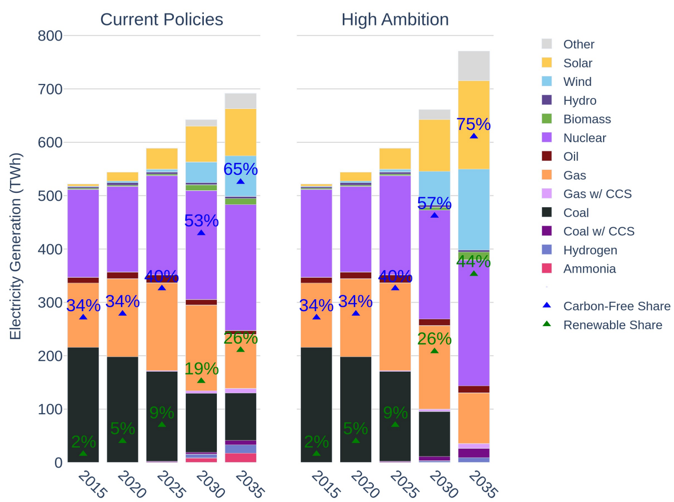


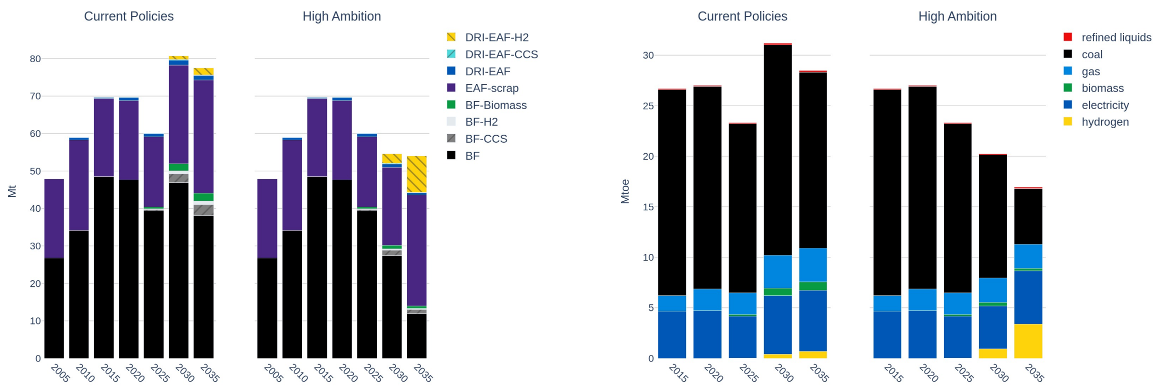
Figure 3. Electricity generation mix by technology in Korea under the *Current Policies* and *High Ambition* scenarios from 2015 to 2035. Carbon-free and renewable energy shares are shown with triangle markers. Total electricity generation is higher under the *High Ambition* scenario, driven by large-scale electrification and clean energy expansion.

Deployment of Carbon-Neutral Technologies and Industrial Transformation

As illustrated in Figure 2, the industrial sector plays a pivotal role in achieving national decarbonization goals in the *High Ambition* scenario, given its substantial share of total greenhouse gas (GHG) emissions and the complexity of its emission sources. Compared to the *Current Policies* trajectory, Korea accelerates the deployment of carbon-neutral technologies across hard-to-abate sectors—such as iron and steel, chemicals, and cement—under this pathway.

Figure 4 illustrates changes in both production technologies and final energy consumption in the iron and steel sector under the two scenarios. Under the *Current Policies* scenario, production remains dominated by conventional blast furnace (BF) technology, even as hydrogen-based direct reduced iron with electric arc furnaces (DRI–EAF–H_2) emerges. DRI–EAF–H_2 and related low-carbon technologies such as DRI–EAF and DRI–EAF–H_2 provide decarbonization pathways but their uptake is limited under *Current Policies* due to weak carbon price signals in the Korea Emissions Trading System and the high costs and technical challenges associated with alternative pathways including carbon capture and storage (CCS)[9]

[9]Large-scale CCS deployment is widely understood to be technically and institutionally challenging in Korea, owing to geological storage



A Production by technology.

B Final energy consumption.

Figure 4. Iron and steel sector outcomes under *Current Policies* and *High Ambition* scenarios. Panel (A) shows production by technology. Panel (B) shows final energy consumption by energy type.

In contrast, the *High Ambition* scenario exhibits a pronounced shift toward low-carbon technologies, especially (DRI–EAF–H_2), and EAF using scrap. These transformations are driven by stronger carbon pricing under the emissions trading system (ETS), a ban on lifetime extensions for existing BF facilities starting in 2030, and expanded scrap use in steel production.

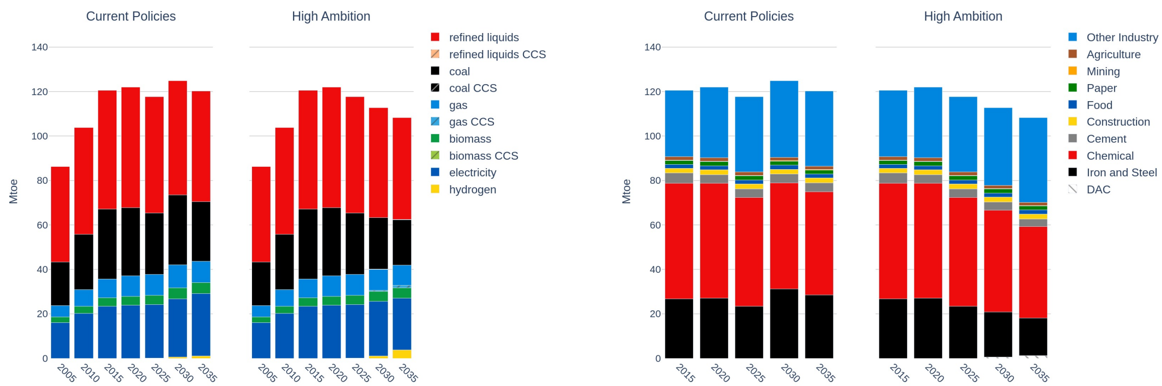
Panel 4B presents the corresponding changes in energy use in the iron and steel sector. Under the *Current Policies* scenario, fossil fuel consumption declines only marginally before rebounding after 2025, with the shares of coal and gas further increasing. At the same time, the limited retrofitting of existing facilities results in only a negligible increase in biomass use. Hydrogen consumption rises only slightly, reflecting the limited uptake of DRI–EAF–H_2 technologies (Panel 4A).

In contrast, under the *High Ambition* scenario, coal use continues to decline steadily after 2025 as blast furnace capacity is progressively replaced by lower-emission technologies, while hydrogen use increases substantially in line with the widespread adoption of hydrogen-based steelmaking, supported by instruments such as carbon contracts for difference (CCfD), targeted technology subsidies, and accelerated cost reductions driven by active R&D. Electricity use also rises sharply: although total final energy demand decreases, electricity consumption continues to grow, reflecting not only the diffusion of DRI–H_2–EAF but also the policy-driven expansion of scrap-based EAF production.

Figure 5 summarizes the transition of final energy consumption in the broader industrial sector by energy type (Panel 5A) and by industry sub-sector (Panel 5B). Under the *Current Policies* scenario, total energy consumption remains relatively flat after 2015, with coal, gas, and refined liquids maintaining dominant roles, although coal is gradually substituted by hydrogen and electricity (Panel 5A). The chemical and iron and steel sectors together account for roughly two-thirds of total industrial energy use (Panel 5B).

In the *High Ambition* scenario, total energy demand decreases moderately by 2035, driven by a significant reduction in coal use and a growing contribution from hydrogen and biomass. This shift is linked to structural

constraints, cost barriers, and the fact that most existing industrial and power facilities are not designed for retrofit capture[49,50]. Although CCS is part of long-term mitigation discussions, recent policy deliberations around Korea's 2035 Nationally Determined Contribution show limited emphasis on CCS at near- and mid-term horizons, with government practice focused more on renewables, electrification, and efficiency measures. Consistent with this context, CCS is not assumed to expand substantially in the iron and steel sector even under the *High Ambition* scenario, which instead emphasizes electrification and hydrogen-based production pathways.



A Final energy consumption by energy type.

B Final energy consumption by industry sector.

Figure 5. Final energy consumption in Korea's industrial sector under *Current Policies* and *High Ambition* scenarios. (A) Consumption by energy type. (B) Consumption by industry sub-sector.

changes in the chemical and iron and steel sectors, as well as efficiency gains associated with increased use of scrap. In the chemical sector, energy demand declines due to both feedstock and fuel substitution, driven by the replacement of conventional naphtha with low-carbon alternatives. In the cement sector, energy use decreases as a result of the accelerated deployment of limestone calcined clay cement (LC_3), which reduces the need for energy-intensive clinker production. The relative shares of construction, paper, and other industrial sectors show moderate increases in both energy use and emissions, reflecting industrial restructuring induced by mitigation policies and the reallocation of activity across sectors. See Figures S5-S7 for final energy consumption by energy type for chemicals, cement, and other industries.

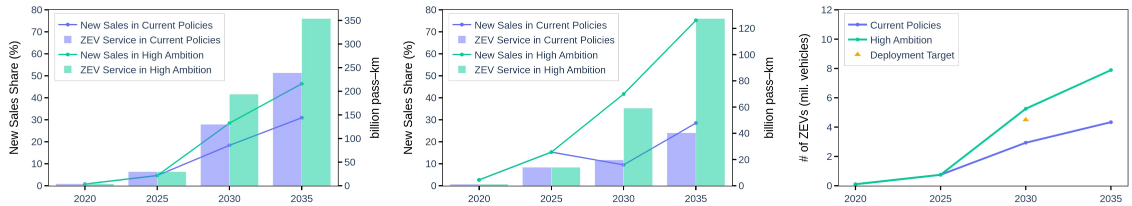
Overall, the *High Ambition* pathway demonstrates that targeted technology deployment, combined with systemic fuel and feedstock switching, can enable substantial emissions reductions in the industrial sector. This transformation not only facilitates the decoupling of emissions from economic growth but also sets the sector on a credible pathway toward long-term decarbonization.

Scaling Up Zero-Emission Vehicle Deployment

The transportation sector is the third-largest contributor to emissions reductions in both scenarios, primarily driven by the rapid deployment of zero-emission vehicles (ZEVs) across passenger and freight categories. Under the *High Ambition* scenario, national GHG emissions from transport decline by 31.7% by 2035 relative to 2018 levels, compared to a 11.0% reduction under the *Current Policies* scenario (Figure 2).

This enhanced outcome is enabled by a combination of strengthened financial incentives, accelerated stock turnover driven by the early retirement of older diesel ICE vehicles and restrictions on new ICE sale. In the passenger segment, ZEVs reach 46.4% of new vehicle sales by 2035 under the *High Ambition* scenario, compared to 30.9% under *Current Policies* (Figure 6). Similarly, freight vehicle electrification accelerates substantially, with ZEVs capturing 75.2% of new freight truck sales in 2035— more than twice the share projected under the *Current Policies* scenario (28.5%).

Beyond electrification, demand-side interventions play a critical complementary role. In the *High Ambition* scenario, mobility demand is moderated through expanded public transit subsidies and the diffusion of the GTX metropolitan rail network, which jointly reduce reliance on private vehicle use. In parallel, strengthened fuel



A Passenger. **B** Freight. **C** Total Number

Figure 6. ZEV new sales share (%) and total transport service by mode, for passenger and freight transport.

economy standards induce sustained annual efficiency improvements of approximately 1.5% for ICEVs through 2035.

These policy levers position the transport sector as a pivotal contributor to Korea's mid-term mitigation strategy, by both accelerating ZEV penetration and managing aggregate transport demand. When service output is converted into vehicle stock, the *Current Policies* scenario falls short of meeting the government's 2030 deployment target of 4.5 million ZEVs (see Table S4 for stock conversion parameters), whereas the *High Ambition* scenario not only meets this target (5.3 million) but reaches nearly 8.0 million ZEVs by 2035. This leads to markedly stronger emissions reductions and a more credible long-term decarbonization pathway.

Building Sector Decarbonization through Electrification and Efficiency

The building sector presents a significant opportunity for near-term decarbonization through the combined deployment of electrification and energy efficiency measures. Under the *High Ambition* scenario, a suite of national policies—including zero-energy building (ZEB) mandates, electrification incentives, energy efficiency resource standards (EERS) for energies supplied to buildings, and mandates for zero-emission heat pumps—drives substantial reductions in fossil fuel use and associated emissions. While financial incentives and supplier-side efficiency obligations (EERS) contribute to this transition, the dominant drivers are regulatory and structural: the extension of ZEB standards to all new buildings, mandatory green remodeling of existing stock, and the regulatory substitution of fossil-based heating with heat pump systems.

As illustrated in Figure 7, total final energy consumption in buildings begins to decline after 2030 under the *High Ambition* scenario, reflecting not only increased electrification but also a structural reduction in centrally supplied energy demand induced by the universal application of ZEB standards and large-scale green remodeling. By 2035, electricity accounts for 68.5% of final energy use in the building sector, compared to 57.5% under *Current Policies*. Oil and gas consumption decline more rapidly under *High Ambition*, while the share of biomass increases slightly, primarily due to policy-driven substitution. The steady growth in electricity use is further supported by regulatory mandates targeting the replacement of fossil-based space and water heating with zero-emission heat pump systems.

Overall, emissions from the building sector fall by 57.4% from 2018 to 2035 in the *High Ambition* scenario—equivalent to a reduction of 30.4 $MtCO_2e$—compared to a more modest 13.5% reduction (7.2 $MtCO_2e$) under *Current Policies* (Figure 2). These results highlight that the deep decarbonization of the building sector is driven primarily by regulatory expansion of ZEB standards, mandatory fuel switching in heating systems, and efficiency gains from green remodeling, rather than by subsidies or supply-side efficiency obligations alone.

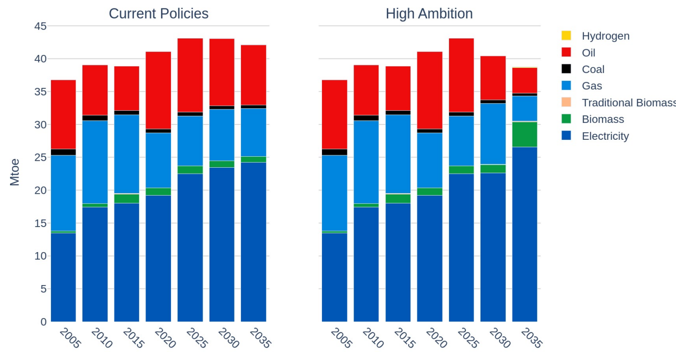


Figure 7. Final energy consumption in the buildings sector by fuel type under *Current Policies* and *High Ambition* scenarios.

Discussion

This study examines the implications of a high-ambition 2035 mitigation pathway for Korea based on detailed sectoral modeling. The results suggest that a 58.9% reduction in national GHG emissions by 2035—broadly consistent with a linear trajectory toward net zero—can be achieved through coordinated actions across the power, industry, transport, buildings, agriculture, waste, and refrigerant sectors, among others. Achieving such outcomes would require both the further strengthening of existing policies and the selective introduction of additional measures to address structural and institutional constraints. The findings highlight specific areas where policy ambition, governance arrangements, and public support mechanisms may warrant reinforcement to facilitate more rapid low-carbon transitions.

In the power sector, a full phase-out of unabated coal by 2035—combined with sustained offshore wind expansion on the order of 4 GW per year—enables an 81.9% reduction in power-sector emissions. While ammonia co-firing may provide limited near-term mitigation, it risks delaying the structural transition required for deep decarbonization and therefore cannot substitute for an early coal exit. Importantly, the timing of coal phase-out emerges as a critical determinant of Korea's mid-term mitigation feasibility. Although the Korean government has currently set 2040 as the target year for coal retirement, our sensitivity analysis indicates that delaying coal exit toward 2040 would substantially erode the feasibility of achieving even the 53% national reduction target by 2035 (see Supplementary Information SI13 for the effect of delayed coal phase-out). This highlights that the coal phase-out schedule is not merely a technical choice but a politically and socially consequential decision that requires broad societal consensus and credible implementation commitments.

In this context, carbon capture and storage (CCS) cannot be regarded as a near-term substitute for structural decarbonization in Korea's power sector. Large-scale deployment of CCS faces substantial technical and economic constraints in the Korean context, given the limited availability of suitable geological storage sites, the absence of CO_2 transport infrastructure, and the fact that most existing coal and gas plants are not capture-ready. Previous studies have highlighted the high costs and logistical challenges associated with offshore CO_2 transport and storage in Korea[49–51].

Moreover, relying on partial abatement options—such as CCS or ammonia co-firing—risks locking in carbon-intensive assets and delaying the full transition toward zero-carbon generation. Such strategies may reduce emissions in the short term, but by postponing the build-out of truly carbon-free capacity, they can ultimately increase total system costs and cumulative emissions over time. In this sense, incomplete mitigation pathways may prove socially more costly than early and decisive investment in renewables, further reinforcing the centrality of large-scale renewable deployment as the backbone of Korea's power-sector decarbonization strategy.

By contrast, solar PV and offshore wind play a pivotal role in Korea's decarbonization strategy, particularly given its severe land constraints for utility-scale renewables. Achieving the modeled pathway requires annual PV deployment of approximately 8 GW. This pace is empirically plausible when benchmarked against recent international experience: despite having less than half of Korea's population and land area, the Netherlands has sustained annual PV additions of around 4.3 GW in recent years[52,53]. When scaled to Korea's geographic and market conditions—and considering Korea's substantially higher solar capacity potential[54]—the assumed PV expansion trajectory should be interpreted as ambitious but feasible rather than excessive.

For offshore wind, the feasibility of a multi-GW deployment trajectory is supported not only by international experience, but also by Korea's own recent Competitive Bidding Roadmap, which prepares auction volumes in the range of 7–8 GW over a two-year horizon and has already attracted sufficient market participation to fully subscribe recent tenders[55]. Beyond nominal capacity targets, recent assessments of Korea's offshore wind resource further reinforce this feasibility from a generation-based perspective. In particular, Choi et al. (2023)[56] estimate that, with the introduction of large-scale turbines and an improvement in the utilization rate toward 42%, offshore wind could deliver power outputs comparable to those implied by a 4 GW annual capacity expansion, even without proportional increases in installed capacity. In this sense, the coal phase-out pathway should be supported not only by capacity growth per se, but also by the deployment of larger turbines and by grid reinforcement that enables higher effective utilization of offshore wind generation.

Importantly, the primary constraint on offshore wind expansion lies less in turbine construction capacity than in institutional and system-level barriers, including fragmented permitting procedures, marine spatial planning, compensation mechanisms for affected stakeholders (e.g., fisheries and local communities), and grid connection bottlenecks. Recent institutional advances such as the 2025 Offshore Wind Promotion Act[57] represent a critical step toward addressing these barriers, but achieving a coal-free power system by 2035 will ultimately depend on sustained reforms in siting, permitting, and multi-level governance rather than on technology deployment alone.

Moreover, electrification across buildings, transport, and industry leads to a substantial rise in electricity demand by 2035, reinforcing that power-sector decarbonization is not merely one mitigation option among others but a precondition for realizing emissions reductions in end-use sectors. Delays in power-sector decarbonization would therefore directly undermine the mitigation effectiveness of electrification. This risk is further compounded by the rapid growth in electricity demand associated with AI and data-center expansion. Our sensitivity analysis shows that, under scenarios of accelerated AI-driven electricity demand growth, insufficient clean power supply leads to rising electricity prices and crowding-out effects that delay electrification in end-use sectors (see Supplementary Information S12 for the implications of accelerated AI-driven electricity demand growth). These interactions underscore that timely and socially grounded power-sector transition is not only a climate imperative but also a prerequisite for maintaining the economic and political viability of economy-wide decarbonization.

In the industrial sector, achieving deep decarbonization by 2035 requires a fundamental transformation of high-emitting subsectors—particularly iron and steel, chemicals, and cement. Under the *High Ambition* scenario, a 35.1% reduction in total industrial emissions is enabled by the accelerated deployment of next-generation mitigation technologies, including hydrogen-based steelmaking, LC3 cement, low-carbon and recycled feedstocks, and CCUS.

However, current carbon pricing policies—most notably Korea's Emissions Trading System (K-ETS)—remain insufficient to induce this transformation on their own. The system's continued reliance on generous free allocations and grandfathering has resulted in persistently low and volatile carbon prices, weakening incentives for firms to invest in capital-intensive breakthrough technologies. These structural limitations risk entrenching incumbent fossil-based production processes and delaying the shift toward low-carbon industrial pathways.

Overcoming these barriers will therefore require a broader and more coherent policy mix that goes beyond carbon pricing alone. In particular, stronger economic incentives—such as investment subsidies, contracts-for-difference–type instruments, or other forms of revenue stabilization for low-carbon technologies—will likely be necessary to close the cost gap between conventional and low-carbon production routes during the transition phase. At the same time, regulatory instruments can play a critical role in accelerating structural change. For example, constraints on lifetime extensions of blast furnace facilities in the iron and steel sector, and the establishment of clear standards for blended cement formulations such as LC3 (including allowable substitution ratios)[58–60], could materially hasten the diffusion of low-carbon production processes.

Targeted public support for research, development, and demonstration (R&D) is also essential, particularly in technology areas that are still in an early stage of commercialization. A salient example is the substitution of fluorinated process gases in semiconductor manufacturing, where green alternatives are emerging but not yet cost-competitive at scale. Proactive government support in such areas could not only accelerate domestic technological learning, but also reduce long-term reliance on imported abatement technologies, thereby lowering economy-wide mitigation costs.

Finally, industrial decarbonization cannot be assessed solely from the supply side. On the demand side, several of Korea's traditionally emissions-intensive industries—historically the backbone of export-led growth—have recently entered phases of slowing or stagnating output growth. Rising carbon prices and abatement costs are therefore likely to interact with sectoral growth trajectories and competitiveness.

Recent empirical literature further suggests that the degree of GDP–emissions decoupling achieved so far in high-income economies remains limited relative to Paris-consistent pathways[46,48], and that efficiency improvements may be partially offset by economy-wide rebound effects[47]. While these findings do not preclude the possibility of green growth, they indicate that industrial decarbonization strategies should not rely on supply-side measures alone.

Accordingly, integrating mitigation policies with a broader green industrial strategy—including the development of new demand centers such as RE100-compliant industrial clusters and low-carbon value chains—will be important for managing the transition in a manner that is both economically and politically sustainable.

The transport and building sectors demonstrate clear progress under the *High Ambition* scenario, with emissions reductions driven by widespread electrification, strengthened efficiency standards, and demand-side interventions. In transport, the convergence of higher ZEV adoption rates, tighter fuel economy standards targeted for ICEVs (approximately 1.5% annually), and expanded public transit subsidies significantly curbs emissions growth despite rising mobility demand. Similarly, in the building sector, the widespread implementation of zero-energy building (ZEB) standards and electrification mandates accelerates the phase-out of fossil fuel use, while maintaining service levels through efficiency gains and improved energy self-sufficiency.

However, current policy discussions remain largely focused on how to introduce new low-carbon technologies and fuels at the margin. Our results indicate that equally critical—and in many cases more decisive—are policies that accelerate the turnover and retrofitting of the existing capital stock. In particular, measures such as the early retirement of aging diesel vehicles, regulatory restrictions on ICE vehicle sales, mandatory green remodeling of buildings, and heat pump substitution mandates for fossil-based heating systems play a central role in unlocking near-term mitigation potential. Without such stock-oriented interventions, the diffusion of low-carbon technologies would be too slow to deliver emissions reductions at the scale and speed required for Korea's 2035 targets.

Despite these advances, other sectors exhibit critical implementation gaps. Korea has formally committed to the Global Methane Pledge and ratified the Kigali Amendment, yet lacks clear policy instruments to meet the associated targets. In the waste sector, a proposed landfill ban from 2026 demands additional incineration capacity, but community opposition and fragmented governance hinder project siting. In agriculture, reductions hinge on manure management, but specific measures—such as incentives for biogas generation or nutrient recycling strategies—remain undefined. Bridging these gaps is vital to ensuring coherence between international commitments and domestic decarbonization strategies.

To sum up, the results of this study highlight that ambitious near-term mitigation is not only feasible for Korea, but also critically important for shaping its long-term climate trajectory. The *High Ambition* pathway explored here demonstrates that, even without reliance on international offsets, a policy package can achieve a 58.9% reduction in domestic net emissions by 2035 relative to 2018, provided that coordinated sectoral transformations are implemented in a timely manner.

This emphasis on early action is strongly supported by climate science, which shows that rapid near-term emissions reductions matter not only for meeting long-term temperature goals but also for limiting peak warming and its associated risks. Pathways that avoid or minimize temperature overshoot entail substantially lower long-term climate risks—including reduced sea-level rise, fewer tipping point triggers, and smaller cumulative impacts on ecosystems and human systems—than those relying on delayed mitigation and later compensation through carbon removal[61,62]. Conversely, postponing mitigation increases the required pace of decarbonization in later decades and amplifies climate damages and economic burdens over the full century, as cumulative emissions ultimately determine peak warming and irreversible impacts[63,64]. In this sense, pathways that appear less demanding in the near term may in fact entail greater long-run adjustment costs by locking in carbon-intensive systems and narrowing future policy options.

From this perspective, the policy package examined in this study should be understood not merely as one possible pathway among many, but as a necessary direction of travel under emerging international conditions, including the Paris Agreement, RE100 commitments, the EU CBAM, and the formation of climate clubs. While such a high-ambition transition is far from easy—requiring stringent regulation, behavioral change, and substantial public investment—it appears increasingly unavoidable. The central policy challenge therefore lies not in whether to pursue deep decarbonization, but in how to overcome institutional and structural constraints so that Korea can align climate ambition with a broader green transition in a socially and economically sustainable manner.

Data Availability

All relevant scenario configurations and policy input files used in this study are available at: `https://github.com/hyuntaechoi634/gcam-rok-v7.1`. The corresponding model output data can be generated by running the model with these inputs using the publicly available GCAM code.

Code Availability

The GCAM model used in this study is based on GCAM 7.1, an open-source integrated assessment model maintained by the Joint Global Change Research Institute (JGCRI). The base GCAM source code can be accessed at: `https://github.com/JGCRI/gcam-core/releases`.

Acknowledgements

We would like to express our sincere gratitude to Jiyong Eom (KAIST), and Sonny Kim (KAIST) for their constructive comments on this study. We also extend our deep appreciation to Minsik Oh (Myongji University) for generously providing the server resources necessary for this research.

Author Contributions Statement

Conceptualization, H.C., S.P., and H.M.; methodology, H.C., S.P., and H.M.; investigation, H.C.; data curation, H.C.; formal analysis, H.C.; writing – original draft, H.C.; writing – review and editing, S.P., and H.M.; supervision, S.P., and H.M.; resources, H.C., S.P., and H.M.; funding acquisition, S.P., and H.M.

Funding

H.M. was supported by the National Research Foundation of Korea, Ministry of Science and ICT (Grant: RS-2025-02312954). S.P. and H.C. were supported by the Research Center for Market and Government.

Supplementary Information

Details of the methods and additional results are provided in the Supplementary Information.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used OpenAI's ChatGPT-5 in order to assist with language editing, text refinement, and clarity improvement. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Supplementary Information

Contents

SI1. Current Policy Landscape and Scenario Design

Since 2015, the Republic of Korea (hereafter, Korea) has progressively developed its national climate policy framework in alignment with the Paris Agreement. Korea formally committed to achieving carbon neutrality by 2050 in October 2020[41], and this commitment was subsequently codified through the enactment of the Framework Act on Carbon Neutrality and Green Growth for Coping with Climate Crisis[14] in September 2021. This Act legally mandates the 2050 net-zero target and establishes the institutional foundation for national carbon neutrality planning, including the formulation of long-term strategies, sectoral roadmaps, and implementation plans.

Parallel to this legislative development, Korea has actively revised its Nationally Determined Contributions (NDCs). In December 2020, Korea submitted its initial NDC targeting a 24.4% reduction in greenhouse gas (GHG) emissions relative to 2018 levels by 2030[65]. This target was subsequently strengthened to a 40% reduction in October 2021[12], accompanied by the introduction of sector-specific mitigation targets for power, industry, buildings, and transport. In March 2023, Korea further updated its NDC in conjunction with the release of the First National Framework Plan for Carbon Neutrality and Green Growth (hereafter CN-GG)[13], which specified detailed policy instruments and implementation strategies by sector.

Importantly, while Korea has legally enshrined its 2050 net-zero target, it has not yet adopted a formally binding framework that specifies cumulative or medium- to long-term emissions constraints consistent with this objective. However, in 2024, the Constitutional Court of Korea ruled that the existing climate policy framework failed to sufficiently protect the fundamental rights of future generations due to the absence of a legally binding and scientifically grounded emissions pathway beyond 2030 toward the 2050 target[15,16]. The Court ordered the government to establish a more concrete and enforceable medium- to long-term emissions trajectory by 2025. This ruling effectively requires Korea to define a post-2030 mitigation pathway that is scientifically grounded and consistent with its net-zero commitment.

Against this backdrop, Korea's recently submitted 2035 NDC, specifying a 53–61% reduction relative to 2018 levels[17], marks an important step in extending mitigation targets beyond 2030. However, a substantial share of this reduction is assumed to be achieved through international mitigation contributions, underscoring the need for a clearer understanding of the scale and feasibility of domestic mitigation efforts. At the same time, existing analyses remain limited in their ability to systematically assess how sector-specific policy measures translate into economy-wide emissions outcomes once system-level interactions and implementation constraints are taken into account.

Accordingly, this study uses the CN-GG as the primary reference for scenario construction, complemented by Korea's Basic Plans for Electricity Supply and Demand[33,34], and relevant framework acts[37–39] and implementation guidelines[66–68] across sectors. In constructing the *High Ambition* scenario, we also reference Korea's historical policy evolution, sectoral net-zero roadmaps for major emission-intensive industries[69–71], expert recommendations from recent reports[56,72], peer-reviewed studies on Korea's net-zero pathways, and international policy developments to ensure both feasibility and policy relevance.

To ensure global consistency of the modeled mitigation pathways, regions outside Korea are represented using exogenous decarbonization trajectories differentiated by major regional blocks. Specifically, all non-Korean regions are aggregated into two groups: the European Union (EU-27), combining EU-12 and EU-15, and the Rest of the World (RoW), comprising the remaining 29 regions. For the EU-27, we assume a CO_2 emissions reduction pathway consistent with the post–Fit for 55 policy framework[73], reaching a 90% reduction relative to baseline by 2040[74] and achieving net-zero CO_2 emissions by 2050. In contrast, the RoW follows a more gradual transition, with CO_2 emissions declining linearly to net-zero by 2060. These regional assumptions provide a coherent global background against which Korea's domestic mitigation pathways are evaluated.

SI2. Overview of GCAM-ROK

The Global Change Analysis Model (GCAM) is an open-source, multisector integrated assessment model that represents interactions among the economy, energy, agriculture, land, water, and climate systems at the global and regional levels[75–79]. *GCAM-ROK* is a nationally customized version of GCAM v7.1, developed to reflect Korea's specific energy system characteristics, policy environment, and socioeconomic context. This customization includes detailed adjustments to the power, industry, transport, and other sectors to improve national policy relevance and analytical accuracy.

In particular, the socioeconomic pathways underlying *GCAM-ROK* are calibrated to reflect Korea's post–COVID-19 long-term economic outlook, with GDP trajectories aligned with recent projections of Korea's potential growth[42,44] rather than pre-pandemic trends. Population assumptions are based on the *Population Projections for Korea: 2022–2072*[43] published by the Korean government, which captures Korea's rapidly aging and declining demographic structure in a consistent manner. A detailed discussion of the construction of these socioeconomic pathways is provided in Supplementary Information S4.

For the power sector, technology share weights were revised to align with Korea's domestic policy directions and market conditions[54]. In the native GCAM v7.1, nuclear power share weights increase gradually after 2020, reflecting an assumed rise in policy and societal preference. In *GCAM-ROK*, however, nuclear share weights were fixed at unity to maintain a neutral stance, recognizing persistent uncertainty in domestic policy direction, social acceptance, and institutional factors[80].

Technologies deemed commercially unavailable or with negligible near-term potential in Korea were excluded by setting their share weights to zero. This includes concentrating solar power (CSP), consistent with the *2020 New and Renewable Energy White Paper*[81], as well as biomass- and oil-fired power with CCS, given their limited technical and economic viability under current market conditions[82].

In the transport sector, modeled service output for battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) was calibrated to reproduce observed vehicle stocks in 2020 and 2025. Vehicle-type-specific assumptions on daily mileage, vehicle lifetime, and load factors were incorporated to ensure internal consistency between service demand and realized vehicle deployment in *GCAM-ROK*. Observed registered vehicle stocks were taken from the *Motor Vehicle Registration Status Report* published by the Ministry of Land, Infrastructure and Transport (MOLIT)[83]. A detailed description of the calibration procedures and underlying data sources is provided in Supplementary Information SI7.

In *GCAM v7.1*, the most recent calibration year for the industrial sector is 2015. As a result, projections of industrial activity beyond this year rely on structural assumptions regarding technology shares, trade patterns, and production growth that do not reflect major post-2015 shocks, including the COVID-19 pandemic and subsequent structural adjustments in key industries. This limitation leads to substantial discrepancies between modeled and observed industrial activity levels in the 2020s, particularly for emission-intensive sectors.

Among these sectors, iron and steel stands out as the dominant source of both process- and energy-related industrial emissions in Korea[18], and as one of the sectors most strongly affected by post-2020 market disruptions.

Under the default GCAM configuration, sectoral production trajectories for iron and steel in 2020 and 2025 diverge markedly from realized market outcomes in Korea, reflecting the model's inability to capture the sharp contraction in steel demand and trade following 2020.

To address this issue, we recalibrated the steel module in *GCAM-ROK* to observed activity levels using official national statistics. Crude steel output was benchmarked against the e-Nara Government Indicator series[84], while detailed information on domestic production, exports, and imports for 2020 and 2025 was taken from the *Steel Industry Trends* report published by the Ministry of Trade, Industry and Energy (MOTIE)[85].

Because GCAM does not endogenously adjust trade structures to reflect the post-2020 contraction in steel imports, the default configuration yields production and emissions trajectories that are misaligned with actual market conditions. We therefore adjusted Korea's steel trade parameters to reconcile modeled production, imports, and exports with observed data while preserving mass balance.

This recalibration ensures that the emissions baseline for Korea's iron and steel sector reflects actual market conditions rather than inherited global trade patterns, thereby improving the credibility of industrial emissions projections in *GCAM-ROK*.

A second important structural limitation in the native GCAM configuration arises in the treatment of the chemical sector, particularly with respect to non-energy feedstock use. In the default GCAM v7.1 setup, CO_2 emissions associated with non-energy feedstock consumption in industrial processes are implicitly assumed to be zero, reflecting a simplified accounting convention rather than physical process realities.

However, a substantial body of literature indicates that non-energy feedstock use in the chemical industry gives rise to significant process-related CO_2 emissions through pathways such as steam cracking, reforming, and oxidation reactions in the production of basic chemicals including ethylene, propylene, and ammonia[86–88]. In particular, carbon embedded in hydrocarbon feedstocks is only partially retained in final products, with a non-negligible fraction released as CO_2 during conversion and separation processes.

To correct this structural bias, we modified the chemical sector representation in *GCAM-ROK* to explicitly account for CO_2 emissions associated with non-energy feedstock use. Specifically, emission coefficients were introduced for major feedstock-based chemical production pathways to reflect process-related carbon release, following the IPCC Guidelines for National Greenhouse Gas Inventories[89] and consistent with empirical estimates reported by[86]. Furthermore, the carbon storage fraction for refined liquids feedstocks was adjusted from the GCAM default of 75% to 90%, reflecting Korea's petrochemical industry structure, in which naphtha-based steam cracking dominates and a large share of feedstock carbon is embodied in exportable chemical products[90]. This adjustment ensures that emissions from feedstock-based chemical production are captured in the industrial process emissions category rather than being artificially suppressed.

As a result, baseline and projected emissions from Korea's chemical industry in *GCAM-ROK* more accurately reflect both energy-related and process-related sources, improving the realism of industrial decarbonization pathways simulated in this study.

In addition, while the default GCAM assumes zero CO_2 storage capacity for Korea due to uncertainty in national geological assessments, the *GCAM-ROK* configuration incorporates recent domestic evaluations of carbon storage potential by introducing an explicit upper bound on CO_2 storage capacity, set at 2,000 $MtCO_2$. This value does not represent an estimate of economically recoverable storage, but rather a modeling ceiling intended to reflect the existence of substantial geological potential and to avoid artificially constraining CCS deployment in scenario analysis. The chosen upper bound is conservative relative to recent government assessments, which indicate a theoretical national storage potential of up to 11.6 $GtCO_2$[91], and is designed to ensure that storage availability does not become a binding constraint within the 2035 modeling horizon.

SI3. Overview of modeling approach

Our modeling approach follows five guiding principles designed to ensure policy realism, internal consistency, and analytical transparency. Each principle is illustrated with examples drawn from the policy set used in this study.

Implementability

Only policies accompanied by clearly identifiable regulatory, fiscal, or institutional instruments were directly represented in the model. In the Korean context, explicit deployment targets for electric and hydrogen vehicles for 2030 and 2040 are stated in government plans; however, these targets were not imposed exogenously in the model in the absence of binding mandates or economic enforcement mechanisms.

Conversely, policies articulating a clear directional intent but lacking operational specificity were incorporated exclusively in the *High Ambition* scenario. For example, Korea's clean hydrogen certification scheme defines eligibility criteria and grading standards but does not yet specify binding quotas or price-based incentives. Accordingly, this measure was treated as aspirational and included only in the enhanced policy set.

Temporal consistency

Policies were assumed to persist beyond their stated planning horizon unless explicitly constrained by sunset clauses or legal expiration. For instance, although the Energy Efficiency Resource Standard (EERS) does not specify fuel-specific reduction trajectories beyond its current phase, it was assumed to remain in force, with recent improvement rates extrapolated forward.

Similarly, subsidies for electric and hydrogen vehicle charging infrastructure were assumed to continue through 2035, reflecting their role as enabling infrastructure rather than temporary market stimulation tools. By contrast, the electric vehicle purchase subsidy is legislated to expire by 2025 and was therefore not extended in the *Current Policies* scenario. In the *High Ambition* scenario, however, its continuation was assumed as part of a strengthened mitigation package.

For the Korean Emissions Trading Scheme (K-ETS), given its early institutional phase and price volatility, carbon prices were represented by long-term average levels rather than short-term market fluctuations.

Quantification discipline

Policy instruments were directly encoded into the model wherever possible (e.g., mandates, standards, price signals, or technology constraints). When direct representation was not feasible, policy impacts were quantified using a hierarchy of evidence: (i) official government estimates, (ii) peer-reviewed studies, and (iii) empirical historical data.

For example, power generation capacity targets by energy source were translated into expected electricity output using capacity factor assumptions embedded in government planning documents, supplemented by academic estimates and NREL data for offshore wind.

As another example, for the direct landfill ban, mitigation impacts were estimated using the U.S. EPA's Waste Reduction Model (WARM)[92], allowing quantification of avoided methane emissions and changes in CO_2 emissions from alternative waste treatment pathways.

Feasibility filtering

The *High Ambition* scenario was constructed by retaining only those measures deemed technically, administratively, and institutionally plausible in light of Korea's recent policy evolution. While GCAM does not explicitly model transmission constraints for Korea, renewable generation outcomes were cross-checked against results from a prior study incorporating transmission expansion scenarios to ensure system-level plausibility[93].

Similarly, for CCS deployment, we introduced an explicit upper bound on CO_2 storage capacity (2,000 $MtCO_2$), not as an estimate of economically recoverable storage, but as a modeling ceiling designed to reflect the existence of substantial geological potential and to avoid artificially constraining CCS deployment. This value is conservative relative to recent government assessments indicating a theoretical national storage potential of up to

11.6 $GtCO_2$, and ensures that storage availability does not become a binding constraint within the 2035 modeling horizon.

Measures such as coal phase-out, accelerated offshore wind deployment, and zero-emission appliance mandates were assessed against domestic policy preparations, international experience, and formal policy proposals to ensure practical feasibility rather than theoretical maximum potential.

Methodological alignment

When multiple modeling approaches were available, we prioritized parameterizations previously validated in academic or government studies to ensure analytical comparability and reproducibility. Among prior GCAM-based policy scenario studies, several have made their full source code publicly available[2,27]. This study actively drew on methodological choices from such open-source works, adapting them as necessary to the Korean context.

SI4. Socioeconomic Pathways

This study explicitly differentiates socioeconomic pathways to reflect the contested nature of long-term growth assumptions under deep decarbonization constraints. A growing body of literature questions the feasibility of sustained economic growth compatible with Paris-aligned mitigation, particularly for high-income economies. Empirical studies highlight insufficient historical decoupling rates[46], large economy-wide rebound effects[47], and limited evidence for absolute decoupling at the required scale[48], challenging optimistic "green growth" narratives embedded in many integrated assessment models.

In light of these debates, rather than relying on a single growth trajectory, this study constructs multiple socioeconomic pathways to systematically test the robustness of Korea's mitigation strategies across a wide range of growth conditions. Population trajectories are based on the official *Population Projections for Korea: 2022–2072* published by Statistics Korea[43]. Population in 2025 is fixed at 51.7 million, and thereafter projected using high-, medium-, and low-variant growth rates.

For GDP per capita, three explicitly differentiated pathways are constructed. The year 2025 is anchored using observed real GDP growth for 2021–2025. From this fixed point, the *high* pathway follows KDI's optimistic projections for per-capita growth, closely resembling conventional growth-oriented baselines[42]. The *mid* pathway adopts KDI's pessimistic projections, representing a conservative but institutionally grounded outlook. The *low* pathway extrapolates a linear trend fitted to Korea's historical per-capita GDP growth decline following Choi (2026)[44,45], yielding a structurally low-growth trajectory consistent with long-run slowdown patterns documented by Kim (2016)[94].

Combining these per-capita GDP pathways with the corresponding population trajectories yields three internally consistent total GDP pathways for the model. These assumptions are summarized in Figure SS1. Importantly, these pathways are not intended as normative endorsements of continued growth or post-growth futures. Rather, they are designed to assess how mitigation feasibility, technology deployment, and system costs vary across fundamentally different macroeconomic conditions, including trajectories consistent with post-growth and secular stagnation perspectives.

Sensitivity results under these revised socioeconomic assumptions are reported in the Supplementary Material, enabling a systematic evaluation of how strongly Korea's mitigation pathways depend on contested growth assumptions.

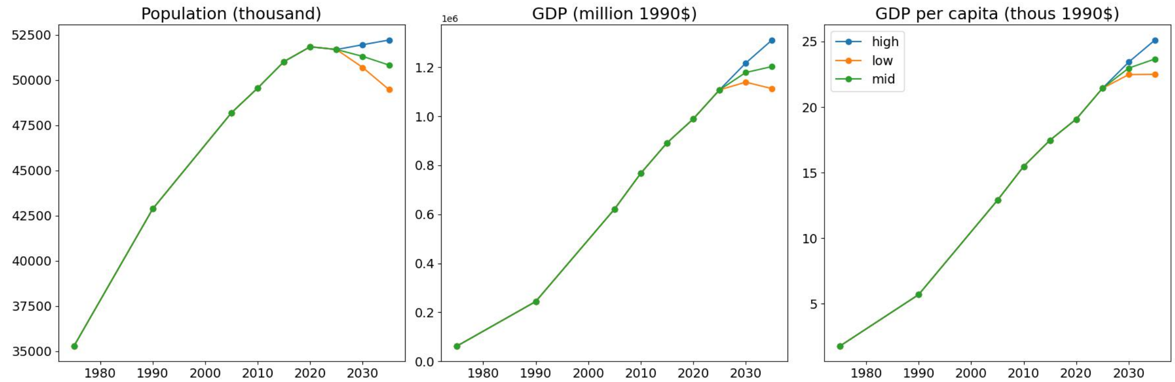


Figure S1. Socioeconomic pathways used in this study. The figure compares the *high*, *mid*, and *low* pathways for population, total GDP, and GDP per capita over the study horizon.

SI5. Electricity Modeling Assumptions

We describe how the core electricity-sector assumptions are constructed under the *Current Policies* and *High Ambition* scenarios, with explicit reference to Korea's institutional and policy context. Detailed numerical values and remaining technical assumptions are reported in Table S1.

Data Source

The primary data source is the *11^{th} Basic Plan for Long-Term Electricity Supply and Demand* (March 2025)[33], which provides capacity and generation projections by energy source for 2024–2038. The *Current Policies* scenario adopts electricity generation trajectories for all major energy sources directly from the approved 11^{th} Basic Plan for Long-Term Electricity Supply and Demand (MOTIE, March 2025), including coal, LNG, nuclear, clean hydrogen and ammonia, total renewables, solar, wind, and other. Because GCAM operates on 5-year time steps (2020, 2025, 2030, 2035, ...), Plan values for 2030 and 2035 are taken directly where available, while historical Plan values are used for 2020 and 2025. Although the Plan provides projections through 2038, this study reflects values through 2035 to match the temporal scope of the analysis. An earlier draft of the Plan, circulated in 2024, contained preliminary values that differ from the approved version; this study uses exclusively the approved March 2025 version.

For parameters not separately reported in the 11th Plan, supplementary sources are used. The *10^{th} Basic Plan*[34] provides the hydrogen-to-ammonia generation decomposition (H_2 6.1 TWh, NH_3 6.9 TWh in 2030), yielding a fixed 46.9%/53.1% split applied to the 11th Plan's aggregate "Clean Hydrogen Plus Ammonia" category. Offshore wind capacity milestones—used to disaggregate the 11th Plan's total wind into onshore and offshore components—are drawn from projections discussed at the Electricity Policy Council meeting during deliberations on the 10th Basic Plan[95]. The "Other" generation category in the 11^{th} Basic Plan is composed of waste-to-energy and battery energy storage systems (BESS). For simplification, these projected generation values are allocated to storage-coupled generation technologies (*PV_storage* and *wind_storage*). The Renewable Portfolio Standard (RPS) obligation schedule is obtained from the Korea Energy Agency's official RPS system description[96]. Because the Korean RPS applies only to generators with 500 MW or greater capacity and employs differentiated Renewable Energy Certificate (REC) weights, the effective renewable share differs from the headline obligation rate; the derivation of the effective RPS is described in the corresponding row of Table S1.

The *High Ambition* scenario departs from the *Current Policies* baseline in the following respects, each grounded in an identifiable policy signal or international commitment. The coal phase-out by 2035 reflects the

G7 commitment to phase out unabated coal power in the first half of the 2030s[97]. Solar capacity tripling by 2030 is consistent with the COP28 global commitment to triple renewable energy capacity[98]. Offshore wind capacity expansion is anchored in the average annual bidding volumes specified in Korea's Competitive Bidding Roadmap for Offshore Wind[55]. Capacity factors for the enhanced solar (linearly increasing to 0.17 by 2035) and offshore wind (linearly increasing to 0.36 by 2035) trajectories are adopted from a prior study incorporating transmission expansion scenarios[93], on the grounds that both the 10th and 11th Long-term Transmission and Substation Facilities Plans[99, 100] emphasize flexible grid-connection planning to accommodate expanded renewable energy integration.

Table S1. Key policy assumptions for the power sector by scenario

Modeled Policy	**Current Policies**	**High Ambition**
Coal Phase-out	Coal-fired power generation follows the trajectory reported in the 11th Basic Plan from 184.9 TWh (2023) to 110.5 TWh (2030), and 88.9 TWh (2035). See S2.	Unabated coal power generation (including ammonia co-firing) is fully phased out in line with the G7 commitment[97] by 2035 following a linear decline from 2025 (168.4 TWh).
Adoption of Co-firing	*Clean Hydrogen Plus Ammonia* generation in the 11th Basic Plan is disaggregated proportionally based on shares in the 10th Basic Plan; co-firing technologies are introduced from 2030. The H_2/NH_3 split is fixed at 46.9%/53.1%, derived from the 10th Basic Plan's 2030 generation mix (H_2 6.1 TWh, NH_3 6.9 TWh)[34].	Ammonia co-firing is not adopted as a mitigation option in the model. Residual coal-fired generation is instead abated through CCS-equipped coal power plants, which supply approximately 26.1 TWh by 2035. Clean hydrogen generation is not fixed but is allowed to compete freely within the gas-sector ceilings based on technology cost, reflecting the uncertainty in future hydrogen cost trajectories.
Solar PV Expansion	Solar generation follows the 11th Basic Plan trajectory: 16.6 TWh (2020), 39.1 TWh (2025), 67.1 TWh (2030), and 88.7 TWh (2035). Implicit capacity factors are derived from the Plan's capacity–generation series.	Installed solar capacity is tripled by 2030 relative to 2023 levels (71.7 GW), consistent with the COP28 commitment[98], and the implied expansion rate is maintained through 2035 (111.4 GW). The capacity factor increases linearly from the 2025 baseline value ($\sim$0.14) to 0.17 by 2035, reflecting improved grid integration enabled by the planned transmission reinforcement program[100]; the 2035 target capacity factor follows[93].
Wind Expansion	Total wind capacity follows the 11th Basic Plan (also the milestones discussed at the 10th Electricity Policy Council Meeting in October 2022, during deliberations on the 10th Basic Plan)[95]. An implicit capacity factor is derived from the Plan's total wind capacity and generation series to capture projected curtailment constraints; offshore generation is then calculated using planned offshore capacity milestones from the 10th Plan deliberations[34], and onshore generation is obtained as the residual.	Offshore wind capacity increases by approximately 4 GW per year, anchored in the average annual bidding volumes specified in Korea's Competitive Bidding Roadmap for Offshore Wind[55], and further supported by the government's subsequent Infrastructure Expansion and Deployment Plan, which establishes the institutional and logistical basis for sustaining this deployment pace through 2030[101]. The offshore capacity factor increases linearly from the 2025 baseline value ($\sim$0.20) to 0.36 by 2035, reflecting improved grid integration under the planned transmission reinforcement program[100]; the 2035 target capacity factor follows[93]. Onshore wind generation is identical to CP.
Nuclear Expansion	Nuclear generation follows the 11th Basic Plan: 204.2 TWh (2030) and 236.0 TWh (2035); 2020 and 2025 values are calibrated using observed data. Assumptions are held constant across scenarios.	

(Continued on next page)

Modeled Policy	Current Policies	High Ambition
LNG: Delayed phase-out	LNG-fired power generation follows the trajectory specified in the 11th Basic Plan across all scenarios: 161.0 TWh (2030) and 101.1 TWh (2035), increasing slightly from 157.7 TWh (2023) to 2030 before declining toward 2035.	
Hydropower generation	Hydropower generation is fixed at 3.7 TWh from 2025 onward, consistent with the 11th Basic Plan.	
Oil-fired generation	No additional oil-fired power capacity is allowed after 2025 in any scenario, consistent with the 11th Basic Plan.	
Energy Storage	The "Other" generation category in the 11th Basic Plan is composed of waste-to-energy and battery energy storage systems (BESS). For simplification, these projected generation values are allocated to storage-coupled generation technologies (*PV_storage* and *wind_storage*), with generation floors distributed proportionally between solar and wind based on their respective generation shares under the *Current Policies* scenario. Total storage floors are 11.8 TWh (2030) and 28.5 TWh (2035).	Storage deployment is scaled proportionally with expanded solar and wind generation, yielding generation floors of 18.1 TWh (2030) and 54.7 TWh (2035).
Renewable Portfolio Standard (RPS)	The effective renewable share is derived from Korea's institutional RPS design[96]. We first compute the ratio of the mandatory supply volume (GWh) to total electricity generation for each year, which yields the realized RPS share accounting for the limited coverage of obligated entities (generators $\geq$500 MW) and differentiated REC weights. This ratio is then extrapolated to model periods, resulting in an effective RPS of approximately 27% by 2035.	A progressive relaxation of institutional constraints is assumed—expanded coverage, higher obligation rates, and REC reform—leading to effective renewable shares of 25% in 2030 and 36% in 2035, consistent with Korea's emerging 2035 NDC range.

Discussions on Key Assumptions

Coal Phase-out. The assumed timeline for coal phase-out constitutes one of the most consequential policy parameters shaping Korea's decarbonization pathway. The baseline *High Ambition* scenario assumes a complete phase-out of unabated coal-fired power generation by 2035. This assumption is situated within Korea's evolving policy context: the Korean government has articulated a clear direction toward a coal phase-out by approximately 2040, and has recently demonstrated strengthened political commitment by expanding the former Ministry of Environment into the Ministry of Climate, Energy and Environment. Against this backdrop, our objective is not to impose an arbitrarily aggressive coal exit, but to examine—through modeling—whether advancing this emerging policy trajectory toward an earlier date remains ambitious yet feasible.

We benchmark this assumption against international experience, including Germany's legally mandated coal exit pathway—originally targeting 2038 but with recent political agreements accelerating coal phase-out to 2030 in parts of the country—as well as the G7 commitment to phase out unabated coal by 2035[97]. These cases demonstrate that rapid coal capacity reduction is politically and technically plausible under coordinated policy intervention. To directly address feasibility concerns, we introduce a sensitivity case in which the coal phase-out is delayed to 2040 (CPO2040); results are presented in SI13.

Nuclear Expansion. Nuclear generation follows the 11th Basic Plan across both scenarios: 204.2 TWh (2030) and 236.0 TWh (2035). The implied capacity expansion from 24.1 GW in 2023 to 32.4 GW in 2035 corresponds to an average annual increase of approximately 0.69 GW, closely matching Korea's historical nuclear build-out rate of roughly 0.64 GW per year during 1997–2016. Both capacity and generation assumptions strictly follow the 11th Basic Plan, which has historically served as Korea's primary planning instrument for nuclear development and has been implemented with relatively high fidelity.

We therefore identify the main feasibility constraint not in reactor construction itself, but in transmission reinforcement and social consensus regarding siting and timing. For this reason, nuclear assumptions are held constant across scenarios and are not used as a lever of ambition differentiation. This assessment is further supported by the Korean government's recent reaffirmation that the construction of new nuclear units under the 11th Basic Plan is being pursued as scheduled[40].

Offshore Wind Expansion. The assumed offshore wind expansion pace of approximately 4 GW per year under the *High Ambition* scenario is not an arbitrary extrapolation, but is anchored to Korea's recent policy and institutional developments. The Korean government's Competitive Bidding Roadmap for Offshore Wind[55] indicates that approximately 7–8 GW of tenders will be launched over roughly two years (H2 2024–H1 2026). Early results from the new tendering scheme indicate material market supply and participation, supporting the view that multi-GW annual procurement is not purely hypothetical. The subsequent Infrastructure Expansion and Deployment Plan[101] further establishes the institutional and logistical basis for sustaining this deployment pace through 2030.

Internationally, we benchmark Korea's high-ambition trajectory against the upper end of global experience. The United Kingdom—one of the most mature offshore wind markets—targets 43–50 GW by 2030[102], implying very large annual additions in the late 2020s; recent UK auctions have also awarded capacity at multi-GW scale. Against this backdrop, 4 GW per year for Korea is highly ambitious, but it does not exceed the upper bound implied by the most aggressive global trajectories—especially when interpreted as a policy-driven high-ambition pathway rather than a central forecast.

Validation Against the 11th Basic Plan

Table S2 compares the generation output (TWh) in the *Current Policies* (CP) scenario with the official projections of the 11th Basic Plan for Electricity Supply and Demand (BPESD; 13th March, 2025) for 2030 and 2035. By design, the CP scenario closely reproduces the 11th Basic Plan generation mix, with deviations of less than 0.3 TWh for every source category.

Table S2. Comparison of power generation output (TWh) with the 11th Basic Plan

	2030			2035			2038
Source	**BPESD**	**CP**	**Diff.**	**BPESD**	**CP**	**Diff.**	**BPESD**
Coal	110.5	110.4	−0.1	88.9	88.8	−0.1	70.9
Nuclear	204.2	204.2	0.0	236.0	236.1	+0.1	248.3
LNG	161.0	160.8	−0.2	101.1	101.2	+0.1	74.3
H_2/NH_3	15.5	15.4	−0.1	32.8	32.8	0.0	43.9
Renewables	120.9	120.9	0.0	179.9	179.9	0.0	205.7
Solar PV	67.1	67.3	+0.2	88.7	88.7	0.0	96.6
Wind	38.8	38.9	+0.1	76.2	76.1	−0.1	88.7
Hydro	3.7	3.7	0.0	3.7	3.7	0.0	3.7
Others	30.5	30.6	+0.1	52.8	52.8	0.0	61.3
Total	642.6	642.3	−0.3	691.5	691.6	+0.1	704.5
Renewables (%)	18.8	18.8	0.0	26.0	26.0	0.0	29.2
Carbon Free (%)	53.0	53.0	0.0	64.9	64.9	0.0	70.7

Note: Diff. = CP − BPESD. Others include new energy and battery storage. The 2038 column reports BPESD projections only, as GCAM operates on 5-year time steps and does not produce outputs for intermediate years.

SI6. Industry Sector Modeling Assumptions

(Continued on next page)

Modeled Policy	Current Policies	High Ambition

Table S3. Key policy assumptions for the industry sector by scenario

Modeled Policy	Current Policies	High Ambition
Carbon Pricing	Carbon prices are calibrated to historical K-ETS data[103][10]. For 2025, the weighted average allowance price over 2016–2022 (42.8 constant 1990 US$/tC) is assumed and held constant through 2035.	Anticipated institutional tightening of the K-ETS—including adjustments in allowance allocation, expansion of auctioning, and strengthened market discipline[104]—is reflected through a rising carbon price path consistent with Hotelling's rule at a 4.5% discount rate, reaching 53.3 constant 1990 US$/tC in 2030 and 66.5 constant 1990 US$/tC in 2035.
Demand Shift in Emission Intensive Industries	Downward adjustments to industrial activity levels in major emissions-intensive sectors are applied based on observed trends in sectoral growth rates. These adjustments represent industry-specific structural demand contraction following and adapting the empirical framework developed in[44].	
Transition to Hydrogen-Based Steelmaking	Hydrogen-based direct reduced iron (H_2-DRI) is assumed to be commercialized from 2035, consistent with provisional targets outlined in the Core Technology Development Program for Carbon Neutrality[37]. No additional investment in conventional blast furnace technology is allowed after 2040[69].	Accelerated R&D support enables the commercialization of H_2-DRI from 2030. The share of H_2-DRI production increases linearly to 55% by 2050, in line with the industry roadmap reported by[69]. New blast furnace investment and lifetime extension are restricted from 2035 onward, reflecting constraints highlighted in recent policy analyses[105]. Secondary steel production based on scrap is assumed to expand following POSCO's transition strategy[106], with scrap-based steel output increasing by approximately 30% every five years, reflecting a progressive shift toward electric arc furnace (EAF) routes and circular-economy-oriented steelmaking.
Feedstock Substitution in Chemicals	No explicit feedstock substitution policies are modeled, reflecting the absence of fully specified and committed policy instruments.	Feedstock substitution targets of 5% by 2030 and 22% by 2035 are assumed based on the net-zero roadmap for the Korean petrochemical industry[72]. In the model, this is approximated by increasing the efficiency of the refined liquids feedstock technology rather than introducing explicit alternative feedstock representations.
Clinker Substitution and Blended Cement Standards	Gradual adoption of blended cement formulations during the 2030s is assumed. The clinker share declines modestly from 85% in 2030 to 82.5% in 2035, with limited expansion of limestone use, consistent with the sectoral roadmap by Korea Cement Association[70].	Cement composition converges toward LC3-type standards. The clinker share declines to 50%, while limestone and calcined clay shares increase to 15% and 30%, respectively, reflecting full adoption of blended cement standards consistent with the industry outlook reported by[58–60,107].
Process Gas Substitution in Semiconductor Manufacturing (F-gases)	Process gas substitution is assumed, with CF_4 and C_2F_6 phased out from 2030, consistent with demonstrated replacement of conventional PFC cleaning gases by F_2-based mixtures in semiconductor manufacturing[108,109].	HFC_{23} and SF_6 are also substituted from 2035, reflecting ongoing development and expected adoption of low-GWP alternative plasma etching chemistries[110,111].

(Continued on next page)

[10] The K-ETS distinguishes three permit types: Korean Allowance Units (KAUs), Korean Credit Units (KCUs), and Korean Offset Credits (KOCs). Trading occurs via exchange (real-time, block, or auction) and over-the-counter (OTC) transactions. For simplicity, this study uses the volume-weighted average price across all permit types and trade channels for each calendar year.

Modeled Policy	Current Policies	High Ambition
Carbon Storage (CCS)	No explicit subsidy for CO_2 storage is assumed, reflecting the absence of a fully specified support mechanism under current Korean policy[112]. CCS deployment is therefore limited by prevailing cost conditions.	Explicit policy support is introduced to reduce effective CO_2 storage costs, converging toward approximately 50 US\$/tCO_2 by 2030, consistent with the government's projected trajectory and recent CCUS industrialization initiatives[113].

SI7. Translating Transport Subsidies into Service Units

The transportation module of GCAM represents policy interventions exclusively in terms of *transport service units*, rather than physical vehicles or infrastructure assets. However, real-world transport policies in Korea—such as purchase subsidies for vehicles and capital subsidies for charging and refueling infrastructure—are typically specified on a *per-vehicle* or *per-infrastructure-unit* basis.

The primary objective of this Supplementary Note is therefore twofold: (i) to document the methodological procedure used to convert vehicle- and infrastructure-level subsidy instruments into service-based subsidy measures compatible with the GCAM framework, and (ii) to report the resulting subsidy values expressed per unit of transport service as applied in the *GCAM-ROK* model.

The conversion is carried out consistently across vehicle types and fuel technologies, ensuring comparability between battery electric vehicles (BEVs), fuel-cell electric vehicles (FCEVs), and conventional internal combustion engine vehicles.

Lifetime Transport Service Representation

In *GCAM-ROK*, transport demand is represented on a lifetime service basis by vehicle type. Transport services are measured in passenger-kilometers (pkm) for passenger vehicles and buses, and in ton-kilometers (tkm) for freight trucks. Annual transport service is assumed to be constant over the vehicle lifetime and is derived from daily utilization, annual operating days, and average load factors, based on Korean transport statistics including KTDB, KADRA, and TMACS[114–116].

To ensure consistency with the discounted representation of costs in the model, lifetime transport service is evaluated in present value (PV) terms rather than as a simple undiscounted sum. Specifically, for each vehicle type i, annual transport service Q_i^{ann} is first computed as:

$$Q_i^{\text{ann}} = D_i \times 365 \times LF_i, \tag{1}$$

where D_i denotes average daily distance traveled (km/day) and LF_i denotes the average load factor (passengers per vehicle for cars and buses, or tons per vehicle for trucks). The present value of lifetime transport service is then given by:

$$Q_i^{\text{PV}} = Q_i^{\text{ann}} \times \sum_{t=1}^{L_i} \frac{1}{(1+r)^t} = Q_i^{\text{ann}} \times \frac{1-(1+r)^{-L_i}}{r}, \tag{2}$$

where L_i is the vehicle lifetime in years and r is the social discount rate, set to 4.5% in this study. Vehicle-specific assumptions used in this study are summarized in Table S4.

Table S4. Transport service assumptions by vehicle type

Vehicle type	Daily distance (km/day)	Load factor	Lifetime (years)	Service unit
Car, Large Car & Truck	44.3	1.26	15.3	passenger-km
Bus	162.0	12.84	15.5	passenger-km
Medium Truck	50.7	4.2	16.8	ton-km

Based on these assumptions, annual and present-value lifetime transport services are calculated accordingly. Passenger cars, large cars, and trucks deliver 20,373.6 passenger-km annually and 221,871.8 passenger-km in present value terms over their lifetime. Buses deliver 759,229.2 passenger-km annually and 8,343,550.0 passenger-km in present value terms over their lifetime. Medium trucks deliver 77,723.1 ton-km annually and 902,692.8 ton-km in present value terms over their lifetime. These present-value service measures constitute the denominator for all subsidy conversions described below.

Conversion of Charging and Refueling Infrastructure Subsidies

Korea's charging and refueling infrastructure support is provided as a one-time capital subsidy per asset (per EV charger or per hydrogen refueling station), while *GCAM-ROK* requires policy inputs in service units (USD per passenger-km or USD per ton-km). We therefore convert an asset-based subsidy into a service-based subsidy by (i) translating the capital subsidy into an implicit subsidy per unit of delivered energy using the present value (PV) of lifetime energy throughput, and (ii) mapping the energy-based intensity into service units using vehicle energy (or fuel) use per vehicle-km and load factors.

Let S^{charger} denote the subsidy per charger (KRW per charger) announced in year y. This value is first converted into constant USD in the model base year (1990) using the annual exchange rate and GDP deflator series employed consistently throughout the model:

$$S^{\text{charger}}_{\$,1990} = \left(\frac{S^{\text{charger}}_{\text{KRW}}}{\text{FX}_y}\right)\left(\frac{\text{DEF}_{1990}}{\text{DEF}_y}\right), \quad (3)$$

where FX_y is KRW per USD and DEF_y is the deflator index in year y.

To compute lifetime energy throughput, we infer the representative annual delivered electricity per charger from observed utilization patterns and an effective power factor. For charger type $j \in \{\text{fast}, \text{slow}\}$, annual throughput is computed as

$$E^{\text{annual}}_j = P_j \cdot \alpha_j \cdot \left(\frac{m_j}{60}\right) \cdot 365 \quad [\text{kWh/charger-year}], \quad (4)$$

where P_j is rated power (kW), α_j is an effective utilization factor capturing average power relative to rated capacity, and m_j is the average charging time (minutes per charger per day).

In practice, m_j is derived from observed daily charging durations aggregated across chargers, following empirical evidence reported by Kim[117], which analyzed electric vehicle charging behavior and utilization factors based on Seoul metropolitan data as of October 7, 2022. These province-level utilization patterns are used to parameterize the national-scale representation of charging behavior in the model, assuming that Seoul provides a conservative and representative proxy for urban charging intensity in Korea. Specifically, we compute

$$m_j = \frac{M^{\text{Seoul}}_j}{N^{\text{Seoul}}_j},$$

where M^{Seoul}_j is the total daily charging minutes across all chargers of type j in Seoul and N^{Seoul}_j is the corresponding number of chargers.

In this study, we use $P_{\text{fast}} = 50$ kW, $N_{\text{fast}} = 1{,}974$, $M^{\text{Seoul}}_{\text{fast}} = 106{,}198$ minutes/day, and $\alpha_{\text{fast}} = 0.7$ for fast chargers, with an assumed lifetime $L_{\text{fast}} = 10$ years. For slow chargers, we use $P_{\text{slow}} = 7$ kW, $N_{\text{slow}} = 26{,}259$, $M^{\text{Seoul}}_{\text{slow}} = 2{,}001{,}958$ minutes/day, $\alpha_{\text{slow}} = 0.85$, and $L_{\text{slow}} = 15$ years.

Discounting is applied using a social discount rate $r = 0.045$ to compute the PV of lifetime throughput via the annuity factor

$$\Phi(L, r) = \sum_{t=1}^{L} \frac{1}{(1+r)^t} = \frac{1-(1+r)^{-L}}{r}, \quad (5)$$

such that the discounted lifetime electricity delivered by charger type j is

$$E^{\text{PV}}_j = E^{\text{annual}}_j \cdot \Phi(L_j, r).$$

The implied charging-infrastructure subsidy per unit of electricity delivered is then given by

$$s^{\text{elec}}_j = \frac{S^{\text{charger}}_{\$,1990}}{E^{\text{PV}}_j} \quad [\$/\text{kWh}], \quad (6)$$

and, when a single public-charging value is required, we compute a blended intensity weighted by each charger type's discounted energy contribution:

$$\bar{s}^{\text{elec}} = \frac{\sum_j S^{\text{charger}}_{j,\$,1990} N_j}{\sum_j E^{\text{PV}}_j N_j} \quad [\$/\text{kWh}]. \quad (7)$$

This energy-based subsidy is finally mapped into transport service units using vehicle electricity intensity per vehicle-km, ε_i (kWh per vehicle-km), and load factors λ_i (passengers per vehicle for cars and buses, and tons per vehicle for freight):

$$s^{\text{service}}_i = \bar{s}^{\text{elec}} \cdot \frac{\varepsilon_i}{\lambda_i} \quad [\$/\text{passenger-km or } \$/\text{ton-km}]. \quad (8)$$

We use $\lambda_{\text{car}} = 1.26$ passengers/vehicle, $\lambda_{\text{bus}} = 15.03 \times 0.63 + 11.40 \times 0.37 = 13.66$ passengers/vehicle, and $\lambda_{\text{truck}} = 4.2$ tons/vehicle, while ε_i is taken from representative vehicle efficiency assumptions consistent with our transport calibration (kWh per vehicle-km).

An analogous procedure is applied to hydrogen refueling infrastructure. Let $S^{\text{station}}_{\text{KRW}}$ denote the per-station capital subsidy (KRW per station) in year y, converted to constant USD using Eq. (1). Let H^{annual} be the total annual hydrogen consumption in the road transport sector (kg-H_2 per year), derived from national hydrogen demand statistics and informed by a utilization study based on Seoul metropolitan data[118,119]. The operational lifetime of a hydrogen refueling station is assumed to be $L_{\text{H2}} = 15$ years.

Using the present value (PV) of lifetime hydrogen throughput,

$$H^{\text{PV}} = H^{\text{annual}} \cdot \Phi(L_{\text{H2}}, r), \quad (9)$$

the implied subsidy per unit of dispensed hydrogen is computed as

$$s^{H_2} = \frac{S^{\text{station}}_{\$,1990} N^{\text{sub}}}{H^{\text{PV}}} \quad [\$/\text{kg-H}_2], \tag{10}$$

where $S^{\text{station}}_{\$,1990}$ is the per-station subsidy expressed in constant 1990 USD, and N^{sub} is the number of subsidized stations. The total number of stations, N^{total}, is used separately to compute the average hydrogen throughput per station implicit in H^{annual}.

For Korea, we use a projected road-transport hydrogen consumption of $H^{\text{annual}} = 15{,}163$ t (i.e., 15,163,000 kg) for 2025[118], a total of $N^{\text{total}} = 437$ operating stations as of mid-2025 based on the Korea Gas Safety Corporation database[119], and $N^{\text{sub}} = 56$ subsidized stations according to the 2026 hydrogen station support guideline.

The resulting energy-based subsidy is then mapped into service units by

$$s_i^{\text{service}} = s^{H_2} \cdot \frac{\eta_i}{\lambda_i}, \tag{11}$$

where η_i is hydrogen consumption per vehicle-km for vehicle type i, computed from certified fuel economy as $\eta_i = 1/(\text{km/kg})$, and λ_i is the corresponding load factor. We use fuel economy values of 95.73 km/kg for passenger FCEVs, 26.29 km/kg for hydrogen buses, and 16.61 km/kg for hydrogen trucks, with load factors consistent with the transport service calibration in Table S4.

Through these conversions, hydrogen refueling infrastructure subsidies are expressed in USD per unit of transport service and can be consistently implemented in *GCAM-ROK* as non-energy input costs (with negative sign to represent a subsidy) under the policy name `charging-infra-subsidy`, ensuring conceptual consistency with the treatment of EV charging infrastructure and other transport policies.

SI8. Transportation Sector Modeling Assumptions

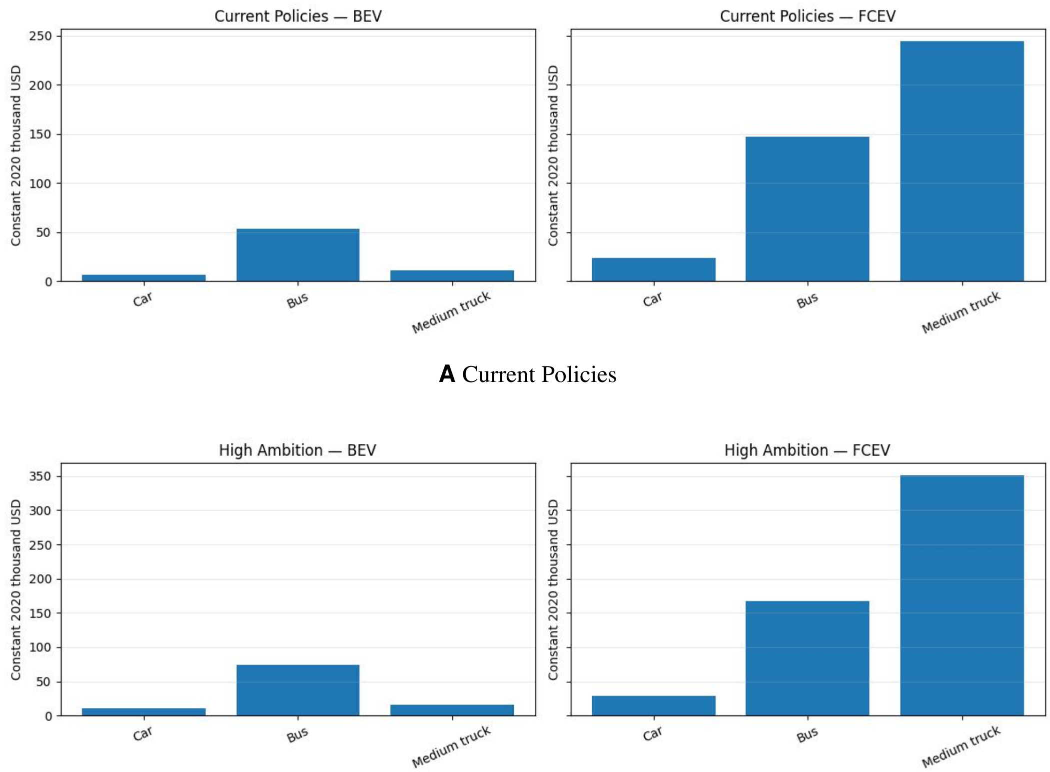
Table S5. Key policy assumptions for the transport sector by scenario

Modeled Policy	Current Policies	High Ambition
Purchase Subsidy for Zero-Emission Vehicles (ZEVs)	Purchase subsidies for BEVs and FCEVs reduce the generalized cost of ZEV adoption and are assumed to sunset after 2025. Subsidy levels are calibrated using average per-vehicle subsidies over 2021–2024 from the Emission-Free Vehicle Integrated Information Portal[120].	Subsidies are maintained at peak levels through 2035 to accelerate ZEV market penetration. See S2.
Charging and Refueling Infrastructure Subsidy for ZEVs	Government support for EV charging and hydrogen refueling infrastructure is represented using multi-year average unit subsidy levels over 2022–2024, converted from CAPEX support into model-applicable service-level subsidies.	Infrastructure support is represented using the maximum (peak) unit subsidy observed within 2022-2024, capturing an intensified policy stance.
Fuel Economy Standards	Vehicle efficiency improvements follow Korea's Administrative Notice on Vehicle GHG and Fuel Economy Standards (2021–2030)[68], implemented on a manufacturer-average basis by vehicle class. Explicit efficiency improvements are applied only to small passenger ICE vehicles (0.7% per year), while other classes adjust primarily through fleet composition.	Regulatory pressure strengthens ICEV efficiency improvements at the vehicle-class level, with fuel economy improving by about 1.5% per year for passenger vehicles and 1.3% per year for Large Car and Truck categories. Compliance is further supported by increased hybrid vehicle sales, which account for 50% of non-EV sales by 2035.
Subsidy for Early Retirement of Diesel ICEs	Early-retirement subsidies apply to Grade 4–5 diesel vehicles aged 20 years or older (passenger cars, large cars, and medium trucks), increasing the retirement rate of eligible vehicles by 9.6 %p per year[121].	Eligibility is expanded to include Grade 3 and below diesel vehicles aged 15 years or older, implying an accelerated phase-out of high-emitting diesel vehicles.

(Continued on next page)

Modeled Policy	Current Policies	High Ambition
Sales Ban of ICE Vehicles	Not explicitly modeled, reflecting the absence of a legally binding ban on new ICE sales in Korea.	Regulatory stringency on new ICE vehicle sales is assumed to increase progressively over time, culminating in a complete ban on new ICE passenger vehicle sales from 2040 onward, consistent with stringent international phase-out timelines[122–125]. For buses, a full ban on new ICE bus sales is assumed from 2035, reflecting fleet characteristics and the feasibility of depot-based electrification.
Vehicle Miles Traveled (VKT) Reduction	Mobility demand-management measures, including modal shifts induced by the expansion of metropolitan rapid transit such as the GTX network, induce a VKT reduction of 0.56% per year over 2025–2035[126].	A stronger VKT reduction of 0.90% per year is assumed over 2030–2035, reflecting reinforced behavioral and demand-moderation policies, alongside further uptake of high-capacity rail-based urban and intercity transport.
Greenship-K	Based on the Ministry of Oceans and Fisheries guidelines (2021), a capital subsidy for environmentally friendly ship construction is applied at 15% of shipbuilding costs.	The subsidy rate increases to 30%, corresponding to the upper bound allowed under the existing policy framework[127].

Figure S2. Assumed subsidy per vehicle by type (2020 US$).



A Current Policies

B High Ambition

SI9. Buildings Sector Assumptions

Renewable energy deployment and energy efficiency support programs of Korea in the buildings sector are primarily administered through the Korea Energy Agency (KEA). Unless otherwise specified in Table S6, this study adopts the design and parameters of building-related renewable energy and efficiency policies currently implemented by the KEA[128] as the reference basis for scenario construction.

Table S6. Key policy assumptions for the buildings sector by scenario

Modeled Policy	Current Policies	High Ambition
Energy Efficiency Resource Standards	Historical energy-efficiency improvement trends observed under the Energy Efficiency Resource Standard (EERS) programs of major public utilities—Korea Electric Power Corporation (KEPCO), Korea Gas Corporation (KOGAS), and Korea District Heating Corporation (KDHC)—are extrapolated through 2035. For each utility, annual energy savings achieved through EERS were normalized by total energy supplied to derive efficiency improvement rates, which were then linearly projected forward. Under these assumptions, cumulative efficiency improvements by 2035 reach 1.4% for electricity and heat, and 0.06% for gas relative to 2018 levels.	We assume that from 2025 onward, the improvement doubles compared to the baseline trend to reach 3% (electricity/heat) and 0.1% (gas) by 2035.
Zero-Energy Building (ZEB) Mandate	The existing ZEB mandate[66, 129] is maintained, applying primarily to new public buildings and large private buildings in accordance with the current regulatory roadmap[11].	The scope of the ZEB mandate is expanded to cover all new buildings, while maintaining the same technical performance levels, thereby increasing the penetration of zero-energy buildings.
Green Remodeling of Existing Buildings	No explicit green remodeling policy for the building sector is assumed.[12]	A mandatory green remodeling policy covering both residential and commercial buildings is assumed, benchmarked to the EU's building renovation framework[131]. Average energy use in buildings is assumed to decline by at least 16% by 2030 and 20–22% by 2035, with renovations prioritized for the worst-performing non-residential (commercial) buildings.
Subsidy for Renewable Energy Capacity	Installation subsidies for building-level solar PV and fuel cells are applied by equipment type, calibrated using average subsidy levels over 2021–2024.	Installation subsidies for building-level solar PV and fuel cells are maintained at peak levels observed over 2021–2024 to accelerate on-site renewable deployment.
Investment Support for Renewable Energy Deployment	Long-term low-interest financing for renewable energy deployment and manufacturing is provided. An interest rate of 1.75% is assumed, implying an implicit subsidy of 3.75% relative to a 5.5% market rate, with policy support covering 35% of total financing.	Financial support intensity is increased, with the implicit subsidy rate raised to cover 5% of total financing costs.

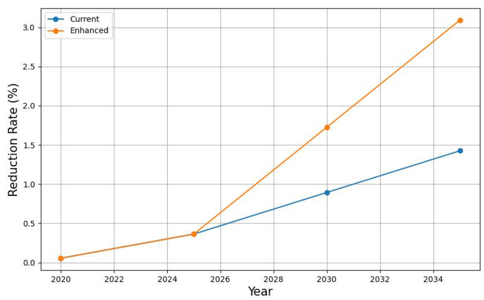
(Continued on next page)

[11] Under Korea's Zero Energy Building (ZEB) roadmap, ZEB standards are defined according to energy self-sufficiency levels, with Grade 5 corresponding to 20% self-sufficiency and Grade 1 to 100%. Importantly, ZEB requirements apply only to new buildings, and do not mandate retrofits of existing structures. Under the current regulatory framework, public buildings with a gross floor area of 1,000 m^2 or larger are required to meet at least ZEB Grade 4, while public buildings 500 m² or larger are subject to ZEB Grade 5 standards. For the private sector, ZEB Grade 5 requirements apply to new buildings with a gross floor area of 1,000 m² or more, including large residential buildings such as multi-unit apartment complexes.

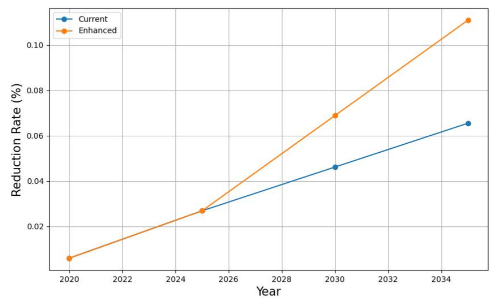
[12] According to[130], Korea's green remodeling support program for private buildings, which had been in place since 2014, was suspended in November 2023 due to low execution rates and implementation challenges. As a result, there is currently no active or concrete policy instrument supporting green remodeling in the private sector.

Modeled Policy	Current Policies	High Ambition
Heat Pump Substitution Mandate for Fossil-based Heating	Not explicitly modeled in this scenario.	A mandatory substitution of fossil-based building heating systems with heat pump–based or fully electric alternatives is assumed to take effect by 2035[13].

Figure S3. Energy Reduction Rate Projections by Fuel Type.



A Electricity and Heat



B Gas

SI10. Other Sector Assumptions

Table S7. Other policy assumptions for hydrogen, waste, DAC, agriculture, and international agreements

Modeled Policy	Current Policies	High Ambition
Clean Hydrogen Credit	Although certification grades for clean hydrogen are defined[134], no explicit incentive mechanism linking certification to investment or deployment is specified. Accordingly, the clean hydrogen certification scheme is not explicitly modeled.	Clean hydrogen targets are met exclusively through Grade 1–2 hydrogen (green and pink hydrogen). Following the First Hydrogen Economy Implementation Plan[38], clean hydrogen accounts for 51.6% of domestic hydrogen supply by 2030 and 63.7% by 2035; blue hydrogen is excluded from the clean hydrogen category.
Direct Landfill Ban	A ban on direct landfill disposal of untreated municipal waste is assumed to apply in the Seoul Metropolitan Area after 2025 and to expand nationwide after 2030[67], yielding emission reductions of 1.73 $MtCO_2e$ by 2030 and 2.23 $MtCO_2e$ by 2035[92].	The direct landfill ban is assumed to be implemented nationwide after 2025, leading to larger emission reductions of 2.44 $MtCO_2e$ by 2030 and 3.17 $MtCO_2e$ by 2035.

(Continued on next page)

[13] While Korea has not yet adopted a formal mandate to require heat pump substitution of fossil fuel heating systems, several jurisdictions have moved toward regulatory phase-outs of fossil boilers. In Europe, Germany plans to end mono-fuel oil boilers in all buildings from 2026, Ireland has banned oil and gas boilers in new buildings (and in existing buildings by 2025), and Slovakia is planning to ban sales and installation of new oil/gas boilers[132]. In the United States, New York State's All-Electric Buildings Act requires all-electric heating and cooking systems in most new buildings by the late 2020s, effectively phasing out fossil fuel heating in those contexts[133].

Modeled Policy	Current Policies	High Ambition
Ratification and Implementation of the UN Plastic Treaty	Not explicitly modeled.	Plastic waste generation is assumed to decline in line with the mitigation ambition currently under discussion in the context of the UN Global Plastics Treaty[135], corresponding to a 25% reduction by 2040 relative to baseline levels. This assumption yields emission reductions of 0.78 $MtCO_2e$ by 2030 and 1.55 $MtCO_2e$ by 2035.
Water-Saving Irrigation in Rice Paddies	Existing policies promote intermittent drainage (61.1%) and continuous flooding with water-saving practices (10%) to mitigate methane emissions from rice cultivation[39,136].	Strengthened enforcement and incentives increase the adoption of continuous flooding with water-saving practices to 30% by 2035, prioritizing higher-impact mitigation options.
Nitrogen Fertilizer Reduction	Not explicitly modeled.	ICT-based precision agriculture and low-input farming practices reduce nitrogen fertilizer and manure inputs, mitigating approximately 31.7% of cropland-related emissions by 2030 and 32.6% by 2035.
Low-Methane Feed	Not explicitly modeled.	Standards for low-methane feed and improved feeding practices reduce enteric fermentation emissions by approximately 0.75 $MtCO_2e$ by 2030.
Smart Farm Diffusion	Smart farming improves productivity by 10%, with coverage rising from 14% in 2025 to 35% by 2035.[137]	Accelerated policy support enables smart farm coverage to reach 35% by 2030 and 50% by 2035, with productivity gains increasing to 20%.
Implementation of the Global Methane Pledge	Not explicitly operationalized due to the absence of an integrated domestic methane policy framework.	Consistent with Korea's commitment under the Global Methane Pledge to reduce methane emissions by 30% by 2030 relative to 2018[138], we impose an economy-wide methane mitigation trajectory through 2030 and assume that the declining trend is sustained by 2035.
Implementation of the Kigali Amendment	Although Korea has ratified the Kigali Amendment[139], the lack of enforceable domestic implementation instruments implies that HFC reductions are not explicitly modeled.	An explicit HFC constraint consistent with Korea's Kigali Amendment commitments is imposed, assuming a linear reduction pathway to an 80% decrease in HFC emissions by 2045 relative to the 2020–2022 average level (30.4 $MtCO_2e$; GIR, 2025), implemented through the adoption of low-GWP alternatives and natural refrigerants.
Deployment of Backstop Technologies (Direct Air Capture)	No deployment of direct air capture (DAC) is assumed.	DAC deployment increases linearly from zero in 2025 to 14.8 $MtCO_2$ by 2050, reflecting its role as a backstop mitigation option in high-ambition pathways. This level corresponds to approximately twice the DAC deployment assumed under Scenario B of Korea's 2050 Carbon Neutrality Scenarios[41].

SI11. Sensitivity Analysis Assumptions

We also assessed emissions projections from the two scenarios by varying assumptions on a few important drivers, including GDP, population growth, oil and gas prices, and the land sink carbon sequestration potential. See Supplementary Table 8 for our sensitivity assumptions, and Supplementary Note 4 for the sources for our core assumptions.

Table S8. Assumptions under sensitivity scenarios (excluding GDP and Population)

Driver	Core Assumptions	Sensitivities
GDP per Capita[42,44]	GDP per capita is assumed to grow by 1.4% per year for 2025-2030, 0.6% for 2030-2035.	**High:** GDP per capita grows by 1.8% for 2025-2030, 1.4% for 2030-2035. **Low:** Per capita GDP growth rate itself decreases from 0.9% in 2026 to nearly 0% in 2030.
Population[43]	Population is assumed to decline by an average of 0.20% per year from 2025 to 2035 (from 51.68 million to 50.82 million).	**High:** Increases slowly, by 0.05% per year, reaching 51.94 million in 2035. **Low:** Declines more quickly, by 0.54% per year, reaching 49.47 million in 2035.
Gas prices	Gas prices are assumed to increase at an average rate of 0.08% per year between 2025 and 2035.	**High:** Gas prices increase at 5.1% per year. **Low:** Oil prices decrease at 2.1% per year.
Oil prices	Oil prices are assumed to increase at an average rate of 0.94% per year between 2025 and 2035.	**High:** Oil prices increase at 3.9% per year. **Low:** Oil prices decrease at 1.3% per year.
LULUCF	LULUCF sector is assumed to sequester 42.1 $MtCO_2$ by 2035.	**High:** LULUCF sector is assumed to sequester 42.1 $MtCO_2$ to 48.2 $MtCO_2$ by 2035. **Low:** Not specified.

SI12. On AI-Driven Electricity Demand Increase

The rapid expansion of artificial intelligence (AI) and large-scale data centers has emerged as a potentially important new driver of electricity demand, raising concerns about its implications for near-term decarbonization pathways. Korea's 11th Basic Plan for Long-term Electricity Supply and Demand[33] projects rapid growth in data center contract power, as summarized in Table S9.

Table S9. Data center contract power projections from the 11th Basic Plan

Year	2023	2024	2025	2026	2027
Contract power (MW)	776	2,514	3,738	4,578	4,718

The 11th Basic Plan reports data center electricity supply of 5.0 TWh in 2023. Given the 2023 contract power of 776 MW, this implies a capacity factor of $5.0/(0.776 \times 8{,}760) \approx 0.735$. Assuming this capacity factor is maintained, 2024 data center electricity consumption is estimated at $2.514 \times 8.760 \times 0.735 \approx 16.2$ TWh.

The 11th Basic Plan already projects data center electricity demand of approximately 18 TWh by 2030 and roughly 25 TWh by 2035 (linearly interpolated from the 2030 and 2036 values reported in the Plan). These projections are already reflected in the *Current Policies* scenario. However, AI-driven demand may exceed these projections, motivating an additional sensitivity analysis.

As of 2024, global data center electricity consumption is estimated at approximately 415 TWh. Under the IEA Lift-Off (high-growth) scenario, global data center consumption exceeds 1,260 TWh by 2030 and reaches approximately 1,700 TWh by 2035[140,141]. The IEA notes that demand growth is likely to be concentrated in the United States and China, implying asymmetric regional impacts; however, we apply uniform proportional growth as an extreme-case assumption for this sensitivity analysis.

Scaling proportionally from Korea's 2024 baseline of 16.2 TWh, projected data center electricity consumption under the IEA Lift-Off scenario is $16.2 \times (1{,}260/415) \approx 49.2$ TWh in 2030 and $16.2 \times (1{,}700/415) \approx 66.4$ TWh in 2035. Subtracting the demand already projected in the 11th Basic Plan yields additional demand of $49.2 - 18.0 = 31.2$ TWh in 2030 and $66.4 - 25.0 = 41.4$ TWh in 2035. As a share of the Plan's total electricity demand, these represent approximately $31.2/642.6 \approx 4.86\%$ in 2030 and $41.4/691.5 \approx 5.99\%$ in 2035.

This additional demand is implemented in *GCAM-ROK* by proportionally inflating the ratio of consumed electricity to generated electricity for 2030 and 2035.

Table S10 summarizes the key results of this sensitivity analysis under both the *Current Policies* and *High Ambition* scenarios.

Table S10. Summary of AI-driven electricity demand sensitivity analysis

	Current Policies		High Ambition	
	Baseline	CP–AI	Baseline	HA–AI
Power generation in 2030 (TWh)	642.3	643.6	661.2	664.0
Power generation in 2035 (TWh)	691.6	692.5	770.7	777.1
Electricity price change in 2035	–	+9.1%	–	+5.7%
Total emissions in 2035 ($MtCO_2e$)	483.7	488.0	304.8	311.7
Power sector emissions in 2035 ($MtCO_2e$)	117.7	118.1	51.7	51.2

An exogenous increase in electricity demand does not translate one-for-one into higher consumption: electricity prices and quantities adjust simultaneously across all sectors. Under *Current Policies*, the electricity price rises by 9.1% in 2035, yet power generation increases by only +0.8 TWh—most of the demand shock is absorbed through price-induced demand reduction elsewhere. Under *High Ambition*, the price increase is smaller (+5.7%) but the generation increase is larger (+6.4 TWh). This asymmetry arises because the CP scenario has limited prior electrification, making demand less elastic: offsetting the shock requires a steeper price signal. The HA scenario already features extensive electrification, so even a moderate price increase sufficiently curtails demand from other sectors.

Power-sector emissions are nearly unchanged by the AI demand shock: +0.4 $MtCO_2e$ under CP and -0.5 $MtCO_2e$ under HA in 2035. Because most of the additional datacenter demand is offset by reduced consumption in other sectors, net power-sector output—and hence emissions—remains largely the same.

Economy-wide emissions, however, rise more substantially: +4.3 $MtCO_2e$ under CP and +6.9 $MtCO_2e$ under HA. The mechanism is crowding out: AI datacenter demand displaces electrification in other end-use sectors, causing those sectors to retain or revert to fossil fuels. Economy-wide emissions therefore increase even though power-sector emissions are nearly flat. The effect is more pronounced under HA precisely because that scenario relies more heavily on electrification as a decarbonization lever; when electrification is crowded out, its climate benefit is partially lost.

The magnitude of this crowding-out effect is model-dependent, hinging on the assumed price elasticity of electricity demand and the economy-wide capacity for electricity supply expansion. If elasticity were lower and supply capacity larger than modeled, the price increase would be smaller and the consumption increase larger, leading to higher power-sector emissions but lower economy-wide emissions (less crowding out of electrification). Regardless of the precise parameter values, these results underscore the importance of integrating AI-driven demand growth into energy and climate planning.

SI13. On Delayed Coal Phase-Out

The assumed timeline for coal phase-out constitutes one of the most consequential policy parameters shaping Korea's decarbonization pathway. To strengthen the empirical and policy grounding of this assumption and to directly address concerns regarding feasibility, we conduct a dedicated sensitivity analysis on alternative coal retirement schedules.

The baseline *High Ambition* scenario assumes a complete phase-out of unabated coal-fired power generation by 2035. This assumption is explicitly situated within Korea's evolving policy context. The Korean government has articulated a clear long-term direction toward a coal exit by around 2040[142], and has recently demonstrated strengthened political commitment by expanding the former Ministry of Environment into the Ministry of Climate, Energy and Environment. Against this backdrop, our objective is not to impose an arbitrarily aggressive coal exit, but to examine—through modeling—whether advancing this emerging policy trajectory toward an earlier date remains ambitious yet feasible.

We also benchmark this assumption against international experience, including Germany's legally mandated coal exit pathway—originally targeting 2038 but with recent political agreements accelerating coal phase-out to 2030 in parts of the country—as well as the G7 commitment to phase out unabated coal by 2035[97]. These cases demonstrate that rapid coal capacity reduction can be politically and technically plausible under coordinated policy intervention.

To directly assess the feasibility and system-wide implications of a slower coal retirement schedule, we introduce a sensitivity case in which the coal phase-out is delayed to 2040 (hereafter CPO2040), while holding other policy assumptions in the *High Ambition* scenario constant. This allows us to isolate the structural role of coal retirement timing in shaping electricity markets and emissions outcomes.

Table S11 compares key outcomes between the baseline *High Ambition* scenario and the delayed coal phase-out case.

Table S11. Comparison of High Ambition scenarios with different coal phase-out timelines

	High Ambition	**HA–CPO2040**
Power generation in 2030 (TWh)	667.4	689.4
Power generation in 2035 (TWh)	787.6	833.0
Electricity price change in 2035	–	−6.4%
Total emissions in 2035 (MtCO_2e)	304.8	339.6
Power sector emissions in 2035 (MtCO_2e)	51.7	103.7

Delaying the coal phase-out reduces electricity prices by approximately 6.4% in 2035, reflecting continued availability of low short-run marginal cost generation. However, this comes at the cost of nearly doubling power-sector emissions (from 51.7 to 103.7 MtCO_2e). Economy-wide emissions also increase substantially, from 304.8 to 339.6 MtCO_2e, although the increase is smaller than in the power sector alone because cheaper electricity accelerates electrification in end-use sectors, displacing direct fossil fuel combustion and partially offsetting the additional power-sector emissions at the system level.

These results indicate that the coal phase-out timeline is not a secondary modeling assumption, but a structurally decisive policy variable for achieving Korea's climate targets. While delaying coal retirement may yield short-term electricity price relief, it substantially undermines emissions reductions in the power sector and weakens the overall decarbonization trajectory. This underscores the critical importance of pursuing an early coal exit as a cornerstone of Korea's climate strategy.

SI14. Korea's 2035 NDC (January 2026)

Table S12. Sectoral emissions and reductions under alternative 2035 NDC targets

Item	Sector	2018	2035 NDC Δ53%		2035 NDC Δ61%	
			Emissions	Δ%	Emissions	Δ%
Net emissions		742.3	348.9	−53.0%	289.5	−61.0%
	Power	283.0	88.3	−68.8%	70.0	−75.3%
	Industry	276.3	209.1	−24.3%	190.6	−31.0%
	Buildings	52.1	24.2	−53.6%	22.8	−56.2%
	Transport	98.8	39.3	−60.2%	36.8	−62.8%
	Refrigerants	23.1	27.4	+18.6%	25.5	+10.4%
	Agriculture, Livestock & Fisheries	27.6	20.0	−27.5%	19.5	−29.3%
	Waste	19.4	9.2	−52.6%	9.0	−53.6%
	Fugitive emissions	3.7	2.6	−29.7%	2.4	−35.1%
	Hydrogen	0.0	8.1	+8.1	6.5	+6.5
	Carbon sinks	−41.6	−38.3	+1.9	−39.3	+0.9
	CCUS	0.0	−11.2	–	−20.3	–
	International offsets	0.0	−29.8	–	−34.0	–

Note: Emissions are in $MtCO_2e$. (Δ%) are reductions relative to 2018 levels.

SI15. On Economy-Wide Energy Consumption

Figure S4 illustrates the evolution of Korea's economy-wide final energy consumption by fuel type under the *Current Policies* and *High Ambition* scenarios from 2015 to 2035.

Under *Current Policies*, total final energy demand remains broadly stable through 2035, with only a modest decline in refined liquids and limited changes in the overall fuel mix. Refined liquids continue to dominate final energy use, declining only gradually from about 115.5 Mtoe in 2020 to 97.2 Mtoe in 2035, reflecting the persistence of oil-based energy use in transport and industry. Electricity demand increases steadily from 44.5 Mtoe in 2020 to 55.1 Mtoe in 2035, indicating ongoing electrification, but without a fundamental restructuring of the energy system. Fossil gas and coal remain substantial contributors, largely due to limited technology and fuel switching in industrial processes and building energy use under existing policies, while hydrogen penetration remains marginal, reaching only about 2.0 Mtoe by 2035.

By contrast, the *High Ambition* scenario exhibits a more pronounced structural transformation of final energy consumption. Most notably, refined liquids decline sharply to about 81.0 Mtoe by 2035, reflecting accelerated electrification and fuel switching in the chemicals industry and transportation. Electricity demand continues to rise to 54.8 Mtoe by 2035, but its role changes qualitatively, increasingly serving as the backbone of end-use decarbonization rather than merely accommodating incremental demand growth.

Hydrogen use expands substantially under *High Ambition*, increasing from negligible levels in 2020 to about 7.1 Mtoe in 2035, indicating its emerging role in hard-to-electrify segments of industry and transport (particularly DRI–H_2–EAF). Biomass consumption also rises more markedly than under *Current Policies*, reaching 8.5 Mtoe in 2035, partly reflecting substitution away from fossil fuels in industrial energy use. Meanwhile, coal and gas decline more decisively, particularly coal, which falls to about 20.7 Mtoe by 2035 compared to 27.2 Mtoe under *Current Policies*.

The overall transition is characterized by a decisive shift away from carbon-intensive fuels toward low-carbon energy carriers, accompanied by efficiency improvements across end-use sectors, alongside more modest contributions from demand-side reductions.. This highlights that Korea's near-term mitigation challenge is driven less by absolute energy scarcity than by the speed and depth of fuel substitution across end-use sectors.

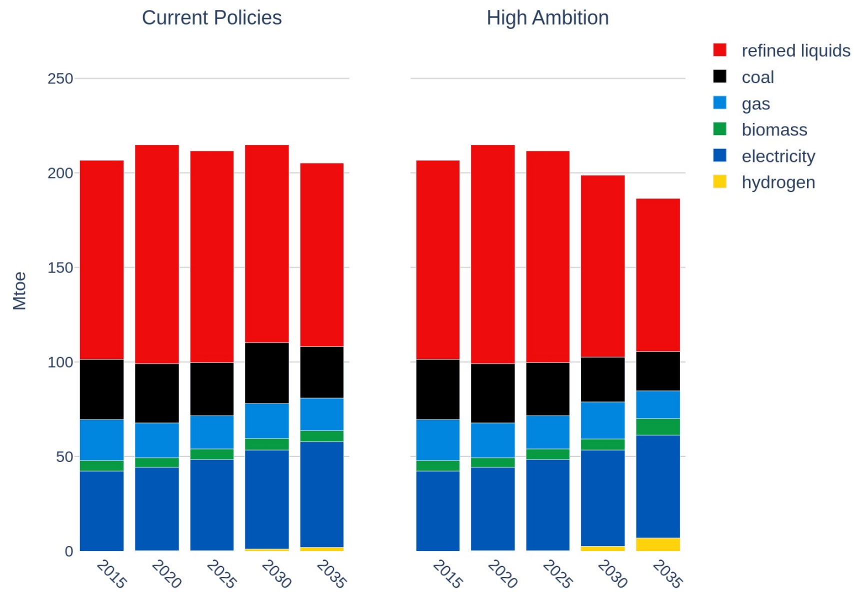


Figure S4. Economy-wide final energy consumption by scenario.

SI16. Supplementary Figures

Figure S5. Final energy consumption in the chemical sector by energy type.

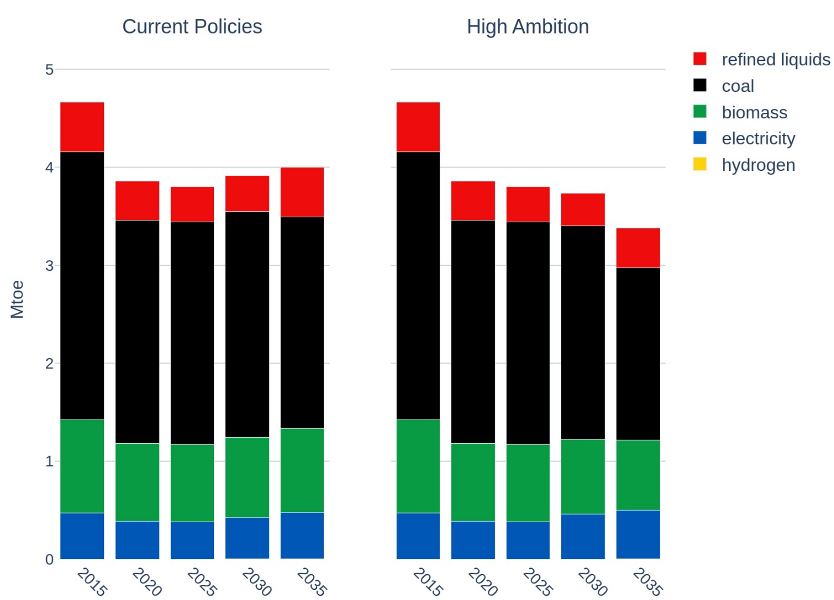


Figure S6. Final energy consumption in the cement sector by energy type.

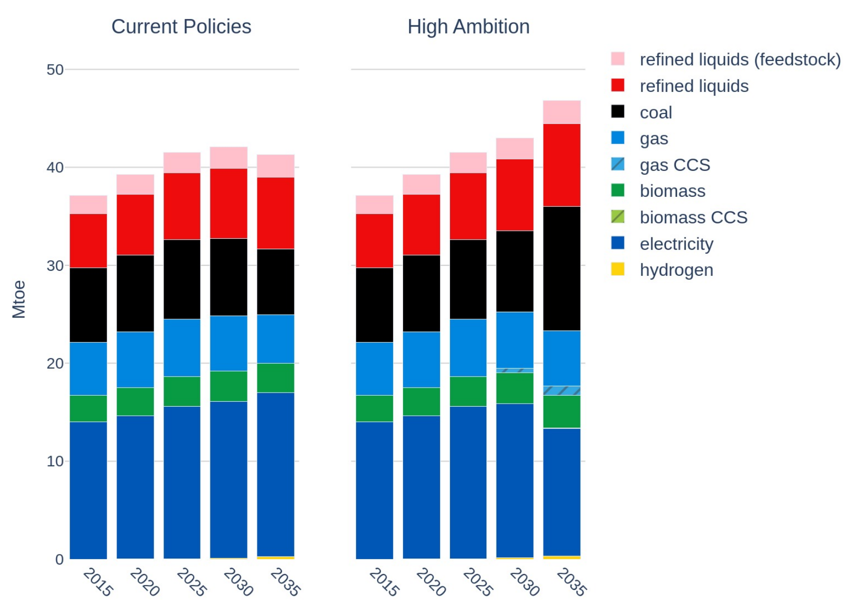


Figure S7. Final energy consumption in other industrial sectors by energy type.

References

1. Iyer, G. *et al.* Ratcheting of climate pledges needed to limit peak global warming. *Nat. Clim. Chang.* **12**, 1129–1135, DOI: 10.1038/s41558-022-01508-0 (2022).
2. Ou, Y. *et al.* Can updated climate pledges limit warming well below 2°c? *Science* **374**, 693–695, DOI: 10.1126/science.abl8976 (2021).
3. Climate Action Tracker. Glasgow's 2030 credibility gap: Net zero's lip service to climate action. https://climateactiontracker.org/publications/glasgows-2030-credibility-gap-net-zeros-lip-service-to-climate-action/ (2021).
4. United Nations Environment Programme. Emissions gap report 2022: The closing window—climate crisis calls for rapid transformation of societies—executive summary. https://www.unep.org/emissions-gap-report-2022 (2022).
5. den Elzen, M. G. J. *et al.* Updated nationally determined contributions collectively raise ambition levels but need strengthening further to keep paris goals within reach. *Mitig. Adapt. Strateg. for Glob. Chang.* **27**, 33, DOI: 10.1007/s11027-022-10008-7 (2022).
6. Grant, N. The paris agreement's ratcheting mechanism needs strengthening 4-fold to keep 1.5°c alive. *Joule* DOI: 10.1016/j.joule.2022.02.017 (2022).
7. Riahi, K. *et al.* Mitigation pathways compatible with long-term goals. In Shukla, P. R. *et al.* (eds.) *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Chapter 3 (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2022).
8. Peeters, M. The global stocktake. In Klein, D., Mehling, M. & Körschgen, H. (eds.) *The Paris Agreement on Climate Change*, 326–346, DOI: 10.4337/9781788979191.00023 (Edward Elgar Publishing, Cheltenham, UK, 2021).
9. UNFCCC. Outcome of the first global stocktake. https://unfccc.int/topics/global-stocktake/about-the-global-stocktake/outcome-of-the-first-global-stocktake (2023).
10. UNFCCC Secretariat. Technical dialogue of the first global stocktake: Synthesis report by the co-facilitators on the technical dialogue. Tech. Rep. FCCC/SB/2023/9, United Nations Framework Convention on Climate Change, Bonn, Germany (2023).
11. Crippa, M. *et al.* Ghg emissions of all world countries – 2025 report. Tech. Rep. JRC143227, Publications Office of the European Union, Luxembourg (2025). DOI: 10.2760/9816914.
12. Government of the Republic of Korea. The republic of korea's enhanced update of its first nationally determined contribution (2021).
13. Government of the Republic of Korea. National framework plan for carbon neutrality and green growth. https://www.2050cnc.go.kr/flexer/view/BOARD_ATTACH?storageNo=1936 (2023).
14. Government of the Republic of Korea. Framework act on carbon neutrality and green growth for responding to the climate crisis. National Assembly of the Republic of Korea (2021).
15. Lee, K. W. & Park, T. J. South korea's landmark ruling on climate justice. *Nat. Hum. Behav.* 1–2, DOI: 10.1038/s41562-025-02174-w (2025).
16. Constitutional Court of Korea. Case on national greenhouse gas reduction targets addressing the climate crisis (2020hun-ma389 et al.), decision of 29 august 2024 (2024).
17. Republic of Korea. The republic of korea's 2035 nationally determined contribution (2025).
18. Greenhouse Gas Inventory and Research Center of Korea (GIR). National Greenhouse Gas Inventory of Korea (1990–2022) (2025).
19. Kim, H. *et al.* Integrated assessment modeling of korea's 2050 carbon neutrality technology pathways. *Energy Clim. Chang.* **3**, 100075, DOI: 10.1016/j.egycc.2022.100075 (2022).
20. Cho, S., Jeong, Y. S. & Huh, J.-H. Is south korea's 2050 carbon-neutral scenario sufficient for meeting greenhouse gas emissions reduction goal? *Energy for Sustain. Dev.* **80**, 101447, DOI: 10.1016/j.esd.2024.101447 (2024).
21. Shin, D. H. *et al.* Carbon emission reduction scenarios in the building sector to achieve carbon neutrality in south korea by 2050. *Energy* 139057, DOI: 10.1016/j.energy.2025.139057 (2025).
22. Lee, H. *et al.* Decarbonization pathways for korea's industrial sector towards its 2050 carbon neutrality goal. *J. Clean. Prod.* **476**, 143749, DOI: 10.1016/j.jclepro.2023.143749 (2024).
23. Jeon, S., Roh, M., Kim, M., Oh, J. & Kim, S. How electric vehicles impact the power grid: A spatially high-resolution analysis of charging demand and power system dynamics. *Energy Strateg. Rev.* **59**, 101756, DOI: 10.1016/j.esr.2025.101756 (2025).
24. Kim, S., Eom, J., Zhang, Y. & Waldhoff, S. The impact of climate change on Korea's agricultural sector under the national self-sufficiency policy. *PLOS ONE* **20**, e0313748, DOI: 10.1371/journal.pone.0313748 (2025).

25. Jeon, S., Roh, M., Kim, M., Jung, Y. & Kim, S. How much should provinces reduce greenhouse gas emissions for the national target achievement? lessons from a scientific approach using gcam-korea. In *Conference Book*, 145 (2022).

26. Bistline, J. *et al.* Actions for reducing us emissions at least 50% by 2030. *Science* **376**, 922–924, DOI: 10.1126/science.abo5793 (2022).

27. Zhao, A. *et al.* High-ambition climate action in all sectors can achieve a 65% greenhouse gas emissions reduction in the united states by 2035. *npj Clim. Action* **3**, 63, DOI: 10.1038/s44168-024-00145-x (2024).

28. Iyer, G. *et al.* A multi-model study to inform the united states' 2035 ndc. *Nat. Commun.* **16**, 643, DOI: 10.1038/s41467-025-55858-2 (2025).

29. Speizer, S. *et al.* Integrated assessment modeling of a zero-emissions global transportation sector. *Nat. Commun.* **15**, 4439, DOI: 10.1038/s41467-024-48424-9 (2024).

30. Mercure, J.-F. *et al.* Environmental impact assessment for climate change policy with the simulation-based integrated assessment model e3me-ftt-genie. *Energy Strateg. Rev.* **20**, 195–208, DOI: 10.1016/j.esr.2018.03.003 (2018).

31. Sognnaes, I. *et al.* A multi-model analysis of long-term emissions and warming implications of current mitigation efforts. *Nat. Clim. Chang.* **11**, 1055–1062, DOI: 10.1038/s41558-021-01206-3 (2021).

32. van Vuuren, D. P. *et al.* Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Glob. Environ. Chang.* **42**, 237–250, DOI: 10.1016/j.gloenvcha.2016.05.008 (2017).

33. Ministry of Trade, Industry and Energy (MOTIE). The 11th Basic Plan for Long-Term Electricity Supply and Demand (2025).

34. Ministry of Trade, Industry and Energy (MOTIE). The 10th Basic Plan for Long-Term Electricity Supply and Demand (2023).

35. Korea Electric Power Corporation (KEPCO). Statistics of electric power in korea (no. 94, 2024). Tech. Rep., Korea Electric Power Corporation, Naju, Republic of Korea (2025).

36. Korea Electric Power Corporation (KEPCO). Monthly statistics of electric power in korea, no. 566. Tech. Rep., Korea Electric Power Corporation (2026).

37. Ministry of Trade, Industry and Energy. Launch of carbon neutral technology development for four major industries (krw 935.2 billion through 2030) (2023).

38. Ministry of Trade, Industry and Energy. First basic plan for hydrogen economy implementation (2021).

39. Ministry of Agriculture, Food and Rural Affairs. 2050 carbon neutrality strategy for the agriculture and food sector (2021).

40. Ministry of Climate, Energy and Environment. New Nuclear Power Plant Construction under the 11th Basic Plan to Proceed as Scheduled. Government of the Republic of Korea (2026).

41. Government of the Republic of Korea. 2050 carbon neutrality scenario (2021).

42. Kim, J.-Y., Kim, J.-H. & Jung, K.-C. Outlook for korea's potential growth rate and policy implications. Tech. Rep., Korea Development Institute (KDI), Sejong, South Korea (2024).

43. Ministry of Data and Statistics. Population projections for korea: 2022–2072. Tech. Rep., Ministry of Data and Statistics, Daejeon, South Korea (2023).

44. Choi, H. *Evaluating Korea's Mitigation Targets under Scenarios of Manufacturing Competitiveness Erosion and Trade Regulation*. Ph.d. dissertation, Seoul National University, Seoul, Republic of Korea (2026).

45. Casey, G., Fried, S. & Peterman, W. B. Climate policy and the long-run interest rate: Insights from a simple growth model. Working Paper, Federal Reserve Bank of San Francisco (2024). DOI: 10.24148/wp2024-37.

46. Vogel, J. & Hickel, J. Is green growth happening? an empirical analysis of achieved versus paris-compliant co2–gdp decoupling in high-income countries. *The Lancet Planet. Heal.* **7**, e759–e769, DOI: 10.1016/S2542-5196(23)00174-2 (2023).

47. Brockway, P. E., Sorrell, S., Semieniuk, G., Heun, M. K. & Court, V. Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications. *Renew. Sustain. Energy Rev.* **141**, 110781, DOI: 10.1016/j.rser.2021.110781 (2021).

48. Wiedenhofer, D. *et al.* A systematic review of the evidence on decoupling of gdp, resource use and ghg emissions, part i: bibliometric and conceptual mapping. *Environ. Res. Lett.* **15**, 063002, DOI: 10.1088/1748-9326/ab8429 (2020).

49. Kang, K., Huh, C., Kang, S., Baek, J. & Noh, H. Estimation of co2 pipeline transport cost in south korea based on the scenarios. *Energy Procedia* **63**, 2475–2480, DOI: 10.1016/j.egypro.2014.11.270 (2014).

50. Jung, J., Huh, C., Kang, S., Seo, Y. & Chang, D. Co2 transport strategy and its cost estimation for the offshore ccs in korea. *Appl. Energy* **111**, 1054–1060, DOI: 10.1016/j.apenergy.2013.06.055 (2013).

51. Kim, J. & Choi, J. A preliminary estimation for ccs storage cost of korea. *Geosystem Eng.* **19**, 11–18, DOI: 10.1080/12269328.2015.1078261 (2016).

52. International Energy Agency. Renewables 2023: Netherlands country profile. Tech. Rep., IEA (2023).

53. Statistics Netherlands (CBS). Solar energy in the netherlands: 2023 update (2023).

54. Choi, H., McJeon, H. & Park, S. An integrated assessment of the 11th basic plan for long-term electricity supply and demand and alternative power generation mix scenarios. *J. Clim. Chang. Res.* **16**, 469–485, DOI: 10.15531/KSCCR.2025.16.3.459 (2025).

55. Ministry of Trade, Industry and Energy. Competitive bidding roadmap of offshore wind (2024).

56. Choi, Y., Park, S., Choi, J., Lee, G. & Lee, M. Evaluating offshore wind power potential in the context of climate change and technological advancement: Insights from republic of korea. *Renew. Sustain. Energy Rev.* **183**, 113497, DOI: 10.1016/j.rser.2023.113497 (2023).

57. Ministry of Trade, Industry and Energy. Act on the Promotion of Offshore Wind Power Deployment and Industry Development. National Law Information Center, Republic of Korea (2025).

58. Mañosa, J., Calderón, A., Salgado-Pizarro, R., Maldonado-Alameda, A. & Chimenos, J. M. Research evolution of limestone calcined clay cement (lc3), a promising low-carbon binder–a comprehensive overview. *Heliyon* **10** (2024).

59. Maraghechi, H., Avet, F., Wong, H., Kamyab, H. & Scrivener, K. Performance of limestone calcined clay cement (lc3) with various kaolinite contents with respect to chloride transport. *Mater. Struct.* **51**, 125, DOI: 10.1617/s11527-018-1255-3 (2018).

60. Rocky Mountain Institute. Unleashing the potential of limestone calcined clay cement (2023).

61. Schleussner, C. *et al.* Overconfidence in climate overshoot. *Nature* **634**, 366–373, DOI: 10.1038/s41586-024-08020-9 (2024).

62. Baur, S., Nauels, A., Klönne, U. & Schleussner, C.-F. The science of temperature overshoots: impacts, uncertainties and implications for near-term emissions reductions (2021).

63. IPCC. Glossary, DOI: 10.1017/9781009157940 (2018).

64. IPCC. *Climate Change 2021: The Physical Science Basis* (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2021).

65. Government of the Republic of Korea. The republic of korea's update of its first nationally determined contribution (2020).

66. Korea Energy Agency. Zero energy building certification overview. https://min24.energy.or.kr/nzeb/BC/BC03/BC03_05_001.do (2025).

67. Ministry of Environment. Direct landfilling of municipal solid waste in the capital area to be banned from 2026 (2021).

68. Ministry of Environment, Republic of Korea. 2021–2030 passenger vehicle greenhouse gas and fuel economy standards administrative notice (2020).

69. Korea Steel Association. Iron and steel carbon neutrality: Current status and roadmap toward net zero (2024).

70. Korea Cement Association. Carbon neutrality in the korean cement industry: Current status and outlook. Tech. Rep., Korea Cement Association, Seoul, Republic of Korea (2024).

71. Lee, S.-J. Carbon neutrality roadmap for korea's petrochemical industry. Presentation material (2024).

72. Kim, S. & Ko, E., Rachel. A net zero roadmap for south korea's petrochemical industry. Tech. Rep., NEXT, Seoul, Republic of Korea (2024).

73. Erbach, G. & Jensen, L. Fit for 55 package. Tech. Rep., European Parliamentary Research Service (EPRS), European Parliament (2022).

74. Heussaff, C. *et al.* Europe's 2040 climate target: Four critical risks and how to manage them. Tech. Rep. Policy Brief 23/2024, Bruegel (2024).

75. Edmonds, J. & Reilly, J. A long-term global energy-economic model of carbon dioxide release from fossil fuel use. *Energy Econ.* **5**, 74–88, DOI: 10.1016/0140-9883(83)90014-2 (1983).

76. Clarke, J. F. & Edmonds, J. A. Modelling energy technologies in a competitive market. *Energy Econ.* **15**, 123–129, DOI: 10.1016/0140-9883(93)90001-8 (1993).

77. Brenkert, A. L., Smith, S. J., Kim, S. H. & Pitcher, H. M. Model documentation for the minicam. Tech. Rep. PNNL-14337, Pacific Northwest National Laboratory (PNNL), Richland, WA, United States (2003).

78. Hejazi, M. *et al.* Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technol. Forecast. Soc. Chang.* **81**, 205–226, DOI: 10.1016/j.techfore.2013.05.006 (2014).

79. Calvin, K. *et al.* GCAM v5.1: Representing the linkages between energy, water, land, climate, and economic systems. *Geosci. Model. Dev.* **12**, 677–698, DOI: 10.5194/gmd-12-677-2019 (2019).

80. Min, I. Y. The rise and fall of nuclear phase-out in south korea: German model and the dynamics of policy learning. *The Pac. Rev.* **39**, 208–230, DOI: 10.1080/09512748.2025.2554364 (2026).

81. Ministry of Trade, Industry and Energy & Korea Energy Agency. 2020 new and renewable energy white paper. Korean official energy white paper on new and renewable energy policies and statistics (2020).

82. Min, K., An, H. & Byun, S. Economic feasibility of using forest biomass as a local energy source. *J. Korean Soc. For. Sci.* **111**, 177–185, DOI: 10.14578/jkfs.2022.111.1.177 (2022).

83. Ministry of Land, Infrastructure and Transport. Motor vehicle registration status report (2020).

84. Statistics Korea. e-nara indicators – *Indicator Code: 1152*. https://www.index.go.kr/unity/potal/main/EachDtlPageDetail.do?idx_cd=1152 (2025).

85. Ministry of Trade, Industry and Energy. Steel industry trends (2024).

86. International Energy Agency. The future of petrochemicals: Towards more sustainable plastics and fertilisers. Tech. Rep., International Energy Agency, Paris (2018).

87. Mallapragada, D. S. *et al.* Decarbonization of the chemical industry through electrification: Barriers and opportunities. *Joule* **7**, 23–41, DOI: 10.1016/j.joule.2022.11.004 (2023).

88. Bataille, C. *et al.* A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the paris agreement. *J. Clean. Prod.* **187**, 960–973, DOI: 10.1016/j.jclepro.2018.03.107 (2018).

89. Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K. (eds.) *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Institute for Global Environmental Strategies (IGES), Hayama, Japan, 2006).

90. Park, H.-C. & Patel, M. K. Naphtha storage fraction and green house gas emissions in the Korean petrochemical industry. *Energy & Environ.* **29**, DOI: 10.1177/0958305X18762446 (2018).

91. Ministry of Trade, Industry and Energy (MOTIE) & Ministry of Oceans and Fisheries (MOF). Joint research team estimates domestic co2 capture and storage (ccs) capacity at 7.3 billion tons, with potential for up to 11.6 billion tons through further development (2021).

92. U.S. Environmental Protection Agency. Waste reduction model. https://www.epa.gov/warm (2020).

93. Park, W. Y. *et al.* A clean energy korea by 2035: Transitioning to 80% carbon-free electricity generation. *Cell Reports Sustain.* **2** (2025).

94. Kim, S.-J. Korean economy: Growth crisis and structural reform. *Econ. Rev.* **55**, 3–27 (2016).

95. Electric Power Journal. Target of 28.9% renewable energy generation share by 2036, including wind power. https://www.epj.co.kr/news/articleView.html?idxno=31848 (2023).

96. Korea Energy Agency. Renewable portfolio standard (RPS) system. https://www.knrec.or.kr/biz/introduce/new_rps/intro_rps.do?gubun=A (2025).

97. G7. G7 climate, energy and environment ministers' communiqué (2024).

98. United Nations Framework Convention on Climate Change (UNFCCC). Cop28 agreement signals "beginning of the end" of the fossil fuel era. https://unfccc.int/news/cop28-agreement-signals-beginning-of-the-end-of-the-fossil-fuel-era (2023).

99. Korea Electric Power Corporation. Long-term transmission and substation facilities plan under the 10th basic plan for electricity supply and demand (2022–2036). Tech. Rep., Korea Electric Power Corporation (KEPCO), Naju, Republic of Korea (2023).

100. Korea Electric Power Corporation. Long-term transmission and substation facilities plan under the 11th basic plan for electricity supply and demand (2024–2038). Tech. Rep., Korea Electric Power Corporation (KEPCO), Naju, Republic of Korea (2025).

101. Ministry of Trade, Industry and Energy (MOTIE). Building the basis for annual deployment of 4 gw of offshore wind by 2030: Announcement of the infrastructure expansion and deployment plan. Korean Government Press Release (2025).

102. Department for Energy Security and Net Zero. Clean power 2030 action plan. Tech. Rep., HM Government, London, United Kingdom (2024).

103. Greenhouse Gas Inventory and Research Center of Korea (GIR). 2023 korea emissions trading scheme report. Tech. Rep., Greenhouse Gas Inventory and Research Center of Korea, Sejong, Republic of Korea (2024).

104. Yu, J. & Lee, S. Revisiting the role of auctioned allowances: Understanding their neutrality in ets market pricing. *Environ. Resour. Econ. Rev.* **34**, 513–540, DOI: 10.15266/KEREA.2025.34.4.513 (2025).

105. Kang, H. & Kwon, Y. Extending the lifespan of gwangyang no.2 blast furnace: A backward step for carbon neutrality. Tech. Rep., Climate Solutions, Seoul, Republic of Korea (2024).

106. Cho, Y.-h., Choi, H.-j. & Han, Y.-b. Posco to boost iron scrap use by over 30% within six years. Pulse by Maeil Business News Korea (2024).

107. Shao, J., Guo, S. & Wang, H. A review of the performance, sustainable applications, and research challenges of limestone-calcined clay-cement (lc3) systems. *Coatings* **15**, 611, DOI: 10.3390/coatings15050611 (2025).

108. Wieland, R., Pittroff, M., Boudaden, J., Altmannshofer, S. & Kutter, C. Environmental-friendly fluorine mixture for cvd cleaning processes to replace c2f6, cf4 and nf3. *ECS Transactions* **72**, 23–34, DOI: 10.1149/07219.0023ecst (2016).

109. Boudaden, J., Altmannshofer, S., Wieland, R., Pittroff, M. & Eisele, I. An approach to reduce greenhouse gases in the semiconductor industry using f2 dissociated in plasma for cvd chamber cleaning. *Appl. Sci.* **8**, 846, DOI: 10.3390/app8060846 (2018).

110. Tsai, W.-T. & Tsai, C.-H. A survey on fluorinated greenhouse gases in taiwan: Emission trends, regulatory strategies, and abatement technologies. *Environments* **10**, 113, DOI: 10.3390/environments10070113 (2023).

111. Kintzel, W., Schmid, M., Rentschler, A., Eisenlohr, J. & Bucher, V. Novel method for plasma etching of printed circuit boards as alternative for fluorocarbon gases. *Int. J. Plasma Environ. Sci. Technol.* **17**, DOI: 10.34343/ijpest.2023.17.e02002 (2023).

112. Government of the Republic of Korea. Act on the capture, transportation, storage, and utilization of carbon dioxide (2023).

113. Industry–Public Research Consortium. Ccus industrial and technological innovation initiative: Challenges and opportunities for commercializing carbon-neutral technologies. Tech. Rep., Industry–Public Research Consortium, Republic of Korea (2023).

114. Korea Transport Database. Passenger trip survey and freight travel demand survey (2022).

115. Korea Automobile Dismantlement & Recycling Association. Average vehicle lifespan statistics (2022).

116. Transportation Monitoring & Analysis Center. Traffic volume survey database (2023).

117. Kim, S. Analysis of electric vehicle charging behavior and factors influencing utilization. *J. Korean Inst. Intell. Transp. Syst.* **23**, 62–72 (2024).

118. Shin, S.-J. Projected road transport hydrogen consumption to reach 15,163 tons in 2025, up 65% yoy (2025).

119. Korea Gas Safety Corporation. Hydrogen refueling station status in korea (as of october 2025) (2025).

120. Ministry of Climate, Energy and Environment. Emission-free vehicle subsidy payment status. https://ev.or.kr/nportal/buySupprt/initSubsidyPaymentCheckAction.do (2024).

121. Ministry of Climate, Energy and Environment. Grade 4 diesel vehicle early retirement substantially expanded this year. https://mcee.go.kr/home/web/board/read.do?boardId=1657050&boardMasterId=1&menuId=10525 (2024).

122. European Parliament. Eu ban on the sale of new petrol and diesel cars from 2035 explained. https://www.europarl.europa.eu/topics/en/article/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained (2022).

123. Burch, I. Survey of global activity to phase out internal combustion engine vehicles. Tech. Rep., Center for Climate and Energy Solutions (C2ES) (2020).

124. International Energy Agency (IEA), Clean Energy Ministerial & Electric Vehicles Initiative (EVI). Global ev outlook 2020: Entering the decade of electric drive? Tech. Rep., International Energy Agency, Paris (2020).

125. InfluenceMap. Zero emissions vehicle (zev) policy. InfluenceMap briefing (2025).

126. Ministry of Climate, Energy and Environment & Konkuk University Industry–Academic Cooperation Foundation. A study on improving the greenhouse gas management framework for small passenger and freight vehicles (ii). Tech. Rep., Ministry of Climate, Energy and Environment (MOCE), Sejong, Republic of Korea (2023).

127. Ministry of Oceans and Fisheries. Implementation guidelines for the green-certified ship deployment support program. Ministry of Oceans and Fisheries, Republic of Korea (2025).

128. Korea Energy Agency. Renewable energy and energy efficiency support programs for buildings. https://www.knrec.or.kr/biz/introduce/new_engy/intro_build.do?gubun=A (2025).

129. Ministry of Environment, Republic of Korea. Details on zero energy building (zeb) certification requirements in korea. Official ZEB information portal (2024).

130. Ko, E. Green remodeling in korea: Current status and strategies for expansion. Tech. Rep., National Assembly Research Service, Seoul, Republic of Korea (2025).

131. European Union. Energy performance of buildings directive (recast) (eu/2024/1275) (2024).

132. European Heat Pump Association. Who's banning fossil fuel boilers? https://ehpa.org/news-and-resources/news/whos-banning-fossil-fuel-boilers/ (2025).

133. New York State Fire Prevention and Building Code Council. All-electric buildings act and fossil fuel equipment ban in new buildings. https://www.climatepolicydashboard.org/policies/buildings-efficiency/electric-buildings (2025).

134. Korea Energy Economics Institute. Clean hydrogen certification system: Certification standards. https://www.keei.re.kr/menu.es?mid=a10211010300 (2024).

135. The Guardian. Un plastic pollution talks must result in ambitious treaty, leading expert says (2025).

136. Kim, G.-Y. *et al.* Effects of water management methods on ch_4 and n_2o emission from rice paddy field. *Korean J. Soil Sci. Fertilizer* **46**, 599–605, DOI: 10.7745/KJSSF.2013.46.6.599 (2013).

137. Ministry of Agriculture, Food and Rural Affairs (MAFRA). The 1st framework plan for smart agriculture promotion (2025–2029). Sejong, Republic of Korea (2025).

138. Ministry of Foreign Affairs of the Republic of Korea. Korea joins global methane pledge to reduce methane emissions by 30% by 2030. Joint Press Release (2021).

139. International Institute of Refrigeration. Republic of korea ratifies the kigali amendment (2023).

140. Korea Energy Economics Institute. World energy market insight, no. 25-8: Global data center electricity demand and supply outlook. Tech. Rep., Korea Energy Economics Institute (KEEI), Ulsan, Republic of Korea (2025).

141. International Energy Agency. Energy and ai. Tech. Rep., International Energy Agency, Paris, France (2025).

142. Ministry of Climate, Energy and Environment. The government aims to phase out coal power by 2040 and will ensure stable electricity supply in accordance with the transition plan. Press release (2025).