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High-ambition climate action in all sectors can achieve a 60% greenhouse gas emissions reduction in Korea by 2035

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ABSTRACT

Under the Paris Agreement's ratchet mechanism, countries are expected to enhance their nationally determined contributions (NDCs), including new targets for 2035. For Korea, one of the world's largest CO_2 emitters, the challenge is to strengthen its existing policy framework to not only ensure the achievement of its 2030 NDC but also support a more ambitious 2035 pathway. This study employs an integrated assessment model to simulate Korea's greenhouse gas emissions pathway under existing policies, including the Carbon Neutrality & Green Growth Basic Plan, the Basic Electricity Plan, and the Core Technology Development Program for Carbon Neutrality. In addition, we develop an enhanced policy scenario reflecting highly ambitious yet feasible measures across all sectors. We find that current policies can reduce emissions by 34% (with a range of 30% to 41%) below 2018 levels by 2035—insufficient to achieve the 2030 NDC. In contrast, the enhanced scenario enables a 60% (with a range of 54% to 64%) reduction without reliance on international offsets. Key drivers include an accelerated coal phase-out, rapid deployment of offshore wind power, restrictions on lifetime extensions of blast furnace capacity, and strengthened zero-emission building standards. These findings provide policy-relevant insights to inform the formulation of a more ambitious and achievable 2035 NDC for Korea.

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Introduction

To achieve the long-term goals of the Paris Agreement—limiting global temperature rise to well below 2°C and pursuing efforts to limit it to 1.5°C—countries are expected to progressively strengthen their near-term climate targets by submitting updated nationally determined contributions (NDCs) every five years, each outlining greenhouse gas (GHG) emissions reduction plans[1]. The second round of NDCs, submitted following the initial 2015 pledges, reflected only a modest increase in ambition[2]. However, limiting warming to 1.5°C will require substantially more aggressive mitigation efforts beyond currently pledged 2030 targets[3–7]. In 2025, countries are expected to submit a third round of NDCs that extend emissions reduction targets to 2035. These forthcoming pledges will be critical in determining whether global emissions pathways can align with the Paris Agreement's long-term temperature objectives. Their formulation is expected to be informed by the outcomes of the first Global Stocktake, concluded at COP28 in 2023, which identified persistent gaps in mitigation progress and called for accelerated action—such as phasing out fossil fuels, scaling up renewable energy, and improving energy efficiency—as well as broadening the scope of NDCs to cover all greenhouse gases[8].

The Republic of Korea (hereafter Korea), one of the world's largest CO_2 emitters, began preparing its 2030 NDC as early as 2015[9]. However, a detailed sectoral policy framework to support implementation was not introduced until 2023, with the release of the First Carbon Neutrality & Green Growth Basic Plan[10]. While the government has committed to reducing emissions by 40% below 2018 levels by 2030 and has legally enshrined a 2050 net-zero target[11], it remains unclear whether the current policy framework is sufficient to deliver on these goals. To date, there has been limited analytical evaluation of the plan's adequacy, and many observers remain skeptical about the feasibility of achieving the targets under existing measures[12–15]. Against this backdrop, Korea faces a critical challenge: to establish a policy framework that not only ensures the delivery of its 2030 NDC but also supports the development of an enhanced and credible 2035 target.

Between 1990 and 2018, national GHG emissions rose by an average of 16.9 $MtCO_2e$ per year, whereas reaching net-zero by 2050 would require annual reductions of 24.5 $MtCO_2e$ over the coming decades—a 3.1% sustained annual decline from 2018 levels, equivalent to a 37.5% cut by 2030 (see Supplementary Figure S5). The official 40% reduction target by 2030 therefore represents a level of ambition that exceeds the linear trajectory consistent with achieving net-zero emissions by 2050. A further challenge lies in the fragmented nature of Korea's sectoral mitigation policies. Although sectoral targets exist—for example in the electricity and industry sectors—many have been formulated in isolation and remain insufficiently integrated into a coherent, economy-wide mitigation strategy. As a result, the aggregate impact of current measures remains uncertain. Compounding these concerns, Korea's 2030 NDC includes 37.5 $MtCO_2e$ in international offsets—equivalent to 12.9% of the total reduction—despite the fact that international carbon market mechanisms remain in early development and face significant regulatory and implementation uncertainties[16] (Supplementary Table S11). Even the government acknowledges that additional domestic mitigation measures will be needed to ensure stable achievement of the 2030 target.

In this study, we assess Korea's GHG emissions trajectory through 2035 using a global integrated assessment model with detailed representation of the energy and industry sectors. We construct a *Current Policies* scenario that reflects existing and legislated policy measures, centered on the 1st Carbon Neutrality & Green Growth Basic Plan. This scenario captures policies that are currently in force, under implementation, or officially planned. In contrast, the *Enhanced Ambition* scenario represents an accelerated policy pathway, incorporating strengthened regulatory mandates, expanded or extended subsidy programs, and faster deployment of emerging mitigation technologies across all sectors. To ensure feasibility, this scenario draws on a range of sources, including policy options currently under consideration by Korean government agencies, as well as recommendations from recent domestic and international academic studies and policy reports.

This study has two main objectives: (1) to evaluate whether Korea's existing policies are sufficient to meet the 2030 NDC, and (2) to assess the emissions reduction potential of an enhanced policy regime through 2035. By comparing outcomes across scenarios, we identify key sectors and policy instruments necessary to close the ambition gap and support the design of Korea's forthcoming 2035 NDC.

While existing literature on Korea has primarily focused on long-term (2050) mitigation outcomes[13,15,17,18] or single-sector analyses[19]—particularly for the electricity sector[14,20,21]—few studies have evaluated the feasibility of near-term NDCs within a comprehensive, sectorally detailed policy framework. Several recent U.S. studies have assessed emissions trajectories under multiple policy scenarios using integrated assessment models[22–24]. Beyond the U.S. context, comparable IAM analyses have been conducted at the global scale, including for the transport sector[25], for economy-wide decarbonization pathways toward the 2°C target[26], for evaluating the long-term implications of current mitigation efforts using multi-model ensembles[27], and for exploring energy, land-use, and emissions trajectories under a green growth paradigm[28]. These global IAM assessments apply policy assumptions at the global or regional scale—such as carbon prices, technology subsidies, or efficiency standards for broad sectors—rather than incorporating the detailed, sector-specific policy frameworks of individual countries.

To address this gap, our analysis integrates Korea's legislated and planned sectoral policies—covering electricity, industry, buildings, transport, agriculture, and waste—into an IAM framework, enabling a realistic assessment of near- and mid-term NDC feasibility. By quantifying GHG mitigation outcomes under both current and enhanced policy scenarios, we provide an evidence-based assessment of Korea's progress toward its 2030 NDC and its readiness to adopt a credible 2035 target, thereby informing both national and international climate strategy.

Methods

Overview of Modeling Approach

We apply a sector-specific, bottom-up policy quantification framework that integrates detailed analysis of individual policy instruments into an economy-wide assessment using GCAM-ROK—a nationally customized version of the Global Change Analysis Model (GCAM). This framework compiles climate policies, regulatory measures, and investment programs from official planning documents, legislative texts, and administrative guidelines, and quantifies their expected impacts—such as changes in costs, energy use, technology deployment, electricity generation, or emissions intensity—based on government data, historical trends, and supplemental bottom-up modeling. These quantified impacts are then translated into calibrated policy levers within GCAM-ROK, enabling cross-sectoral simulations that maintain sectoral specificity and an empirically grounded representation of the national mitigation landscape.

GCAM is an open-source, multisector model developed by the Joint Global Change Research Institute of Pacific Northwest National Laboratory[29–33]. It represents economic, energy, agriculture, land, water, and climate systems for 32 geopolitical regions, with detailed coverage of GHG and air pollutant emissions, global concentrations, radiative forcing, and temperature change. The model also captures land allocation, water use, and agricultural production across 396 land sub-regions and 235 water basins. Korea is modeled as an independent region, enabling national-scale climate policy assessments. Numerous studies have applied GCAM to Korean mitigation pathways[15,19,34,35]. This study uses GCAM v7.1[36], which is publicly available[1] and calibrated to historical statistics through 2015.

[1] http://jgcri.github.io/gcam-doc

For this study, GCAM-ROK was updated to calibrate the model to 2020 national statistics, reflect the latest renewable energy cost assumptions[37], and incorporate recent sectoral outcomes for energy and industry[38,39]. Model customization is described in Supplementary Note 2. Additionally, in line with 2023 UNFCCC reporting guidance, all GHG emissions are expressed in CO_2-equivalents using IPCC AR5 100-year GWP values[40].

Policy Scenario Construction

We construct two policy scenarios to evaluate Korea's greenhouse gas mitigation pathway through 2035: (1) a *Current Policies* scenario representing the policy landscape as of early 2025, and (2) an *Enhanced Ambition* scenario reflecting a high-mitigation pathway aligned with the 2050 carbon neutrality goal. The first scenario captures currently implemented and legislated measures, while the second builds on the same structure but strengthens key elements to close the ambition gap.

Both scenarios are developed from a detailed sector-by-sector mapping of climate policies compiled from national planning documents, legislative texts, administrative guidelines, and technical reports (see Supplementary Notes 5–9). To ensure consistency and credibility, all policies were screened according to five principles (illustrated with examples in Supplementary Note 3):

1. **Exclusion of non-implementable targets**—policies without enforceable mechanisms or legal authority were omitted.

2. **Temporal consistency**—policies were assumed to persist unless a sunset clause was specified.

3. **Quantitative impact estimation**—effects were derived from historical data, expert judgment, or peer-reviewed studies when not explicitly stated.

4. **Feasibility filtering**—enhanced measures were limited to those technically and administratively plausible given Korea's institutional capacity.

5. **Methodological alignment**—parameterizations were chosen to align with validated approaches from prior academic or government studies.

The *Current Policies* scenario incorporates major strategies such as the 1st Carbon Neutrality & Green Growth Basic Plan, the 11th Basic Plan for Long-Term Electricity Supply and Demand, the Core Technology Development Program for Carbon Neutrality, and sectoral legislative frameworks across power, industry, transport, buildings, and agriculture. Examples include the Renewable Portfolio Standard, the Korea Emissions Trading System, Zero-Energy Building mandates, zero-emission vehicle subsidies, and agricultural methane reduction programs. For instance, the ZEB mandate for new public buildings is modeled by reducing final energy demand intensity in new building stock, while the post-2025 landfill ban in the Seoul Metropolitan Area is represented by lowering landfill CH_4 emissions factors using the U.S. EPA's WARM model (see Table 1 for a complete list).

The *Enhanced Ambition* scenario retains the same policy architecture but intensifies key measures—such as accelerated coal phase-out, expanded offshore wind and solar deployment, broader ZEB coverage, stricter fuel economy standards, and higher carbon pricing—to align with a high-mitigation pathway. Enhancements build on current domestic policies as the baseline, incorporating additional measures informed by international climate agreements, foreign policy experiences, domestic policy proposals, and recent modeling studies. Parameter choices draw on government studies, research reports, and relevant academic literature to ensure consistency with established knowledge.

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 *Enhanced Ambition* scenario. These scenarios, described in detail in the Methods section, represent two alternative policy environments—one reflecting legislated and implemented policies as of early 2025, and the other representing a plausible expansion and reinforcement of those measures, which results in a mitigation pathway broadly consistent with Korea's 2050 net-zero target.

Each scenario includes a comprehensive set of sector-specific policies that influence emissions across power, industry, transportation, buildings, and land-use systems. The *Current Policies* scenario captures Korea's baseline mitigation framework, while the *Enhanced 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 ability to meet its 2030 target and to define a credible and enhanced 2035 NDC. A full description of modeled policy assumptions is provided in Supplementary Notes 5–9. For implementation-level details, including parameter settings and data sources, see the `policy-implementation` directory of the publicly available GCAM-ROK repository ([2]), which contains annotated Jupyter Notebook files documenting each sector's policy representation.

Under the *Current Policies* scenario, moderate mitigation is achieved primarily through existing regulatory instruments, including the Renewable Portfolio Standard (RPS), the Emissions Trading Scheme (ETS), and targeted subsidy programs for clean technologies. In the power sector, a gradual transition is modeled LNG co-firing, moderate renewable energy expansion, and partial coal retirement. Nuclear power output rises modestly, while solar photovoltaic (PV) and offshore wind deployments follow existing government targets. The industrial sector includes early investments in hydrogen-based direct reduced iron (HyREX) steelmaking, limited uptake of limestone calcined clay cement (LC^3), and partial replacement of perfluorocarbon (CF_4) and sulfur hexafluoride (SF_6) gases in semiconductor production. The national carbon price is held constant at its 2023 level of 8,870 KRW/tCO_2 (*Korean won per metric ton of carbon dioxide*), while other sectors reflect current mandates—for example, in zero-emission vehicle (ZEV) adoption, fuel economy improvement targets, and Zero-Energy Building (ZEB) requirements for public buildings. Agricultural practices retain current shares of Intermittent Drainage (ID) and Continuous Flooding with Water Saving (CF+WS) in rice cultivation, and methane (CH_4) and hydrofluorocarbon (HFC) controls remain limited in scope.

By contrast, the *Enhanced Ambition* scenario simulates an accelerated decarbonization pathway enabled by stronger regulatory signals, expanded investment programs, and more stringent performance standards. Key measures include a complete coal phase-out by 2035, annual additions of 4 GW in offshore wind capacity, and a tripling of installed solar PV by 2030. The ETS carbon price rises to 30,411 KRW/tCO_2 through the introduction of carbon contracts for difference (CCfDs), while complementary measures—such as tighter fuel economy standards for both passenger and freight vehicles, extended ZEV subsidies, a lowered ZEB threshold for private buildings, nationwide landfill bans, a methane tax, and an HFC tax aligned with the European Union Emissions Trading System (EU ETS)—deliver additional emissions reductions across sectors. Agriculture adopts larger shares of CF+WS practices, reduces nitrogen (N) fertilizer use, and deploys low-methane livestock feed, while direct air capture (DAC) capacity is doubled relative to the level outlined in Option B of Korea's 2050 Carbon Neutrality Scenario[41].

[2] https://github.com/choiHenry/gcam-core/tree/cht/proj/korea-2035

Table 1. Sector-specific policy assumptions for the *Current Policies* and *Enhanced Ambition* scenarios modeled using GCAM.

Sector	*Current Policies* Scenario	*Enhanced Ambition* Scenario
Electricity	• Based on the 11th Basic Plan for Electricity Supply and Demand (2024–2038). • Coal generation declines from 184.9 TWh (2023) to 88.9 TWh (2035); ammonia co-firing introduced. • LNG fills the gap, peaking at 161.0 TWh in 2030 before declining. • Nuclear expands to 26 units (236.0 TWh) by 2035. • Renewables: Solar grows from 21.2 GW (2022) to 54.8 GW (2030); offshore wind from 0.1 GW to 25.1 GW. • RPS maintained at current trajectory.	• Complete coal phase-out by 2035, including co-firing; ammonia co-firing replaced by CCS. • Offshore wind capacity expands by 4 GW/year to 2035. • Solar PV capacity triples by 2030 vs. 2022. • RPS target raised to >35% by 2035, supporting higher renewable penetration.

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Sector	*Current Policies* Scenario	*Enhanced Ambition* Scenario
Industry	• Hydrogen-based direct reduced iron (HyREX) commercialized after 2035. • Blast furnace (BF) lifetime extensions prohibited after 2040; scrap use remains constant. • ETS carbon price fixed at 8,870 KRW/tCO_2 (2023 level). • Limestone calcined clay cement (LC3) introduced post-2030. • Perfluorocarbon (CF_4) and SF_6 phased out after 2030 in semiconductors.	• BF extensions banned from 2025, with full phase-out by 2035; scrap use rises +30% every 5 years. • ETS price rises to 30,411 KRW/tCO_2 by 2035 through carbon contracts for difference (CCfDs). • Biomass feedstock use in petrochemicals; 7.6% substitution from recycled plastics. • HFC-23 and C_2F_6 eliminated post-2030.
Buildings	• ZEB Grade 5: public $\geq$1,000 m^2 from 2020; private $\geq$500 m^2 from 2023. • Annual efficiency gains: electricity/heat +1.96%, gas +0.50% to 2030. • Financing subsidies maintained at 35%. • Energy Efficiency Resource Standard (EERS) unchanged.	• ZEB Grade 4 for all new private buildings $\geq$500 m^2 from 2030. • Efficiency improvement rate doubles post-2030; zero-emission appliance mandate from 2040. • Financing subsidies increased to 55%; EERS strengthened to 2% by 2035.

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Sector	*Current Policies* Scenario	*Enhanced Ambition* Scenario
Transportation	• ZEV purchase subsidies (avg. 5.2 M KRW/LDV) until 2025; infrastructure subsidies (1.255 M KRW/ZEV) through 2035. • Diesel ICEV retirement subsidies from 2024, raising retirement rate to 14.1%. • Passenger vehicle fuel economy improves +30% by 2030.	• ZEV subsidies extended to 2035; infrastructure subsidies expanded. • Fuel economy improves +45% for passenger and +30% for freight vehicles by 2035. • Complete ICEV sales ban in 2035.
Agriculture	• Rice paddies: Intermittent Drainage (61.1%) and CF+WS (10%) maintained.	• CF+WS share rises by +20% by 2035. • Nitrogen fertilizer use reduced to 115 kg/ha by 2030 (–43.9% from 2020). • Biomethane production from manure; low-methane feed cuts enteric CH_4 by 13.2%.

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Sector	*Current Policies* Scenario	*Enhanced Ambition* Scenario
Other sectors	• Clean hydrogen share: 50% of total by 2030, 100% by 2050 (incl. blue hydrogen). • Landfill ban for Seoul metro from 2025; Kigali HFC phase-down implemented.	• Only green and pink hydrogen eligible for clean hydrogen credit. • Nationwide landfill ban; UN Plastics Treaty cuts plastic waste 40% by 2040. • Methane and HFC taxes aligned with EU ETS. • DAC capacity: 2.95 $MtCO_2$ (2030) to 5.2 $MtCO_2$ (2035).

Under the *Current Policies* scenario, total GHG emissions are projected to decrease by 26.2% in 2030 and 33.7% in 2035 relative to 2018 levels (Figure 1). This represents an average annual reduction of approximately 9.4 $MtCO_2e$/year from 2020 to 2030, and 11.8 $MtCO_2e$/year between 2030 and 2035. Despite steady reductions, this scenario falls short of meeting Korea's 2030 nationally determined contribution (NDC), which calls for a 40% cut relative to 2018 levels. Notably, this gap persists even with the optimistic prospect of international offset mechanisms.

The *Enhanced Ambition* scenario achieves deeper decarbonization, with emissions declining by 40.6% in 2030 and 60.0% in 2035 relative to 2018. These correspond to annual reduction rates of 20.7 $MtCO_2e$/year (2020–2030) and 30.5 $MtCO_2e$/year (2030–2035). Importantly, the enhanced policy suite allows Korea to not only meet but exceed its 2030 NDC without relying on international offsets. Also, the *Enhanced Ambition* scenario guides the reduction rate aligned with the linear net-zero 2050 pathway.

To account for uncertainties in major economic and technical parameters, we explored alternative assumptions regarding GDP and population growth, technological advancements, fossil fuel price trajectories, and the available domestic carbon storage capacity. Under these sensitivity cases, emission reductions in the *Current Policies* scenario range between 30.1% and 40.9% by 2035, whereas the *Enhanced Ambition* scenario achieves between 54.0% and 64.2% reductions (see Supplementary Note 10 for details).

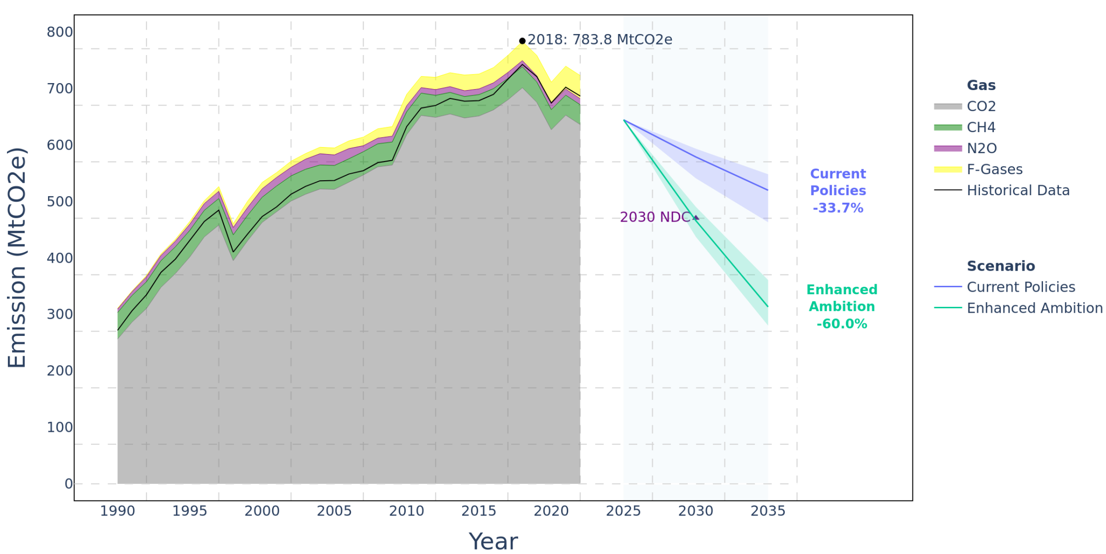


Figure 1. GHG emissions trajectories for Korea from 1990 to 2035. Emissions from 1990 to 2022 are based on historical data provided by the Greenhouse Gas Inventory and Research Center of Korea (GIR, 2025), disaggregated by gas. Emissions trajectories from 2025 onward are driven by scenario assumptions. 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.

Figure 2 shows that the power sector accounts for the largest share of total emissions reductions under both scenarios, contributing approximately 236.8 $MtCO_2e$—about 50.3% of total reductions—in the *Enhanced Ambition* scenario. Notably, the difference in mitigation outcomes between the two scenarios is nearly as large in the industrial sector (58.9 $MtCO_2e$) as in the power sector (58.9 $MtCO_2e$), underscoring the critical role of strengthened industrial policies in achieving higher ambition. Indeed, the industrial sector exhibits the greatest disparity in reduction rates: under the *Current Policies* scenario, emissions are reduced by only 11.8% by 2035 (6.3% by 2030), nearly matching the 11.4% sectoral target specified in Korea's 2030 NDC. By contrast, the *Enhanced Ambition* scenario delivers a 33.7% reduction in industrial emissions by 2035—an improvement of 22.3%p.

Other sectors—including transportation, buildings, fluorinated gases, waste, and land use—also contribute meaningful, though smaller, shares of total mitigation. In the *Enhanced Ambition* scenario, transportation, buildings, and F-gases collectively account for 15.7% of total emissions reductions, while direct air capture (DAC) and land-based carbon sinks provide supplementary contributions to closing the ambition gap.

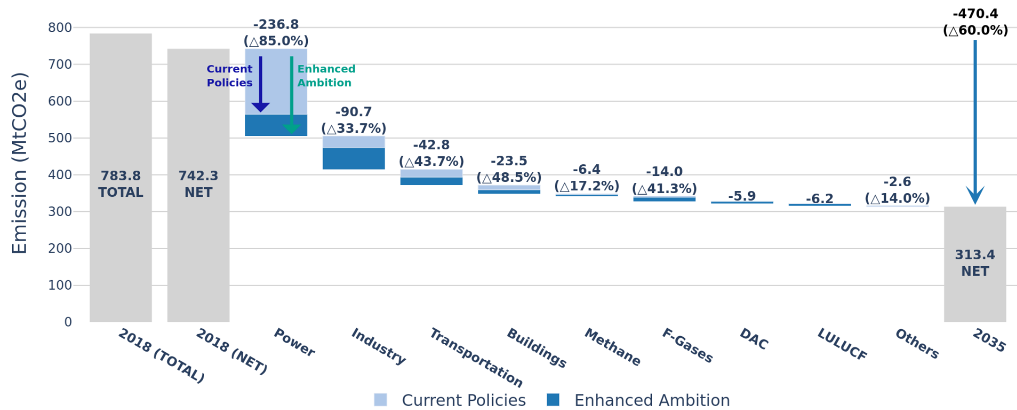


Figure 2. Sectoral contributions to GHG emissions reductions from 2018 to 2035 under the *Current Policies* and *Enhanced Ambition* scenarios. Bars represent absolute reductions relative to 2018 emissions, with percentage reductions shown in parentheses. The reductions are calculated against 2018 total emissions (783.8 $MtCO_2e$), not net values. Light blue bars indicate reductions under the *Current Policies* scenario, while dark blue bars represent additional reductions under the *Enhanced Ambition* scenario. "Others" includes residual emissions from sectors not covered under CH_4 or F-gases, such as agriculture, waste, and fugitive emissions.

Decarbonizing the Electricity Sector

The power sector delivers the largest contribution to Korea's total GHG emissions reductions by 2035 under both modeled scenarios. As illustrated in Figure 3, electricity generation from fossil fuels—particularly coal—declines substantially in both scenarios, while carbon-free technologies, including renewables and nuclear, occupy an increasing share of the generation mix. In the *Current Policies* scenario, total electricity generation closely follows the demand projections outlined in the 11^{th} Basic Plan for Long-Term Electricity Supply and Demand (BPESD), reaching 642.6 TWh in 2030 and 691.5 TWh in 2035. By contrast, the *Enhanced Ambition* scenario sees a marked increase in electricity generation, with the renewable energy (RE) share approximately 8%p higher than in the *Current Policies* scenario.

Under the *Current Policies* scenario, emissions from the power sector are reduced by approximately 127.4 $MtCO_2e$ by 2035, representing a 63.8% decline from 2018 levels. The share of carbon-free electricity rises from 35% in 2020 to 65% in 2035, with renewables contributing 33%. This transition is primarily driven by moderate growth in solar and wind capacity and continued reliance on nuclear power. However, a significant portion of electricity remains generated from insufficiently abated fossil fuels, particularly coal and natural gas with co-firing. A more detailed presentation of the *Current Policies* scenario and the 11th BPESD is provided in Supplementary Note 5.

Notably, emissions in 2030 decrease by only 47.9%, closely aligning with the sectoral target set in Korea's 2030 NDC. However, because the national target relies in part on international offsets—whose availability and credibility remain uncertain—this alignment does not necessarily indicate that the target is secure. Among all domestic sectors, the power sector is widely regarded as the most capable of achieving rapid emissions reductions and compensating for shortfalls in other sectors. Its lower-than-expected reductions therefore raises concerns about the feasibility of meeting Korea's 2030 climate target without additional domestic mitigation measures.

The *Enhanced Ambition* scenario accelerates the phase-out of unabated coal (including co-firing) and supports large-scale deployment of renewables. By 2035, the share of carbon-free electricity reaches 69%, with renewables accounting for 41%, a significant increase from 2020 levels. These gains are enabled by rapid deployment of wind and solar technologies, as well as CCS-equipped fossil generation. S

Although CCS remains relatively expensive in Korea[42–44], its deployment—both in gas- and coal-fired plants—expands significantly by 2035 under the *Enhanced Ambition* scenario. This outcome reflects the model's reliance on CCS to satisfy rising electricity demand that cannot be met by renewables and nuclear energy alone. However, the large-scale feasibility of CCS within the coming decade remains uncertain due to cost, infrastructure, and regulatory challenges. The modeled reliance on CCS—despite its unfavorable economics—suggests that even the *Enhanced Ambition* scenario may underinvest in renewable energy expansion. To reduce dependence on a technology with uncertain scalability, further acceleration of renewable deployment—particularly in distributed solar and wind—may be warranted, alongside stronger end-use efficiency measures, especially in the buildings sector.

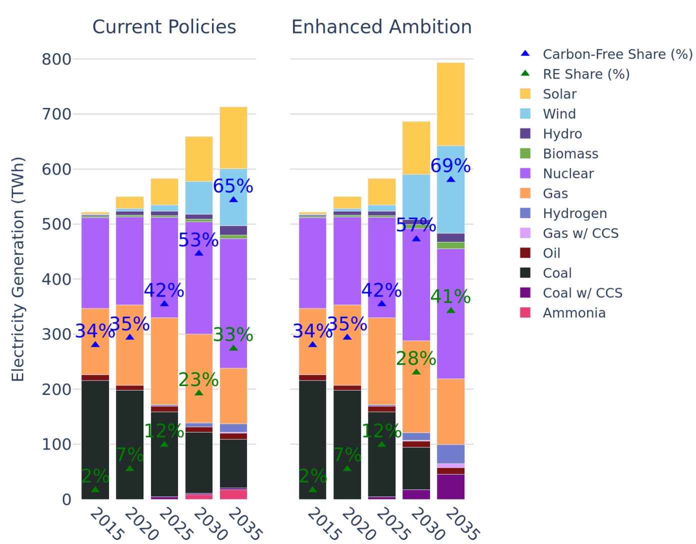
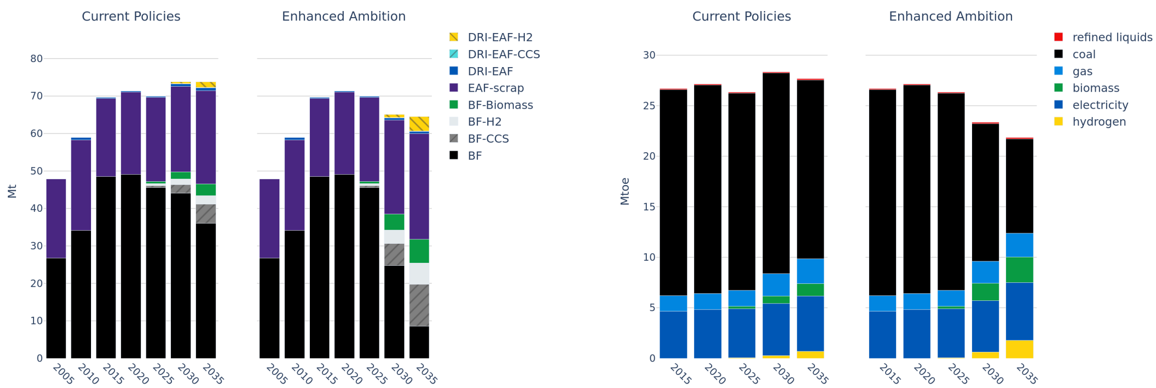


Figure 3. Electricity generation mix by technology in Korea under the *Current Policies* and *Enhanced Ambition* scenarios from 2015 to 2035. Carbon-free and renewable energy shares are shown with triangle markers. Total electricity generation is higher under the *Enhanced Ambition* scenario, driven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



A Production by technology.

B Final energy consumption.

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

Deployment of Carbon-Neutral Technologies and Industrial Transformation

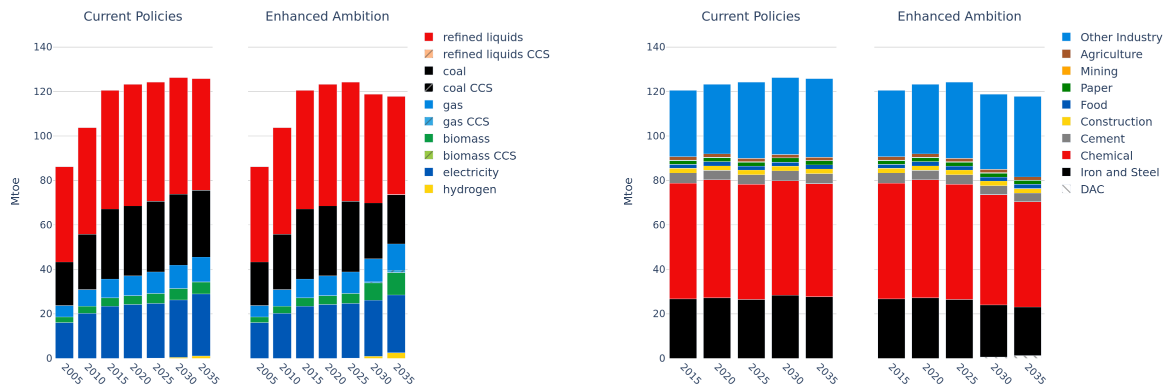
As illustrated in Figure 2, the industrial sector plays a pivotal role in achieving national decarbonization goals in the *Enhanced Ambition* scenario, given its substantial share of total greenhouse gas (GHG) emissions and the complexity of its emission sources. Compared to the *Current Policies* trajectory, Korea accelerates the deployment of carbon-neutral technologies across hard-to-abate sectors—such as 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 though hydrogen-based steelmaking using direct reduced iron with electric arc furnaces (DRI–EAF–H_2) is introduced by 2030. The uptake of mitigation options—such as BF with carbon capture and storage (BF–CCS), BF with biomass co-firing (BF–biomass), DRI–EAF, and DRI–EAF–H_2—remains limited. This reflects the continued expansion of BF capacity and the weak carbon price signal (Panel 4A).

In contrast, the *Enhanced Ambition* scenario exhibits a pronounced shift toward low-carbon technologies: hydrogen-based DRI–EAF (DRI–EAF–H_2), DRI–EAF with CCS (DRI–EAF–CCS), EAF using scrap, and retrofitted BF systems are deployed at increasing scale. 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. Under the *Current Policies* scenario, fossil fuel consumption declines only marginally, though coal use drops more noticeably due to increased deployment of BF retrofits. Hydrogen consumption increases slightly, reflecting the limited uptake of DRI–EAF–H_2 (Panel 4A). In the *Enhanced Ambition* scenario, coal use falls more sharply as BF capacity is replaced with lower-emission technologies, and hydrogen use increases substantially in line with the broader adoption of hydrogen-based steelmaking.

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 demand remains relatively flat, with coal, gas, and refined liquids maintaining dominant roles (Panel 5A). The chemical



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 *Enhanced Ambition* scenarios. (A) Consumption by energy type. (B) Consumption by industry sub-sector.

and iron and steel sectors together account for roughly two-thirds of total industrial energy use (Panel 5B).

In the *Enhanced 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 changes in the chemical and iron and steel sectors, as well as efficiency gains associated with increased recycling. In the chemical sector, energy demand declines due to the expansion of plastic recycling and the substitution of fossil-based feedstocks with bio-based 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 smaller sectors—such as construction, paper, and other industries—remain largely unchanged.

Overall, the *Enhanced Ambition* pathway demonstrates that targeted technology deployment, combined with systemic fuel 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.

Figure 6 shows that the iron and steel sector delivers the largest share of total industrial emissions reductions, accounting for a 67.2 $MtCO_2e$ decrease (Δ60.3%) by 2035 under the *Enhanced Ambition* scenario. This is followed by the chemical sector, which reduces emissions by 14.9 $MtCO_2e$ (Δ27.2%), and the cement sector with a reduction of 11.9 $MtCO_2e$ (Δ27.8%). However, other subsectors show an emissions increase of about 3.3$MtCO_2e$, driven by relative shifts in production volumes across industries as a result of the overall mitigation policies.

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 *Enhanced Ambition* scenario, national GHG emissions from transport decline by 43.7% by 2035 relative to 2018 levels, compared to a 21.6% reduction under the *Current Policies* scenario (Figure 2).

This enhanced outcome is enabled by a combination of strengthened financial incentives and stricter fuel economy standards. In the passenger segment, ZEVs reach 55.3% of new vehicle sales by 2035 under the

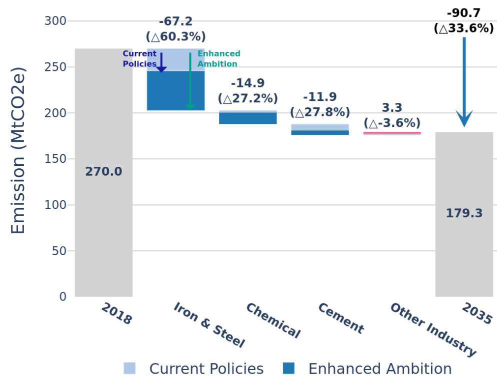


Figure 6. Sectoral contributions to GHG emissions reductions from 2018 to 2035 by industry sub-sector under the *Current Policies* and *Enhanced Ambition* scenarios. Bars represent absolute reductions relative to 2018 industrial emissions, with percentage reductions shown in parentheses. Light blue bars indicate reductions under the *Current Policies* scenario, while dark blue bars represent additional reductions achieved under the *Enhanced Ambition* scenario. "Other" includes residual emissions from smaller industrial sub-sectors not separately categorized.

Enhanced Ambition scenario, more than doubling the 25.9% share under *Current Policies*. Similarly, freight vehicle electrification accelerates substantially, with ZEVs capturing 60.7% of new freight truck sales in 2035—also more than twice the rate projected in the baseline scenario.

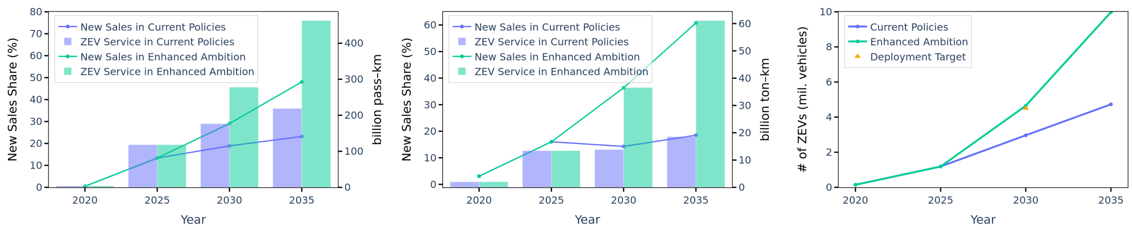
Nonetheless, given vehicle turnover rates, new sales translate gradually into stock-level changes. By 2035, only 40.6% of the national light-duty vehicle (LDV) fleet is electrified in the *Enhanced Ambition* scenario. In contrast, under the *Current Policies* scenario, stock electrification remains below 15.5%. Beyond electrification, demand-side interventions play a critical role. In the *Enhanced Ambition* scenario, policies such as increased public transit subsidies—specifically, an expansion of the K-Pass rebate from 20% to 30%—help reduce private vehicle dependence. Additionally, strengthened fuel economy standards require a 45% improvement in average vehicle efficiency by 2035.

Taken together, these policy levers position the transportation sector to play a pivotal role in Korea's mid-term mitigation strategy, both by accelerating the market share of ZEVs 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 (4.5 million ZEVs, see Table S2 for parameter values for conversion), whereas the *Enhanced Ambition* scenario not only achieves the target but nearly doubles the number of ZEVs by 2035. The result is a marked enhancement in emissions reductions and a more sustainable 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 *Enhanced Ambition* scenario, a suite of national policies—including strengthened zero-energy building (ZEB) standards, electrification incentives, energy efficiency resource standards (EERS) for buildings, and mandates for zero-emission appliances—drives substantial reductions in fossil fuel use and associated emissions.

As illustrated in Figure 8, total final energy consumption in buildings begins to decline after 2030 under the



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

Figure 7. ZEV new sales share (%) and total transport service by mode under Current Policy and Enhanced Ambition scenarios, for passenger and freight transport.

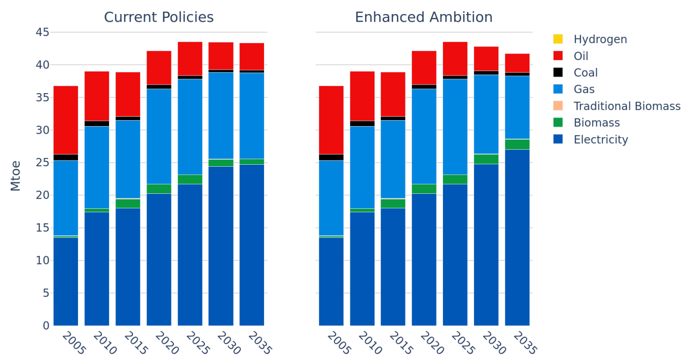


Figure 8. Final energy consumption in the buildings sector by fuel type under *Current Policies* and *Enhanced Ambition* scenarios.

Enhanced Ambition scenario, reflecting the widespread implementation of ZEB standards for private buildings and a broader shift in the energy mix toward electrification. By 2035, electricity accounts for 62.7% of final energy use in the building sector, compared to 54.5% under *Current Policies*. Oil and gas consumption decline more rapidly under *Enhanced Ambition*, while the share of biomass increases slightly, primarily due to policy-driven substitution. The steady growth in electricity use is further supported by electrification mandates targeting space and water heating.

Overall, emissions from the building sector fall by 48.5% from 2018 to 2035 in the *Enhanced Ambition* scenario—equivalent to a reduction of 23.5 $MtCO_2e$—compared to a more modest 16.2% reduction (7.9 $MtCO_2e$) under *Current Policies* (Figure 2). These results highlight the central role of electrification mandates and ZEB standards in decarbonizing the building stock and achieving national climate targets.

Discussion

This study offers critical insights for shaping a high-ambition 2035 NDC for Korea, drawing on detailed modeling of sector-specific mitigation pathways. Our analysis indicates that a 60.0% reduction in national GHG emissions by 2035—consistent with a net-zero trajectory—can be achieved through coordinated, cross-sectoral efforts spanning electricity, transport, industry, and buildings. Realizing this level of ambition will likely depend on both the scaling-up of current policies and the introduction of additional measures that address structural and institutional barriers. The findings point to areas where policy ambition could be elevated, governance frameworks strengthened, and public support mechanisms enhanced to accelerate low-carbon transitions across all sectors.

In the electricity sector, a full phase-out of unabated coal by 2035—coupled with annual offshore wind additions of at least 4 GW—enables an 85.2% reduction in power-sector emissions. Coal mitigation strategies that rely primarily on ammonia co-firing provide only limited abatement and risk delaying the structural transition needed for deep decarbonization. By contrast, offshore wind plays a pivotal role, especially given Korea's limited land availability. Its scalability is further supported by institutional advances such as the 2025 Offshore Wind Promotion Act. Achieving power-sector decarbonization will depend on proactive governance, streamlined permitting, and effective multi-stakeholder coordination.

Moreover, electrification across buildings, transport, and industry leads to a substantial rise in electricity demand by 2035, reinforcing the need not only for a clean energy transition but also for an expansion in total generation capacity to ensure system reliability and economy-wide emissions reductions. To meet these dual challenges, foundational reforms are urgently needed to accelerate the deployment of both solar and offshore wind. Solar PV expansion remains constrained by siting regulations—such as minimum distances from residential areas—while offshore wind is hampered by fragmented permitting processes and a lack of transparent compensation mechanisms. A coordinated, multi-level governance framework is essential to enhance social acceptance, reduce project delays, and align institutional roles for accelerated clean energy deployment.

In parallel, scaling up advanced energy storage solutions, including pumped thermal electricity storage, can play a critical role in integrating high shares of variable renewables while maintaining grid stability. As recent work shows, careful modeling of storage charging and discharging capabilities is essential for accurately assessing its system value and ensuring efficient investment decisions[45].

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 *Enhanced Ambition* scenario, a 33.7% reduction in total industry emissions is enabled by rapidly scaling next-generation mitigation technologies such as hydrogen-based steelmaking, cement LC3, low-carbon and recycled feedstocks, CCUS (carbon capture, utilization, and storage), and increased plastic recycling to cut demand for virgin petrochemical inputs and lower both energy use and process-related emissions.

Current carbon pricing policies—particularly the national emissions trading scheme (ETS)—remain insufficient to drive this transformation. The system's reliance on generous free allocations and grandfathering methods has resulted in persistently low carbon prices, undermining incentives for firms to invest in breakthrough technologies. These structural weaknesses in the ETS risk entrenching existing fossil fuel–based infrastructure and delaying the shift toward low-carbon alternatives.

However, these transitions face institutional, technical, and political barriers. Korea's 2021 update to its 2030 NDC lowered the industrial sector's mitigation target from 14.5% to 11.4% below 2018 levels (Table S11), citing practical constraints such as limited material supply and the near-term unavailability of key technologies[9]. While the adjustment was framed by government authorities as a realistic recalibration based on domestic conditions, it also drew criticism from civil society groups and experts who argued that the revised target signaled a weakening of ambition and cast doubt on the country's longer-term decarbonization pathway[46]. These concerns highlight the need for targeted financial support—such as carbon contracts for difference (CCfDs) that guarantee a fixed carbon price to offset cost gaps—and stronger demand-pull instruments like green public procurement, alongside translating sectoral decarbonization roadmaps into actionable policies with clear regulatory and investment signals.

The transport and building sectors demonstrate clear progress under the *Enhanced 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, 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. However, the growing electricity demand from both sectors—alongside industry—highlights the need for timely expansion of low-carbon power generation to safeguard energy security and ensure consistency with economy-wide mitigation goals.

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 by 2035 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.

Taken together, these findings underscore that achieving a 60.0% reduction in national GHG emissions by 2035 is not only attainable under ambitious policy conditions, but also essential for aligning Korea's mid-term targets with its net-zero commitment. While the power sector delivers the largest share of emissions reductions—driven by coal phase-out and accelerated renewable deployment—deep decarbonization of industry will likely demand broader societal consensus and stronger policy resolve, given the structural complexity of required transitions. The *Enhanced Ambition* scenario outlines a credible pathway grounded in sector-specific transformations, institutional reforms, and targeted public support. In parallel, achieving meaningful reductions in methane, F-gases, waste, and agriculture will require additional measures beyond current policy frameworks. As illustrated in the *Enhanced Ambition* scenario, instruments such as methane and HFC taxes, landfill bans, and manure management incentives offer concrete pathways for closing these gaps. These findings highlight the need for strengthened policy instruments and improved inter-ministerial coordination to ensure coherence between international commitments and domestic implementation. Overall, the results provide a robust analytical foundation for formulating a more ambitious and implementable 2035 NDC, ensuring that Korea not only fulfills its 2030 pledge but also secures a durable trajectory toward long-term decarbonization.

Data Availability

All relevant model outputs and processed results used in this study are available at: https://github.com/choiHenry/gcam-core/tree/cht/proj/korea-2035. This repository contains summary tables, emissions trajectories, and sectoral data supporting the figures and conclusions in the paper.

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 customized GCAM input files, scenario configurations, and output processing scripts used in this analysis are publicly available at: https://github.com/choiHenry/gcam-core/tree/cht/proj/korea-2035. The base GCAM source code can be accessed at: https://github.com/JGCRI/gcam-core/releases.

Supplementary Information

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

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Supplementary Information

High-ambition climate action in all sectors can achieve a 60% greenhouse gas emissions reduction in Korea by 2035

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Contents

Supplementary Note 1. Current Policy Landscape and Scenario Design

Since 2015, South Korea has prepared its Nationally Determined Contribution (NDC) for 2030 and has legislated its 2050 carbon neutrality target. The 2020 "2050 Carbon Neutral Strategy" presents two scenarios outlining sectoral goals and strategies for achieving net-zero emissions by 2050. In 2023, Korea updated its 2030 NDC and released the 1st Carbon Neutrality and Green Growth Basic Plan (hereafter CN-GGBP), which specifies 2030 reduction targets and implementation strategies by sector. These principles have since been concretized in individual sectoral strategies such as the 11th Basic Plan for Electricity Supply and Demand and the 2050 Carbon Neutrality Strategy for Agri-food.

This study uses the CN-GGBP as the primary reference for scenario construction. For each sector, additional references—including official roadmaps, government plans, and approved strategies—were used as secondary baselines. In constructing the *Enhanced Ambition* scenario, we also referenced Korea's historical policy evolution, expert recommendations from recent reports, peer-reviewed studies on Korea's net-zero pathways, and international policy developments to ensure feasibility and credibility.

The modeling of Korea's power sector in this study is based on the 11th Basic Plan for Long-term Electricity Supply and Demand (BPESD). The BPESD is a national plan updated biennially to ensure stable electricity supply while balancing cost-effectiveness and environmental sustainability. It sets out a 15-year outlook for generation capacity and transmission infrastructure and serves as a central implementation roadmap for achieving sectoral targets [5].

The 11th BPESD covers projections from 2023 to 2038, and this study reflects the plan's targets up to 2035. Key elements of the plan include a gradual phaseout of coal-fired power plants, increased ammonia co-firing at existing coal facilities, and the interim role of LNG in replacing aging coal assets. After 2030, the gap left by coal retirements is expected to be filled primarily by expanded renewable generation. Where the 11th BPESD lacks explicit detail, we assume continuity with the 10th BPESD.

The *Enhanced Ambition* scenario builds on these foundations by incorporating additional policy signals, including the G7 agreement on coal phaseout, Korea's emerging domestic discussion of a 2040 coal exit, its COP28 commitment to tripling renewable capacity, the enactment of the Offshore Wind Promotion Act, and MOTIE's offshore wind auction framework announced in 2024.

In South Korea, major industrial sectors—including iron and steel, petrochemicals, and cement—have each declared net-zero emissions targets by 2050 and developed sector-specific decarbonization roadmaps. In the iron and steel sector, the strategy centers on scaling up hydrogen-based direct reduction technology (H2REX, Hydrogen Reduction of Iron using EXploration technologies) and significantly expanding the use of steel scrap in electric arc furnaces (EAF). In the petrochemical sector, key mitigation pathways include the adoption of biomass-derived feedstocks such as bio-olefins and the deployment of electricity-based naphtha cracking technologies. In the cement sector, the strategy focuses on deploying blended cements such as Limestone Calcined Clay Cement (LC3), which significantly reduce process emissions by replacing clinker with calcined clay and limestone.

These mitigation technologies are primarily supported under the Ministry of Trade, Industry and Energy's (MOTIE) "Carbon Neutral Technology Development Program for Four Major Industries." Although MOTIE initially proposed a budget of 6.729 trillion KRW for the program, it was ultimately approved with only 935.2 billion KRW—a reduction of 86%.

In addition, Korea's Emissions Trading Scheme (K-ETS), which covers 70–80% of the country's total direct GHG emissions, has seen limited price impact due to generous grandfathering and lax allocation. As a result, the carbon price declined steadily after 2020 and is projected to remain at around 8,870 KRW/tCO_2 in 2025.

In the *Enhanced Ambition* scenario, the carbon price is assumed to rebound to its 2020 short-term average (30,411 KRW/tCO_2) through the introduction of carbon contracts for difference (CCfD) and tax credits for emissions reduction technologies. Also consistent with growing policy attention to lifetime extensions of blast furnaces, new regulations are assumed to prohibit lifetime extension of existing blast furnaces after 2025, with a complete ban in effect by 2035. Moreover, the ratification of the UN Plastics Treaty is assumed to accelerate the integration of recycled plastics as feedstocks in petrochemical production, increasing the share of recycled inputs by 2040.

In its 1st Basic Plan for Carbon Neutrality and Green Growth, South Korea has set a target to deploy 4.5 million electric vehicles (EVs) by 2030. The primary policy instrument to accelerate the adoption of eco-friendly vehicles is purchase subsidies, governed by the Act on the Promotion of Development and Distribution of Environmentally Friendly Motor Vehicles (commonly referred to as the "Eco-friendly Vehicle Act"). The specific subsidy amounts are annually determined by the Ministry of Environment's administrative guidelines.

The government offers two main types of subsidies: purchase subsidies for EVs and charging infrastructure subsidies. The purchase subsidy is currently scheduled to sunset in 2025, while support for charging infrastructure is planned to gradually decline through 2035. In addition, early retirement subsidies are available for old diesel internal combustion engine vehicles (ICEVs).

In the *Enhanced Ambition* scenario, we assume that current subsidies for eco-friendly vehicles are either extended or increased. Furthermore, we incorporate a regulatory ban on new ICEV sales, modeled after recent legislation in the European Union. While the EU has enacted a complete ban on ICEV sales after 2035, the Korean policy is assumed to phase out ICEV sales by 2040. In addition, existing fuel economy standards are assumed to be extended and strengthened beyond their current design.

In the building sector, the principal current policy instrument is the Zero Energy Building (ZEB) mandate, which requires new buildings—especially public and large private buildings—to meet a minimum share of renewable energy generation. To accelerate ZEB deployment, a range of subsidy programs have been introduced. The deployment of building-integrated renewable energy systems is led by the Ministry of Trade, Industry and Energy and the Korea Energy Agency, with separate support schemes for commercial and residential buildings, including installation subsidies and low-interest financing options.

Under the *Enhanced Ambition* scenario, a zero-emission appliance mandate is introduced as part of a green remodeling initiative for aging buildings. This mandate requires the gradual replacement of conventional appliances, such as fossil-fuel-based heating and cooling systems, with zero-emission alternatives.

Mitigation strategies for the agriculture sector are guided by the 2050 Carbon Neutrality Strategy for Agri-Food, which includes targets across multiple areas such as water management for rice paddies, nitrogen fertilizer reduction, enteric fermentation control, and conversion of livestock waste to energy. However, while the targets are clear in terms of direction and long-term ambition, they often lack detailed implementation mechanisms and short-term timelines. For this reason, many of the agricultural mitigation policies are included more comprehensively in the *Enhanced Ambition* scenario than in the *Current Policies* scenario.

Beyond the core sectors of power, industry, transport, buildings, and agriculture, South Korea has also set targets in emerging areas such as clean hydrogen and direct air capture (DAC). Korea has ratified key international agreements including the Global Methane Pledge and the Kigali Amendment. Nevertheless, due to the lack of detailed implementation instruments in these areas, most of the relevant mitigation actions are also included under the *Enhanced Ambition* scenario.

Table S1 summarizes the key sector-specific policy frameworks referenced as secondary sources in this study.

Table S1: Sectoral Policy Frameworks Used as Secondary References

Sector	Key Policy Framework
Power	1st Basic Plan for Electricity Supply and Demand
Industry	Carbon Neutrality Technology Development Program for Four Major Industries, Sector-Specific Roadmaps
Transport	Framework Act on Environmentally-Friendly Vehicles
Buildings	Green Building Support Act
Agriculture	2050 Carbon Neutrality Strategy for Agri-Food
Other	1st Hydrogen Economy Master Plan; Act on Carbon Dioxide Capture, Transportation, Storage, and Utilization

Supplementary Note 2. 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[3]. 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.

For the power sector, GDP and population trajectories were adjusted based on Statistics Korea's post-COVID-19 projections, and 2020 generation outputs by technology were calibrated using Korea Electric Power Corporation (KEPCO) statistics to ensure realistic scenario baselines.

Technology share weights relating to power sector were revised to align with domestic policy directions and market conditions. In the base GCAM, nuclear power share weights gradually increase after 2020, reflecting an assumed rise in policy and societal preference. In GCAM-ROK, however, nuclear share weights were fixed at 1 to maintain a neutral stance, recognizing ongoing uncertainty in domestic policy direction, social acceptance, and institutional factors.

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*[22] assessment of low market feasibility, and biomass or oil-fired power with carbon capture and storage (CCS), given limited technical and economic viability. Oil-fired generation accounted for only 0.6% of total generation in 2023, with no eligible units ($>$ 100 MW) built since 2007, and biomass combined heat and power has demonstrated marginal profitability under current market conditions[18].

In the transport sector, vehicle-type-specific assumptions on daily mileage, lifespan, and load factor (or service output) were applied to calibrate the 2020 stock of electric vehicles (EVs) and fuel cell electric vehicles (FCEVs) in GCAM-ROK. For buses, instead of separately specifying daily mileage and load factor, the annual service output per vehicle (passenger-kilometers per year) was used. Table S2 summarizes these assumptions together with the observed 2020 registered units, which serve as the calibration baseline for the model.

Table S2: Basic assumptions and 2020 registered units for EV and FCEV by vehicle type.

Vehicle type	Daily mileage (vkt/veh/day)	Lifespan (years)	Load factor / Service output	2020 Registered units
Car (EV)	33	15.3	1.26 pass/veh	117,616
Bus (EV)	–	15.3	824,767 pass-km/veh/year	1,837
Medium truck (EV)	47	16.8	4.2 ton/veh	15,436
Car (FCEV)	33	15.3	1.26 pass/veh	10,831
Bus (FCEV)	–	15.3	824,767 pass-km/veh/year	75
Medium truck (FCEV)	47	16.8	4.2 ton/veh	0

In the industrial sector, iron and steel production is the dominant source of process and energy-related emissions. We therefore calibrated the steel module to observed 2020 activity in Korea using the official e-Nara indicator for crude steel output [28]. Specifically, baseline GCAM trade flows did not capture the sharp decline in steel imports in 2020, which would otherwise overstate domestic production (and emissions) when matching apparent consumption. We corrected this by adjusting Korea's 2020 steel trade parameters—constraining imports downward and reconciling production, imports, and exports—so that modeled domestic production aligns with the e-Nara series while preserving mass balance (production + imports - exports = apparent consumption). This calibration ensures that the emissions baseline for iron and steel reflects observed market conditions rather than default global trade shares.

In the default GCAM base model, Korea is assumed to have no available CO_2 storage capacity, reflecting the high uncertainty surrounding national geological storage estimates. In contrast, our GCAM-ROK configuration incorporates recent domestic assessments of carbon storage potential, adopting an estimated capacity of 2,000 $MtCO_2$. This update allows CCS deployment in Korea to be represented more realistically in mitigation scenarios while remaining consistent with the latest national geological survey data.
Sources: TMACS[30], KADRA[13], KTDB[16], MOLIT[21].

Supplementary Note 3. Overview of modeling approach

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

Exclusion of non-implementable targets — We did not include targets that lacked corresponding policy measures or implementation mechanisms. In the Korean context, explicit deployment targets for electric and hydrogen vehicles for 2030 and 2040 are clearly stated in government plans, but these targets themselves were not directly incorporated into the model scenarios in the absence of enforceable instruments. Conversely, when a policy had a clear directional intent but lacked sufficient specificity in its implementation design, it was classified under the *Enhanced Ambition* scenario. For example, the “measures to reduce enteric fermentation” policy outlines a general mitigation direction for the livestock sector but, due to the absence of quantified actions or binding requirements, was included only in the enhanced scenario set.

Temporal consistency — Policies were assumed to persist beyond their stated planning horizon unless explicitly limited by a sunset clause. For example, while the Energy Efficiency Resource Standard (EERS) does not specify future fuel-specific reduction rates, it was assumed to remain in force; thus, current efficiency improvement rates were estimated and extended into the future. In contrast, the electric vehicle purchase subsidy is legislated to expire by 2025, and was therefore not modeled beyond that year in the *Current Policies* scenario. However, in the *Enhanced Ambition* scenario, we assumed that the current subsidy effect continues beyond 2025.

Quantitative estimation of impacts — Where policies lacked explicit numerical mitigation effects, we derived estimates from historical data, expert judgment, or peer-reviewed studies. For example, for the direct landfill ban policy, the resulting GHG mitigation potential from diverting waste to incineration or recycling was estimated using the U.S. Environmental Protection Agency's Waste Reduction Model (WARM)[31]. This allowed us to quantify avoided methane emissions from landfills as well as changes in CO_2 emissions from alternative waste treatment pathways.

Feasibility filtering — In the *Enhanced Ambition* scenario, we retained only those measures deemed technically and administratively plausible given Korea's recent policy and institutional capacity. While the GCAM framework does not impose explicit transmission constraints for the Korea region, we cross-checked renewable generation outcomes against results from prior study incorporating a transmission expansion scenario to ensure validity[24]. When considering measures such as coal phase-out, rapid offshore wind expansion, or zero-emission appliance mandates, we drew on evidence from ongoing domestic policy preparations, relevant international experiences, and formal policy proposals to assess their feasibility.

Methodological alignment — When multiple modeling approaches were available, we prioritized parameterizations previously validated in academic or government studies to ensure analytical comparability. Among prior GCAM-based studies on policy scenarios, several have made their full source code publicly available[23, 33]. This study actively incorporated methodological choices from such open-source works, adapting them where necessary to the Korean context.

Supplementary Note 4. Core model assumptions

This study uses a set of core assumptions for drivers including economic growth, population growth, fossil fuel prices, demand impacts of the COVID-19 pandemic, and technology costs (Supplementary Table 2). Our GDP growth assumptions are aligned with the long-term macroeconomic outlook provided by the Korea Development Institute [12], while population projections follow Statistics Korea's long-term population forecast [27]. Economic impacts associated with COVID-19 in 2020 and subsequent recovery in the following years have also been incorporated into these assumptions.

Table S3: Core assumptions for GCAM-ROK analysis

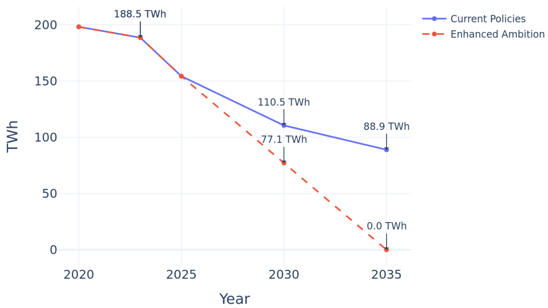
Drivers	**Scenario assumptions**
Economic Growth	Gross domestic product (GDP) increases by 2.1% per year on average from 2015 to 2035, peaking at 2.5% annually between 2020 and 2025, then slowing to 1.8% and 1.5% in the subsequent decades, consistent with KDI's long-term potential growth rate outlook.
Population Growth	Population peaks at 51.8 million in 2020 and then declines by 0.13% per year on average through 2035, consistent with Statistics Korea's medium-variant projection.
Fuel Prices	Gas price is assumed to drop by 19.5% year-on-year in 2020, increase by 89% in 2021, then decrease at an average rate of 7.1% per year through 2025. Prices increase 0.1% on average between 2025 and 2035. Oil price is assumed to drop by 33.9% year-on-year in 2020, increase by 78.4% in 2021. Prices increase at an average rate of 0.7% per year between 2021 and 2035.
Technology Costs	Technology costs are updated with the National Renewable Energy Laboratory (NREL) Annual Technology Baseline 2022 assumptions.
Transportation	Daily mileage, lifespan, and load factor assumptions are applied to calibrate 2020 EV and FCEV stocks by vehicle type, as detailed in Table S2.

Supplementary Note 5. Electricity Modeling Assumptions

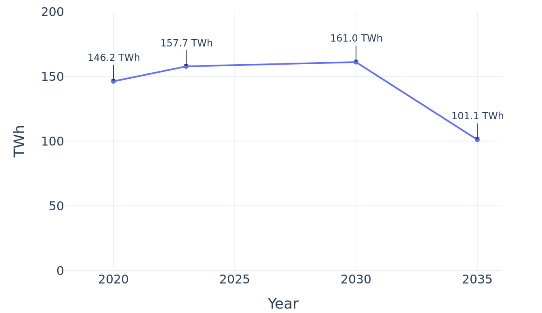
Modeled policy	***Current Policies***	***Enhanced Ambition***
Coal phaseout	Coal-fired generation declines from 184.9 TWh in 2023 to 88.9 TWh by 2035; no new coal plants after 2025.	Unabated coal (including ammonia co-firing) is fully phased out by 2035.

Coal with CCS	Not explicitly modeled.	Coal with CCS is deployed in lieu of ammonia co-firing.
LNG replacing aging coal	LNG replaces aging coal units. Generation rises from 157.7 TWh in 2023 to 161.0 TWh in 2030, then falls by 10.1 TWh by 2035.	
Hydrogen and ammonia co-firing	Co-firing generation increases from 0.0 TWh in 2023 to 32.8 TWh by 2035.	Ammonia co-firing is not used; coal with CCS and renewables substitute unabated coal.
Nuclear expansion	Nuclear generation increases from 180.5 TWh in 2023 to 236.0 TWh by 2035.	
Solar expansion	Capacity grows from 21.2 GW (2022) to 54.8 GW (2030) and 74.8 GW (2038); generation derived using Korea-specific PV capacity factors.	Solar capacity triples by 2030 under COP28-consistent assumptions.
Onshore wind expansion	Capacity increases from 1.64 GW (2023) to 7.9 GW by 2035, consistent with the 10th BPESD review; generation uses Korea onshore wind capacity factors.	
Offshore wind expansion	Capacity rises from 0.1 GW (2023) to 25.1 GW by 2035; generation uses Korea offshore wind capacity factors.	Rollout of 4 GW/year per MOTIE's 2024 plan.
Grid expansion	Grid infrastructure expands in line with the 11th BPESD to enable renewable integration and maintain system reliability.	

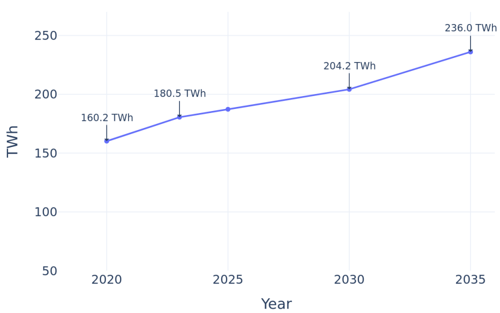
Note: Capacity factors are derived from PyPSA-Earth [25] using Copernicus ERA5.



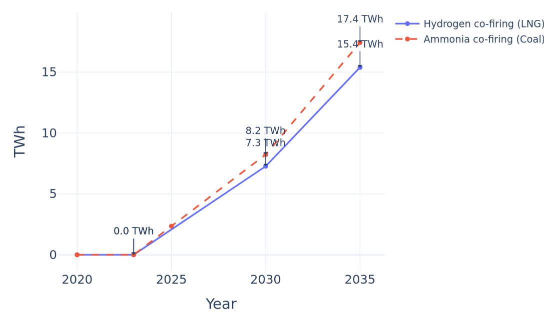
(a) Coal



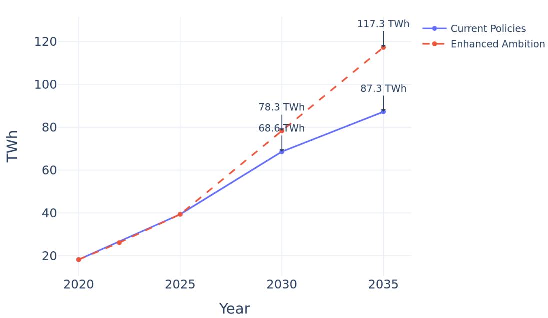
(b) LNG



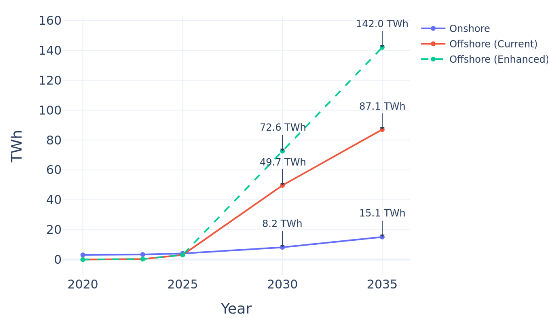
(c) Nuclear



(d) Co-firing



(e) Solar



(f) Wind

Figure S1: Modeled assumptions for power generation by fuel.

Supplementary Note 6. Industry Sector Modeling Assumptions

Modeled policy	*Current Policies*	*Enhanced Ambition*
Commercialization of H_2-DRI (H2REX)	Under the Carbon Neutrality Technology Development Program for the four major industries, hydrogen-based DRI is demonstrated and commercialized by 2035.	
Ban on lifetime extension of blast furnaces	Lifetime extensions banned after 2040, consistent with the steel sector's 2050 neutrality pledge.	Ban advances from 2025 with full prohibition by 2035 [2].
Steel scrap utilization	Scrap use remains near current levels.	Scrap-based production rises by ∼30% every five years with financial/regulatory support, consistent with POSCO's plan to boost scrap use by >30% within six years from 2024 [4].
K-ETS (cap-and-trade)	Carbon price held at 8,870 KRW/tCO_2 in 2025 (RE100 platform) [8].	Allowance prices rise toward ∼30,411 KRW/tCO_2 using CCfDs and targeted incentives to stabilize low-carbon investment signals [8].
Low-carbon cement (LC_3)	LC_3 is commercialized post-2030 under the Carbon Neutrality Technology Development Program.	
Biomass-based chemical feedstocks	Not explicitly modeled.	Increased adoption of bio-derived feedstocks (e.g., PEF, bio-polyols) improves economic viability and scale [17].
Plastic recycling in chemicals	Following UN plastics treaty progress [29, 1], the recycling rate rises to 25% by 2040; chemical recycling reduces refined-liquid feedstock coefficients proportionally.	

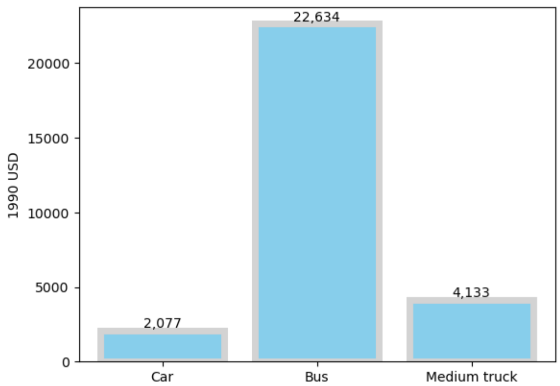
Semiconductor F-gas mitigation	CF_4 and SF_6 phased out via clean processes.	HFC_{23} and C_2F_6 also eliminated.
CBAM coverage	CBAM certificates: iron/steel from 2025, chemicals from 2027. Liabilities computed as (EU–KR carbon price differential) × export share.	
CCS incentives	Absent explicit Korean subsidy under the CO_2 Act [7], assume \$42/tCO_2 support.	Increase to \$84/tCO_2, reflecting U.S. IRA 45Q credit [10].

Supplementary Note 7. Transportation Sector Modeling Assumptions

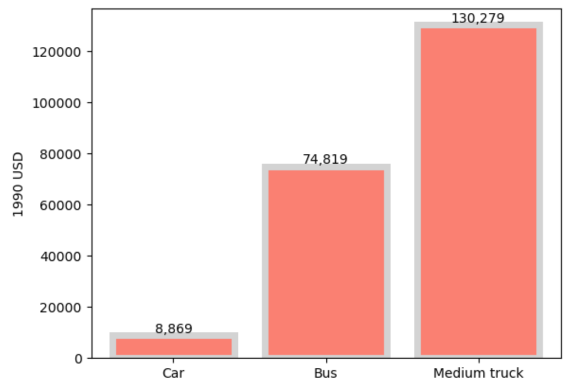
Modeled Policy	***Current Policies*** **scenario**	***Enhanced Ambition*** **scenario**
ZEV purchase incentives	Purchase subsidies for ZEVs are projected to reach on average 5.2 million KRW per EV of LDV 4W for year 2021–2024, which varies by sub-national region, vehicle type, and use. The subsidy is scheduled to expire in 2025. Figure S2 shows average subsidy levels by vehicle types.	The ZEV purchase subsidy is extended at current levels through 2035.
Subsidies for charging infrastructure for ZEVs	From the Ministry of Environment's subsidy guidelines, we compiled annual data on total charging infrastructure subsidies for both battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). The total subsidies were averaged across infrastructure types, and the annual average was divided by the corresponding target number of vehicles to estimate the infrastructure subsidy per vehicle. On average, the per-vehicle infrastructure subsidy is estimated at 125 constant 1990 US$. Figure S3 presents the projected subsidy trajectories by year for BEVs and FCEVs.	Subsidies for charging infrastructure are expanded, and per-unit support is sustained at 1.255 million KRW through 2035.

Incentives for early retirement of diesel ICEVs	Subsidies are offered for scrapping old diesel ICEVs (grade 4–5), with the retirement rate projected to rise to 14.1%—about 9.6 percentage points above the historical average of 4.5%—based on the 2024 target retirement rate reported by Korea Economic Daily [14].	
Fuel economy standards	Under existing fuel economy policies, passenger vehicle standards are strengthened from the 2020 baseline to 70 gCO_2/km in average GHG emissions and 33.1 km/L in average fuel economy by 2030—equivalent to about a 30% improvement over 2020 levels [19].	Fuel economy standards are extended to 2035 with an additional 15% improvement from 2030 levels. Freight vehicle standards also improve by 30% between 2025 and 2035.
Phase-out of ICEV sales	Not explicitly modeled in this scenario.	A regulatory ban on ICEV sales is included as a modeling assumption informed by international and domestic policy proposals rather than enacted legislation. France plans to phase out sales of gasoline and diesel vehicles by 2040 [26], while the EU aims for all new cars to be zero-emission by 2035 [6]. In South Korea, the incoming administration has proposed a non-binding pledge to end ICE vehicle registrations by 2035 [9].

Figure S2: Average purchase subsidy per vehicle by type (2021–2024, 1990 US$).



(a) BEV purchase subsidies



(b) FCEV purchase subsidies

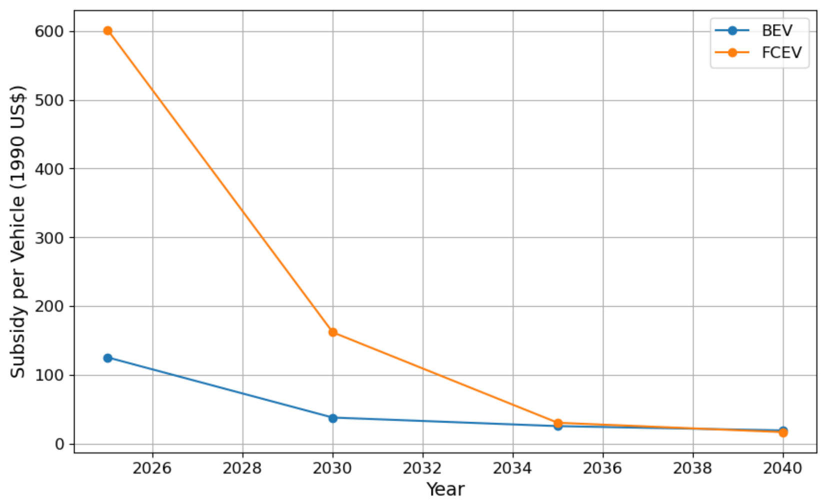


Figure S3: Subsidy per vehicle for BEVs and FCEVs (1990 US$) based on Ministry of Environment subsidy guidelines. Estimates are obtained by dividing the total charging infrastructure subsidies by the annual target number of vehicles. The average infrastructure subsidy per vehicle is 125 constant 1990 US$.

Supplementary Note 8. Buildings Sector Assumptions

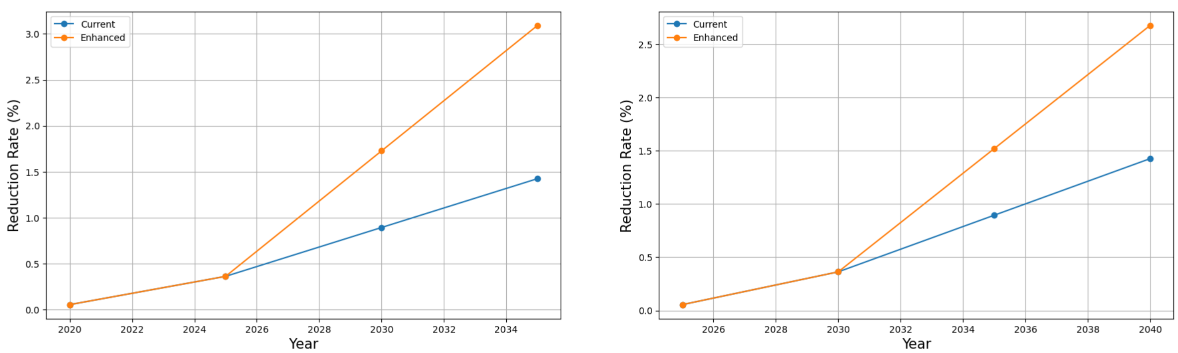
Modeled Policy	***Current Policies*** **scenario**	***Enhanced Ambition*** **scenario**
Zero Energy Building (ZEB) regulation	According to Korea's ZEB policy, public buildings ≥1,000 m^2 must meet ZEB standards (Grade 5) from 2020; covered buildings ≥500 m^2 require ZEB certification from 2023; and from 2025, Grade 5 design standards are required for large private buildings such as multi-unit apartments [20].	In the Enhanced Ambition scenario, from 2030 we apply Grade 4 (ESSR ≥40%) to new private buildings ≥500 m^2. Modeling mimics the impact via equivalent full self-sufficiency floor area and adjusted shell conductance in GCAM to reflect reduced heating and cooling demand.
Energy efficiency resource standards for buildings	Historical reduction trends (from EERS and utility data) are extended through 2035. By 2030, annual efficiency improvements reach 1.96% (electricity/heat) and 0.50% (gas) Figure S4 illustrates the efficiency improvement rates by energy company.	We assume that from 2030 onward, the improvement doubles compared to the baseline trend.
Zero-emission appliance mandates	Not explicitly modeled in this scenario.	Zero-emission appliance mandates are introduced, including a gradual phase-out of fossil-fuel based heating. All gas heating equipment is replaced by electricity after 2040.

Investment support for renewable energy deployment	The Ministry of Trade, Industry and Energy provides long-term low-interest financing for renewable energy deployment and manufacturing. As of Q4 2024, the interest rate is 1.75%. Assuming a market interest rate of 5.5%, this implies a 3.75% implicit subsidy. The policy assumes 35% of total financing is covered.	The subsidy rate is increased to cover 55% of total financing.
Installation subsidies for renewable energy capacity	Solar and fuel cell installation subsidies are provided based on equipment type. The average subsidy level from 2021 to 2024 is assumed.	The maximum subsidy level from 2021 to 2024 is assumed to continue for solar and fuel cell installations.

Table S8: Zero Energy Building (ZEB) Regulation in South Korea[15]

Category	**Year**	**Floorspace Threshold**	**Required Grade / ESSR**
Public Buildings	2020	≥500 m^2	Grade 4 / ESSR ≥40%
	2030+	≥500 m^2	Grade 3 / ESSR ≥60%
Private Buildings	Current	≥1,000 m^2	Grade 5 / ESSR ≥20%

Figure S4: Energy Reduction Rate Projections by Fuel Type.



(a) Electricity and Heat

(b) Gas

Supplementary Note 9. Other Sector Assumptions

Modeled Policy	*Current Policies* scenario	*Enhanced Ambition* scenario
Adoption of water-saving irrigation practices for rice paddies	The Ministry of Agriculture plans to subsidize Intermittent Drainage (ID) and Continuously Flooding with Water Saving (CF+WS), targeting adoption rates of 61.1% and 10% respectively. These practices reduce GHG emissions by 74.9% and 30.7%[11].	Adoption rate of CF+WS is expanded by 20% by 2035.
N Fertilizer Reduction	Not implemented in this scenario.	A nitrogen fertilizer reduction policy is introduced, aiming to lower fertilizer use from the 2019 baseline of 262 kg/ha to 115 kg/ha by 2030 (–43.9%).
Utilization of biomethane for on-farm energy supply	Not implemented in this scenario.	A technology is introduced to convert agricultural residues into biomethane for on-farm energy generation.
Measures to reduce enteric fermentation	Not explicitly implemented in this scenario	Low-emission livestock feed and additives are adopted, reducing methane emissions by 13.2% by 2030.

Credit mechanism for clean hydrogen	the share of clean hydrogen is projected to reach 50% by 2030 and 100% by 2050[32]. We linearly interpolated the clean hydrogen shares for the years between 2030 and 2050. For this policy, *clean hydrogen* is defined broadly as including all hydrogen types except grey hydrogen.	Only green and pink hydrogen are eligible; blue hydrogen is excluded.
Ratification and implementation of international environmental agreements	Not explicitly implemented in this scenario	Methane and HFCs are taxed in alignment with EU-ETS under the Global Methane Pledge and Kigali Amendment. Additionally, under the UN Plastics Treaty, plastic waste generation is reduced by 40% by 2040.
Deployment of backstop technologies	Not implemented in this scenario.	By 2030, direct air capture (DAC) is deployed. By 2030, 2.95 $MtCO_2$ is captured, rising to 5.2 $MtCO_2$ by 2035.

Supplementary Note 10. Sensitivity analysis

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 S10: Assumptions under sensitivity scenarios (excluding GDP and Population)

Driver	Core Assumptions	Sensitivities
GDP	GDP is assumed to grow by 2.1% per year on average from 2020 through 2035.	**High:** GDP grows by 3.2% per year on average through 2035. **Low:** GDP grows by 1% per year on average through 2035.
Population	Population is assumed to decline by an average of 0.10% per year from 2025 to 2035 (from 51.45 million to 50.87 million).	**High:** Declines more slowly, by 0.086% per year, reaching 51.00 million in 2035. **Low:** Declines more quickly, by 1.26% per year, reaching 45.48 million in 2035.
Fuel prices	Gas prices are assumed to decrease at an average rate of 7.1% per year from 2021 through 2025. Prices increase 0.1% on average between 2025 and 2035.	**High:** Gas prices increase at 1.1% per year (2021–2025), and 3.2% per year (2025–2035). **Low:** Gas prices decrease at 12.9% per year (2021–2025), then increase at 2.1% per year (2025–2035).
Oil prices	Oil prices are assumed to increase at an average rate of 0.7% per year between 2021 and 2035.	**High:** Oil prices increase at 2.1% per year. **Low:** Oil prices decrease at 3.7% per year.
LULUCF	LULUCF sector is assumed to sequester 47.8 MtCO2 and 13.2 MtCO2 by 2035 under Enhanced Ambition and Current Policies, respectively.	**High:** LULUCF sector is assumed to sequester 47.8 MtCO2 and 26.4 MtCO2 by 2035 under Enhanced Ambition and Current Policies, respectively. **Low:** LULUCF sector is assumed to sequester 13.2 MtCO2 and 0 MtCO2 by 2035 under Enhanced Ambition and Current Policies, respectively.

Supplementary Note 11. Supplementary Table and Figures

Table S11: South Korea's 2030 Emissions by Sector (Adjusted April 2023)

ITEM	Sector	2018 emissions ($MtCO_2e$)	2030 emissions Previous (Oct 2021)	Adjusted (Apr 2023) ($MtCO_2e$, %)
Emissions	Total emissions	727.6	436.6 (40.0%)	436.6 (40.0%)
	Transition	269.6	149.9 (44.4%)	145.9 (45.9%)
	Industry	260.5	222.6 (14.5%)	230.7 (11.4%)
	Buildings	52.1	35.0 (32.8%)	35.0 (32.8%)
	Transportation	98.1	61.0 (37.8%)	61.0 (37.8%)
	Agriculture, livestock, and fisheries	24.7	18.0 (27.1%)	18.0 (27.1%)
	Waste	17.1	9.1 (46.8%)	9.1 (46.8%)
	Hydrogen	(–)	7.6	8.4
	Fugitive emissions, etc.	5.6	3.9	3.9
Absorption / removal	Carbon sinks	(–41.3)	–26.7	–26.7
	CCUS	(–)	–10.3	–11.2
	International reduction	(–)	–33.5	–37.5

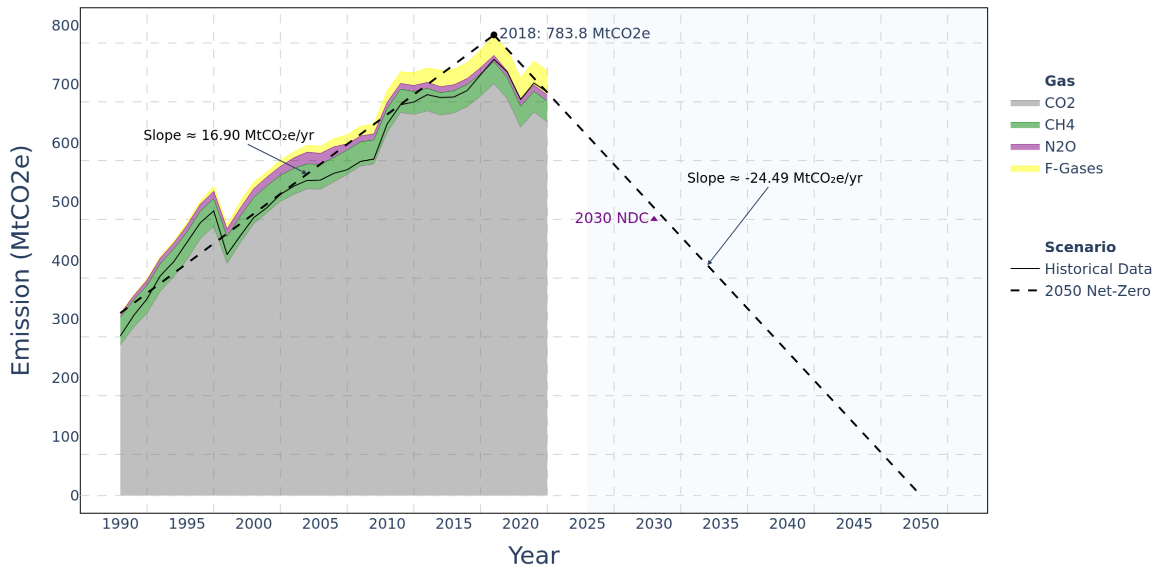


Figure S5: GHG emissions trajectories for Korea from 1990 to 2050. Emissions from 1990 to 2022 are based on historical data provided by the Greenhouse Gas Inventory and Research Center of Korea (GIR, 2025), disaggregated by gas. Emissions trajectories from 2025 onward shows the linear reduction pathway to net-zero 2050.

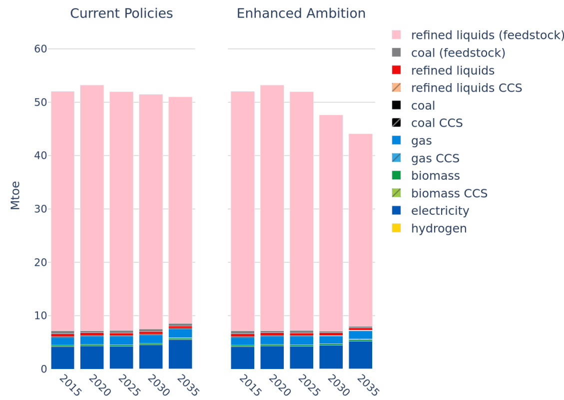


Figure S6: Final energy consumption in the chemical sector under the *Current Policies* and *Enhanced Ambition* scenarios.

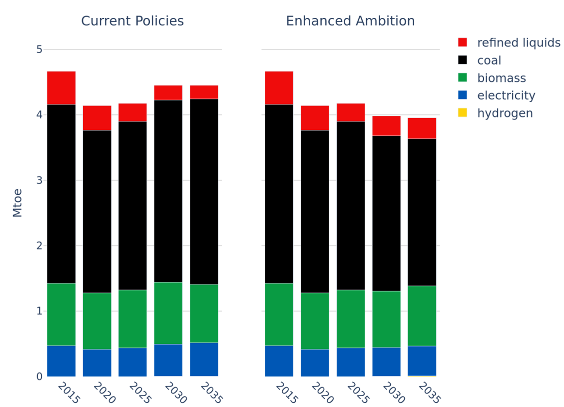


Figure S7: Final energy consumption in the cement sector under the *Current Policies* and *Enhanced Ambition* scenarios.

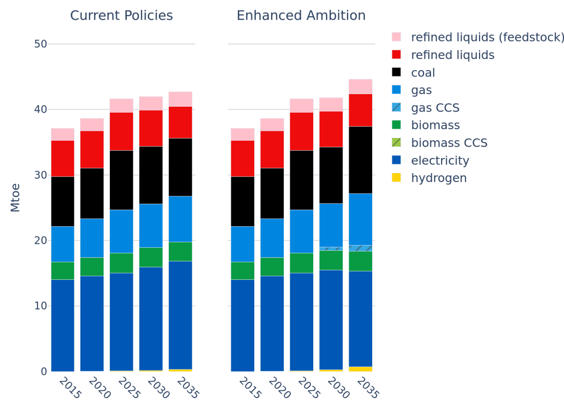


Figure S8: Final energy consumption in the other industry sectors except iron and steel, chemical, and cement under the *Current Policies* and *Enhanced Ambition* scenarios.

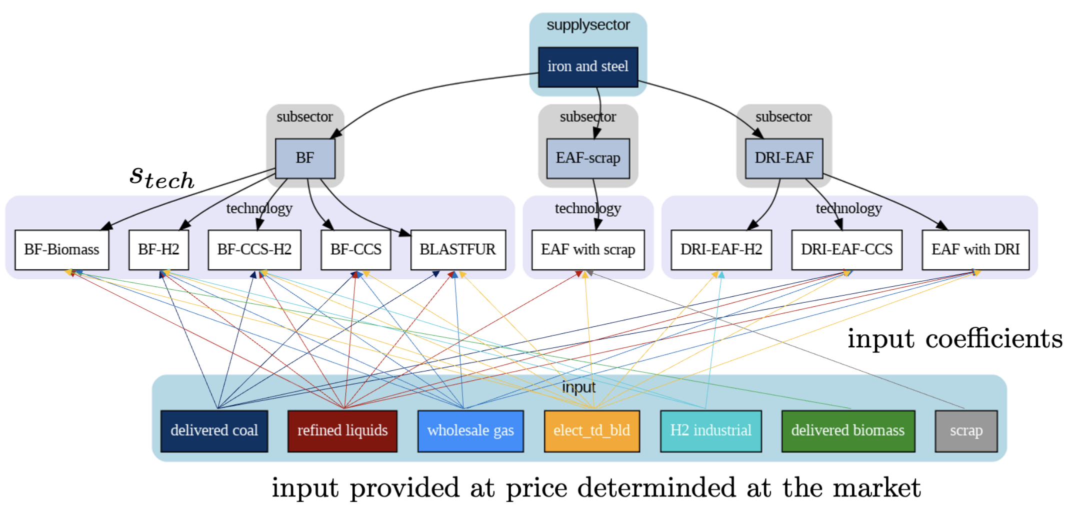


Figure S9: The structure of Iron and Steel industry in GCAM-ROK.

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