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Steel Sector Pathways for Korea's 2050 Carbon Neutrality

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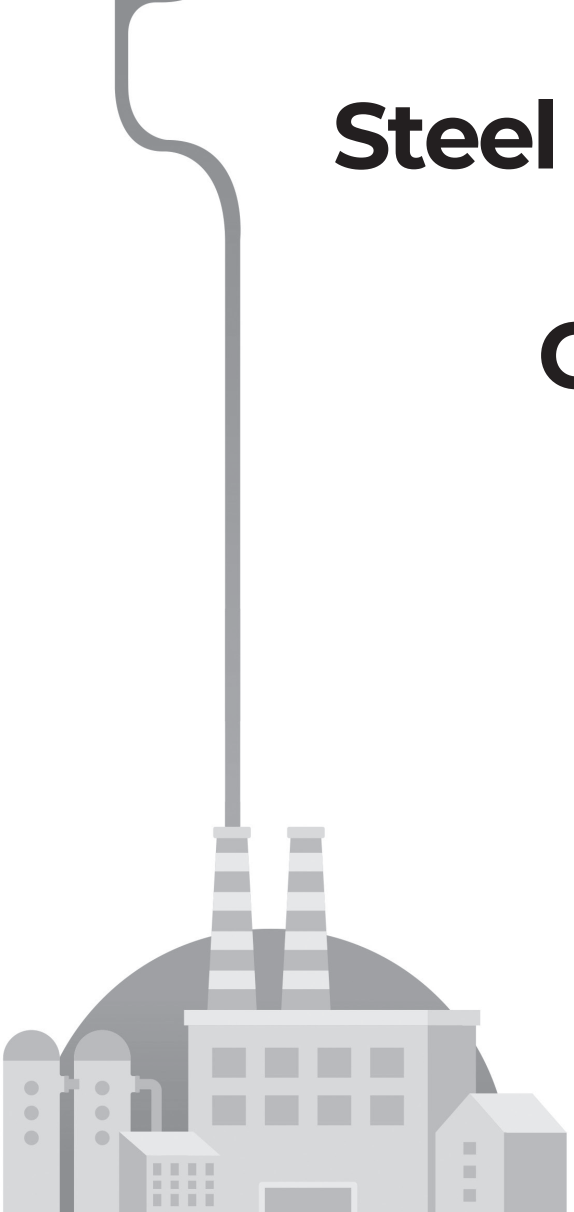

Exploration of 2050 Net Zero Pathways for the Korean Steel Industry Through Customized GCAM Modeling

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Executive Summary

Net zero is unattainable without the decarbonization of carbon- and energy-intensive industries, which emit vast volumes of greenhouse gases (GHGs). In Korea, the industrial sector, which remains extremely energy-intensive, is largely responsible for the country's GHG emissions. In 2017, for instance, its emissions were matched only by those of the energy supply sector. Of the many industries, steel, in particular, requires rapid decarbonization. The steel industry was the largest emitter of GHGs in 2018, accounting for 39 percent of all industrial GHG emissions and 13.1 percent of the country's total GHG emissions.

The South Korean government's recent 2050 carbon neutrality declaration was followed by an announcement of its enhanced nationally determined contribution (NDC) and several decarbonization scenarios, precipitating discussions on how to curtail GHG emissions from the steel industry to deliver the country's 2030 and 2050 GHG reduction targets. Grappling with the issue, academia, industry, and civic groups have put forward policy ideas and technology development plans for individual subsectors of the steel industry. Prior to this report, no studies had conducted a comprehensive assessment of steel decarbonization scenarios based on an integrated assessment model (IAM) comprehensively linking all of the country's economic activities and GHG emissions.

This study applied GCAM-KAIST 2.0, a customized version of GCAM-KAIST 1.0 created specifically for the Korean steel industry, to develop internally consistent GHG emission scenarios for the industry (GCAM-KAIST being the first-ever integrated analysis model for South Korea). This study evaluates the changes that the NDC imposes on the steel industry and suggests the following implications.

First, South Korea's achievement of its 2050 carbon neutrality targets will not automatically mean that the steel industry will also reach net zero by that year, since the industry will still be consuming energy from coal and gas, directly giving off emissions. Improvements should be made so that those direct emissions from the industry may be set off as much as required by cuts in indirect emissions generated for the industry. Electrification of the steel industry and greater use of hydrogen as an energy source will play a crucial role in facilitating this decarbonization. This means that net zero cannot be reached without longer-term investments aimed at increasing renewable energy power generation and green hydrogen production.

Second, a decarbonization pathway for the steel industry that will help the achievement of the 2050 national carbon neutrality targets should involve the accelerated introduction of hydrogen-based electric arc furnaces with direct reduced iron (DRI-EAF-H_2) and DRI-EAF with carbon capture and storage technologies (DRI-EAF-CCS), thereby accelerating the shift away from blast furnaces that cannot capture and store carbon. Additionally, the number of electric arc furnaces with scrap steel (EAF-scrap) should also be enlarged considerably.

Third, while a decrease in steel production enabled by higher efficiency in steel consumption will not by itself do much to reduce GHG emissions from the industry, it will at least lead to decreases in power generation and hydrogen production. This highlights the importance of considering ways to improve steel consumption efficiency in planning investments for the power and hydrogen production sectors to achieve carbon neutrality.

1.0 Introduction

1.1 2050 Carbon Neutrality Declaration and Enhanced NDC

The Framework Act on Carbon Neutrality and Green Growth (hereinafter the "Framework Act on Carbon Neutrality") was enacted in September 2021, close to year after the South Korean President's October 2020 declaration regarding the country's aim to reach net zero by 2050 *(Reference 4. Government of the Republic of Korea, 2020)*. In October 2021, the 2050 Carbon Neutrality Commission (hereinafter the "Carbon Neutrality Commission") proposed several carbon neutrality scenarios.

During the same period, the government also announced an enhanced nationally determined contribution (NDC)—net emissions of 436.6 million tons by 2030, which represents a 40 percent reduction from the total 787.6 million tons of GHG emissions in 2018. This ambitious new NDC was set in consideration of the carbon neutrality scenarios and the Framework Act on Carbon Neutrality, as well as international trends.

The enhanced NDC envisions industrial emissions declining to 222.6 million tons by 2030, 14.5 percent below the 2018 level of 260.5 million tons. The steel industry is expected to install electric arc furnaces when extending existing facilities or building new ones and to accelerate the commercialization of next-generation technologies *(Reference 1. Relevant ministries (2021a); Reference 5. Ministry of Trade, Industry and Energy (2021))*.

1.2 GHG Emissions from Industry and Steel: Where We Are and How to Slash Emissions

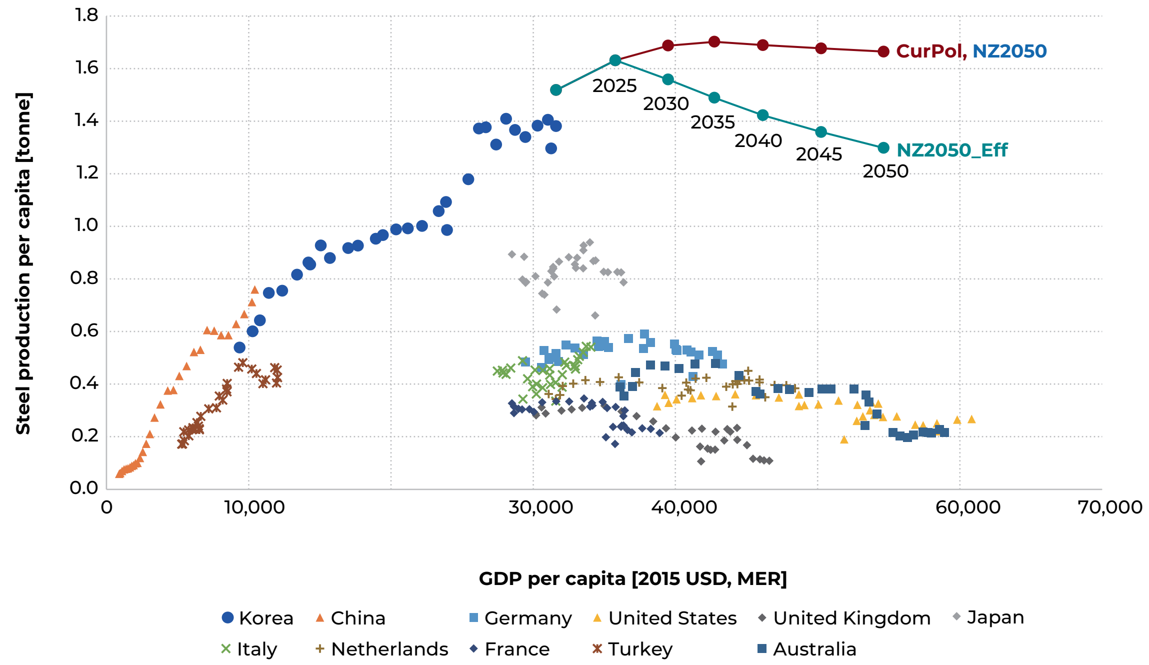
The industrial sector was responsible for 36 percent of the country's total GHG emissions in 2017 excluding its indirect emissions (the percentage rises to a staggering 54 percent if the indirect emissions are included), running neck and neck with the energy sector. Both face an urgent call to slash emissions *(Reference 5. Ministry of Environment (2020))*.

The massive industrial emissions are linked to the heavy presence of highly energy-intensive manufacturing industries in Korea. In 2017, steel generated 104.9 million tons CO_2eq of GHG gases,

followed by petrochemicals (40.8 million tons CO_2eq), cement (35.6 million tons CO_2eq), and oil refining (15.5 million tons CO_2eq). These four industries account for about 76 percent of total industrial emissions. Notably, steel and metals (two industries notorious for high GHG emissions) represent greater emissions share in the Korean industry than in other major countries *(Reference 12. KIET (2021))*.

As shown in Figure 1, steel production per capita is much higher in South Korea than elsewhere. In 2018, the country's steel industry generated roughly 101 million tons CO_2eq of GHG emissions, accounting for 39 percent of all industrial emissions and 13.1 percent of the country's total GHG emissions *(Reference 3. Solutions for Our Climate (2021))*.

Figure 1. 1990 -2020 Steel Production Per Capita in Major Countries



Source: Reference 18. World Bank (2022); Reference 19. World Steel Association (2022)

The enhanced 2030 NDC and the 2050 carbon neutrality scenarios, both announced in October 2021, aspire to 222.6 million tons CO_2eq of industrial GHG emissions by 2030 and 51.1 million tons CO_2eq by 2050, compared to 260.5 million tons CO_2eq in 2018. The primary means to reduce GHG emissions from the steel industry include hydrogen technologies, raw material recycling, higher energy efficiency, carbon dioxide capture and storage, low-carbon fuels and raw materials, and cuts in emissions from industrial processes *(Reference 6. Energy Transition Korea (2020))*.

South Korea's national roadmap focuses on three main means of decarbonizing the steel sector: (1) introducing electric arc furnaces when facilities are expanded or newly built while turfing out antiquated blast furnaces; (2) greater use of electric arc furnaces in refining scrap steel for crude steel production; and (3) replacing the carbon-based blast furnace-converter furnace route by means of HDRI technologies. For the country to reach the 2050 net zero target, it is important to evaluate the essential changes for the steel sector, being both the largest overall GHG emitter in the country and local industry. Experts have already proposed various technology development plans and GHG reduction policies for individual industries that are believed to help push the country toward the attainment of carbon neutrality *(Reference 1. Relevant ministries (2021a); Reference 2. Relevant ministries (2021b); Reference 5. Ministry of Trade, Industry and Energy (2021))*. There is also literature that analyzes the changes that the Korean steel industry needs to undergo with global-level integrated analysis models *(Reference 17. Yu.S. et al.(2021); Reference 9. Bataille et al., (2021))*. However, no report has been made on a consistent scenario assessment by an integrated assessment model that links all economic activities, energy systems and policies, and national GHG emissions. To address this gap, the GCAM-KAIST 1.0 integrated analysis model, developed for South Korea, was customized and applied to the Korean steel industry as GCAM-KAIST 2.0. Drawing upon the modelling tool, this study develops three GHG emission scenarios with internal consistency, identifies what changes the steel industry needs to make for the national GHG reduction targets to be delivered and makes several policy suggestions (see Appendix 4.2).

1.3 Structure of the Report

By assessing steel industry decarbonization scenarios that are aligned with South Korea's 2050 carbon neutrality targets, this report aims to determine the changes the Korean steel industry should make in the mid and long term. To ensure internal consistency of the GHG scenarios that it develops, this study applied an integrated assessment model (IAM): GCAM-KAIST 2.0. Developed based on the Global Change Analysis Model (GCAM), which was used in Intergovernmental Panel on Climate Change (IPCC) assessment reports, GCAM-KAIST 2.0 reflects the country's unique energy systems and policies.

This report first explains what assumptions are applied to develop the three scenarios used for assessment— scenario CurPol, scenario NZ2050, and scenario NZ2050_Eff. Second, it formulates a reduction pathway for each of the three scenarios and assesses the burden of reaching net zero for each of the sectors considered. Then, the reductions and energy system transitions found

1.0 Introduction Exploration of 2050 Net Zero Pathways for the Korean Steel Industry

to be required are analyzed. The analysis evaluates the changes in the energy mix of the electric power sector, which is critical to decarbonization, and discusses vital transitions in Korean industry, including its steel sector. Finally, this report will suggest the overall orientation of the steel industry's transformation and provide policy proposals based on the scenario analysis results.

2.0 Body

2.1 Scenario Design

Combining technological and economic considerations, this study projects GHG emissions from the Korean steel industry and thereby determines the requirements for its decarbonization in line with the national goal of net-zero carbon emissions by 2050. To that end, the study develops two scenarios— dubbed CurPol ('Current Policy') and NZ2050 (Net Zero 2050')—and then constructs another scenario—NZ2050_Eff ('Net Zero 2050 Efficiency')—for further sensitivity analysis. The assumptions for the individual scenarios are as follows:

1. **CurPol:** This scenario incorporates South Korea's current position in steelmaking technologies, drawing upon the energy and climate policy instruments proposed by the Korea Institute for Industrial Economics and Trade (KIET) that are already in place or soon to be implemented. The power facility plans and power generation forecasts for the years to come until 2034 that are indicated in the ninth Power Supply Master Plan and the fifth New and Renewable Energy Master Plan are used to project mid- and long-term energy mix forecasts for the power sector, while the preferable demand schedules for the three major energy-consuming sectors—building, industrial, and transportation—that are estimated in the third Energy Master Plan are used to project mid- and long-term demand for energy nationwide and by specific sectors. In addition, GDP and population estimates are made based on forecasts from the KIET and Statistics Korea. Capital expenditures (CapEx) of each power generation source are estimated based on forecasts from Bloomberg New Energy Finance (BNEF) and the National Renewable Energy Laboratory (NREL).

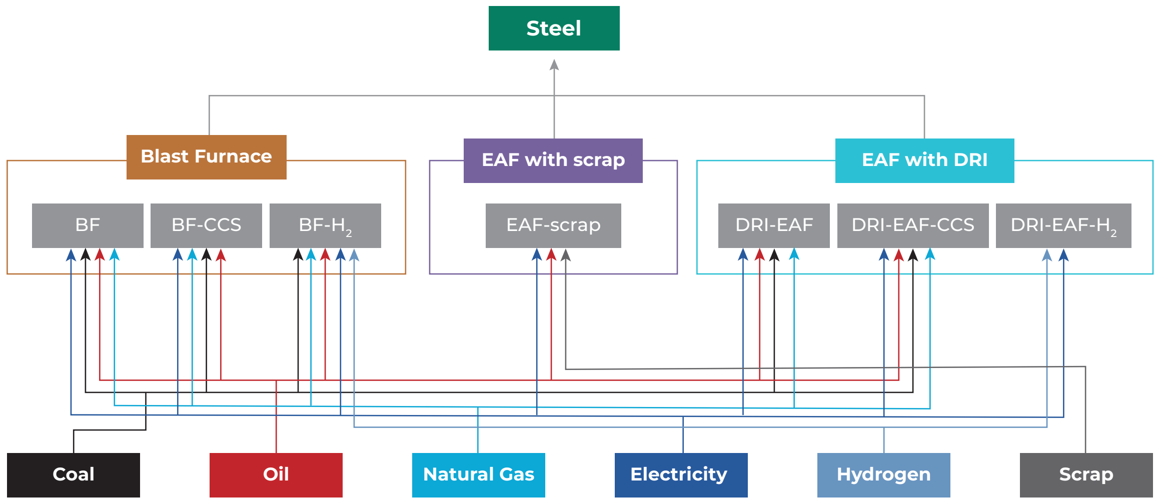
2. **NZ2050:** Like CurPol, this scenario assumes the same parameters for the country's position in steelmaking technologies today, drawing upon the KIET's steel production forecasts *(Reference 11. KIET (2018))* and considering the energy and climate policy instruments that are currently in place. One key difference between the two scenarios lies in the manner that emissions decrease over the years. NZ2050 assumes that annual GHG emissions decline at a uniform rate from 2025 (Year 1) until net zero is achieved by 2050. NZ2050 also imposes carbon prices (which are not considered in CurPol) and presumes that regulation on GHG emissions linearly weakens from 2025 to 2050. It should be noted that this scenario imposes the same carbon price on all the sectors considered, making the marginal abatement cost (MAC) identical for all of them, while also assuming the ongoing cost-effective endeavors to reduce emissions.

3. **NZ2050_Eff:** This scenario adopts the same assumptions as NZ2050, except that it presumes steel production linearly decreases by 22 percent from 2025 to 2050 *(Reference 17. Yu et al (2021))*. The reduction in production is enabled by increased efficiency – such as the extension of the lifespans of buildings, building design improvement and optimization, recycling of steel, use of lighter materials using high-strength steel alloys, and higher steel production efficiency.

GCAM-KAIST 2.0 is based on the GCAM developed by Pacific Northwest National Laboratory (PNNL) in order to develop quantitative scenarios that are internally consistent and explainable. GCAM is a representative integrated analysis model and has been used in consecutive IPCC assessment reports. It is an assessment system that explains how climate change happens due to GHG emissions from economic activities of countries around the world, derived in terms of production and consumption of diverse goods, market equilibria and prices, fuel replacement, and how the economic feasibility of technologies affect their competitiveness. A brief explanation of the GCAM method is annexed to this report (see Appendix 4.2). The levels of steel production per capita that the three scenarios assume are far higher than those of other advanced countries. This is due to the conservative approach adopted by this study in calculating reductions in steel production as a decarbonization tool (Figure 1). This report compares and evaluates what the three scenarios demonstrate about national GHG emissions, primary and final energy, the power generation and hydrogen production sectors, and total industrial energy consumption and energy consumption by the steel industry.

2.2 Steelmaking Technologies Represented by the Model

Figure 2. Representations of Steelmaking Technologies by GCAM-KAIST 2.0.

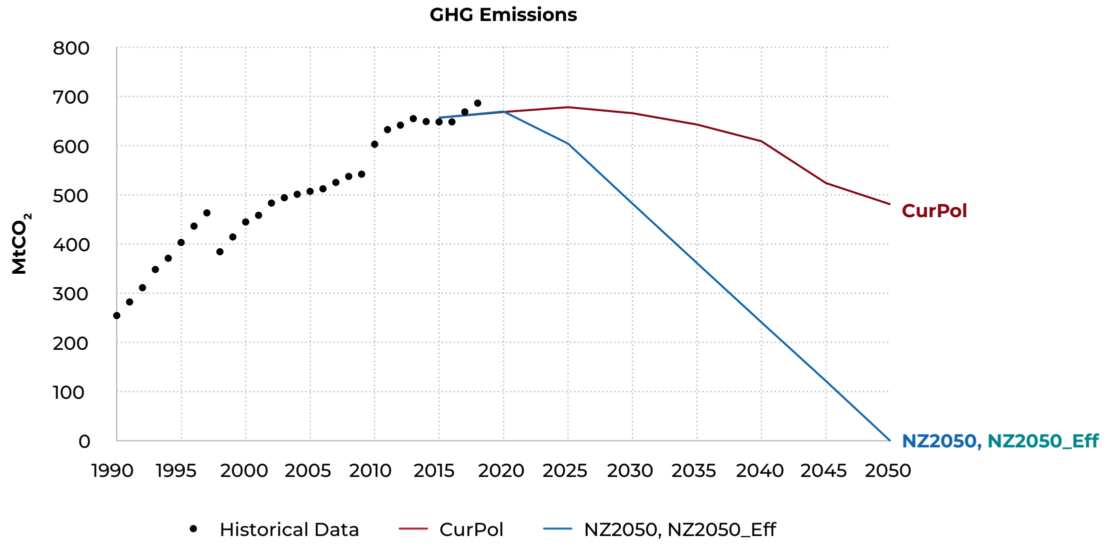


GCAM-KAIST 2.0 covers seven steelmaking technologies. They may be grouped into three broad routes: the blast furnace route (BF), the electric arc furnace route using scrap steel (EAF with scrap or EAF-scrap), and the electric arc furnace route using DRI (EAF with DRI or DRI-EAF). The blast furnace route is divided into three: the conventional blast furnace route, the blast furnace route with a carbon capture and storage system (BF-CCS), and the blast furnace route that uses hydrogen for heating (BF-H_2). EAF with DRI is also further divided: the CCS (DRI-EAF-CCS) route and the hydrogen DRI technology (DRI-EAF-H_2) route. The model also includes one route involving the use of EAF-scrap technology, which can draw upon coal, petroleum, gas, electricity, and/or hydrogen as energy sources. The model also shows the structure of scrap consumption for electric arc furnaces that process scrap steel. The assumptions for each route are taken from Decarbonizing the Steel Sector in Paris-Compatible Pathways, a 2021 report on steel decarbonization scenarios by E3G and PNNL *(Reference 17. Yu et al. (2021))*[1].

1 The assumption of this report are primarily based on the paper "Decarbonizing China's iron and steel industry from the supply and demand sides for carbon neutrality" *(Reference 14. Ren et al. (2021))* and the report Iron and Steel Technology Roadmap: Towards more sustainable steelmaking by the IEA *(Reference 10. IEA (2020))*.

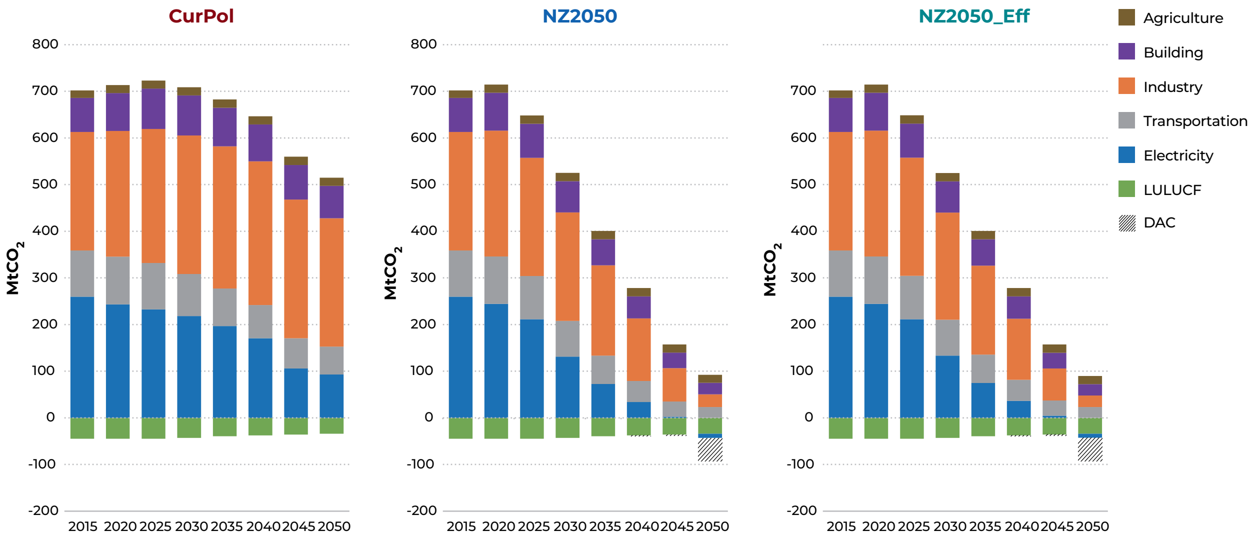
2.3 Analysis of National GHG Emissions

Figure 3. Reduction Pathways by Scenario



GCAM-KAIST 2.0 analysis results suggest that if the current policies are maintained (as per scenario CurPol, which stands for "Current Policies"), GHG emissions would decrease only about 30 percent between 2020 and 2050, without reaching the net zero goal (Figure 3). It is therefore evident that, without far more aggressive and extensive GHG reduction and climate policies, the country would not be carbon neutral by 2050.

Figure 4. GHG Emissions by Sector and Scenario

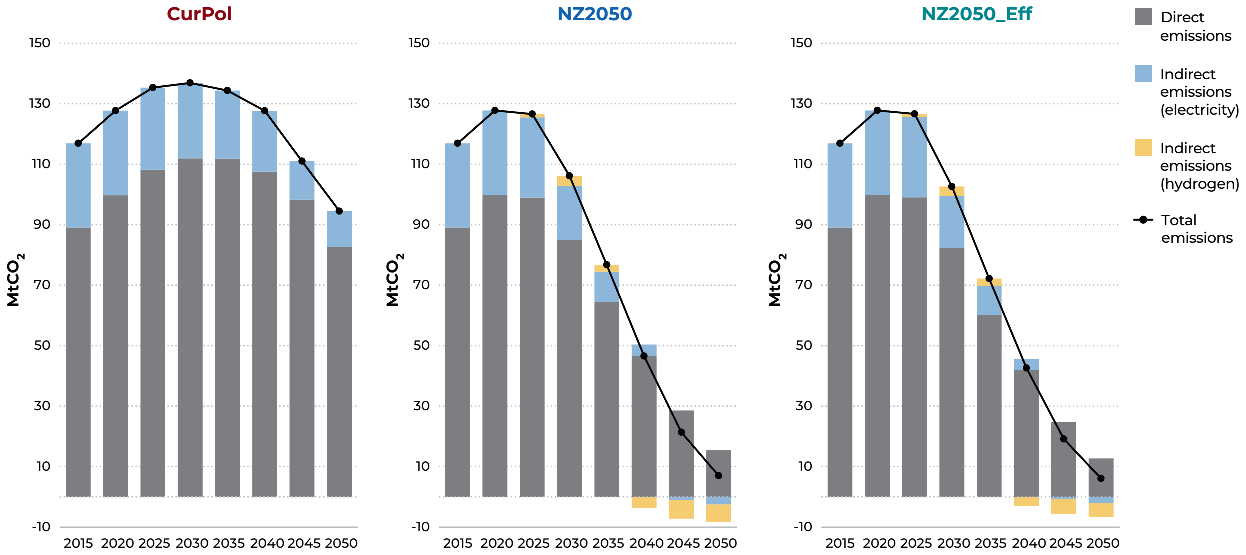


The power, industrial, and transportation sectors are all expected to play a pivotal role in the country's efforts to reduce GHG emissions because they generate so much and thus have the potential for great reductions (Figure 4). The building and agricultural sectors stand on the opposite end of the spectrum and are expected to contribute little toward driving the country to net zero.

In the CurPol scenario, national GHG emissions peak in 2025 and then decline gradually. A decrease in GHG emissions from power will be overshadowed by an increase from industry, but every other sector than these two represents more or less the same percentage through the years.

However, if the country runs in the race to net zero (as per scenarios NZ2050 or NZ2050_Eff), GHG emissions are forecast to shrink rapidly in the power, industrial, and transportation sectors. In addition, GCAM-KAIST 2.0 suggests that a range of negative emissions technologies (NETs) should be introduced to offset the GHG emissions that will inevitably occur to a degree that is required for the attainment of net zero by 2050. These NETs are connected to land use, land-use change and forestry (LULUCF), bio-energy with carbon capture and storage (BECCS), and direct air capture (DAC). As evident from Figures 3, 4, and 5, the minute differences between the two net zero scenarios show that a reduction in steel production from more efficient steel consumption will have only a slight impact on GHG emissions (mapped out in scenario NZ2050_Eff).

Figure 5. Carbon Dioxide Emissions from the Steel Industry

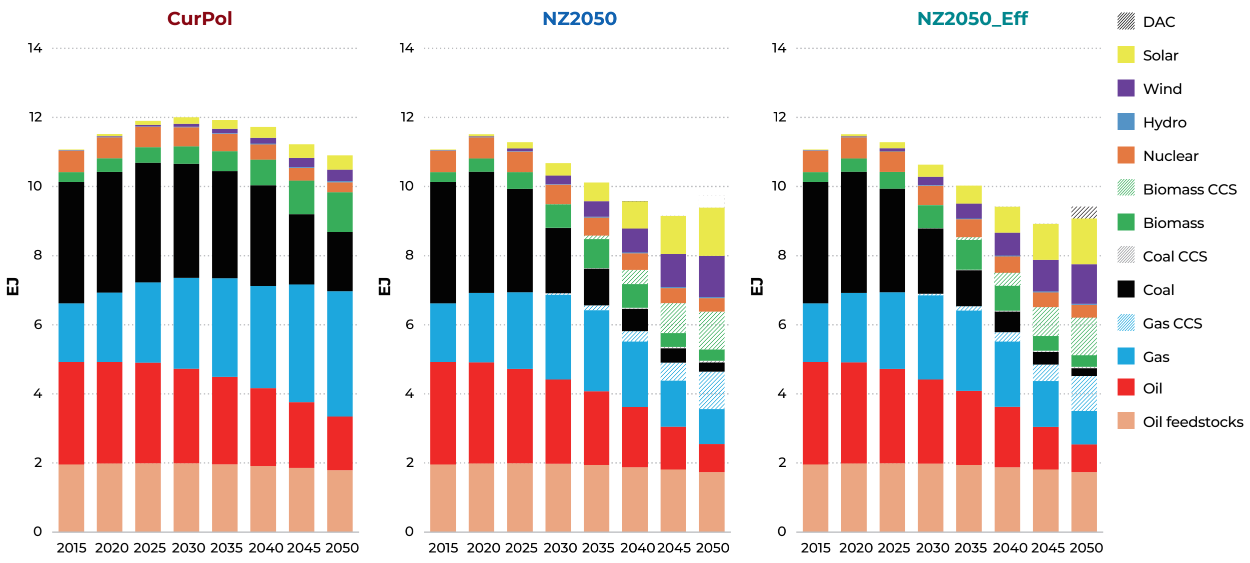


Scenario CurPol expects that carbon dioxide emissions from steel will peak in 2030 and then diminish by degrees until 2050. Indirect emissions will decline into 2050 as renewable energy and CCS will play a greater role in power generation, but the sheer volume of emissions will remain problematic.

The NZ2050 and NZ2050_Eff scenarios forecast that carbon dioxide emissions will plummet to five percent of the level of 2020 by 2050. This means that South Korea's achievement of its 2050 carbon neutrality goal does not mean net-zero carbon dioxide emissions directly from the steel industry. However, the scenarios project that much of the direct emissions from steel will be offset by reductions in indirect emissions in the hydrogen production and power sectors attributable to greater consumption of clean hydrogen and clean power in steelmaking.

2.4 Primary Energy Analysis Results

Figure 6. Primary Energy Consumption by Energy Source



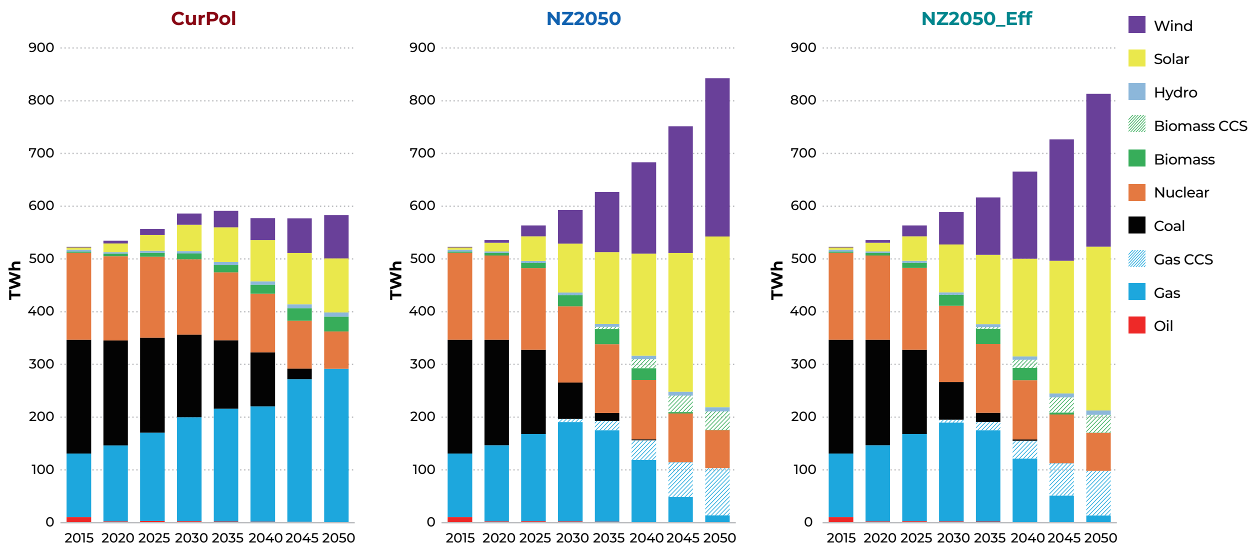
The CurPol scenario forecasts that primary energy consumption will culminate around 2030 and then gradually decline (Figure 6). In the NZ2050 and NZ2050_Eff scenarios, however, primary energy consumption begins to decrease about ten years earlier as rising carbon prices are reflected in energy prices, leading to contracting coal consumption.

Results also show that current policies do not portend radical changes in the makeup of energy sources. Gradual abatement in coal and petroleum consumption cannot chip away at the overall fossil fuel total in primary energy due to a steady increase in natural gas consumption (CurPol scenario, Figure 6). Nevertheless, solar, wind, and biomass will record growth of about seven-fold, 16-fold, and three-fold, respectively, from 2020 to 2050.

On the contrary, the NZ2050 and NZ2050_Eff scenarios paint more promising pictures in which the ratio of fossil fuels in primary energy supply halves from 2020 to 2050 and solar and wind skyrocket by 22 times and 60 times, respectively, with biomass also impressively quadrupling (Figure 6).

2.5 Power Generation and Hydrogen Production Analysis Results

Figure 7. Power Generation by Energy Source



What stands out with the energy mix in overall power generation is the drastic phasing-out of coal in accordance with the ninth Power Supply Master Plan (Figure 7). However, the pace of change for each energy source in the energy mix varies across scenarios.

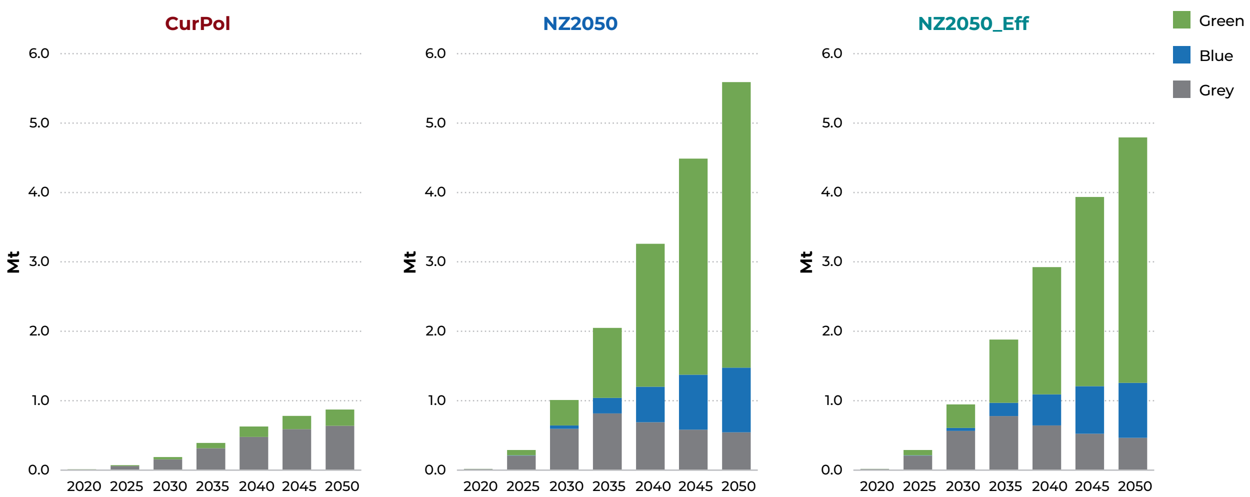
GHG emissions from power generation are forecast to more than halve over the next 30 years, even in the CurPol scenario. This represents a major change in the energy mix. The scenario also expects that implementation of the ninth Power Supply Master Plan will bring down the ratio of coal by 35 percent from 2020 to 2035, with renewable energies and gas-fired power generation soaring 250 percent and 150 percent, respectively.

The NZ2050 and NZ2050_Eff scenarios see coal removed more rapidly from power generation and solar, wind, and biomass growing more dramatically than in CurPol (Figure 7). The net-zero scenarios forecast that the percentage of coal in power generation will drop to a mere ten percent by 2030 and virtually fizzle out. Renewable energies will grow rapidly—about seven-fold and about 20-fold—by 2030 and 2050 compared to 2020, leading to 65-percent growth in total power generation compared with today.

It is thus obvious that climate policy-driven decarbonization of the power generation sector can help reduce GHG emissions to a great extent. The NZ2050 and NZ2050_Eff scenarios can better cut emissions from the sector than CurPol: 40 percent more by 2030 and 110 percent more by 2050. GCAM-KAIST 2.0 sees the use of CCS in gas-fired power generation taking off in 2030, propelling the decarbonization of the sector. The model also suggests that BECCS (which combines biomass generation with carbon capture and storage) will enable net negative emissions (NNE) in power generation in 2045 and beyond. GCAM-KAIST 2.0's NZ2050 scenario predicts a cumulative volume of carbon dioxide captured in the sector at 800 million tons by 2050.

Interestingly, annual power generation is about five percent lower in NZ2050_Eff than in NZ2050. The gap reiterates the need to consider steel consumption efficiency in decision-making on power generation facility investment.

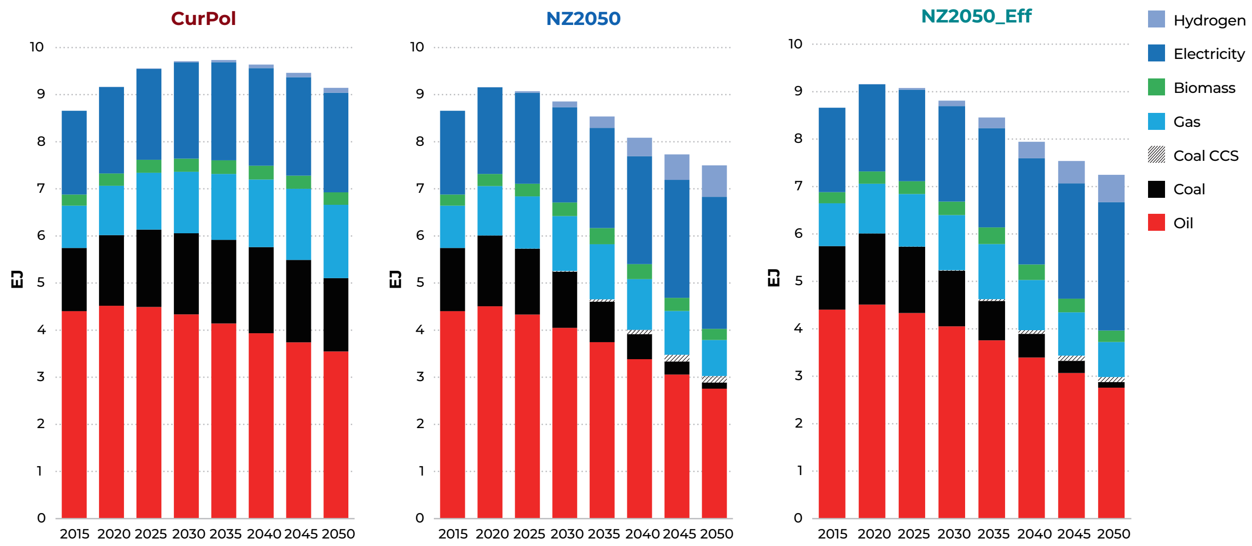
Figure 8. Hydrogen Production by Production Method



In GCAM-KAIST 2.0, hydrogen is sub-classified as grey hydrogen (hydrogen derived from natural gas, steam methane reforming (SMR) or hydrogen obtained as off-gas), blue hydrogen (grey hydrogen but with CCS), and green hydrogen (hydrogen acquired through water electrolysis by renewable electricity). The CurPol scenario predicts that about one million tons of hydrogen will be produced in 2050, most of it grey and the remainder green. In NZ2050, more than five million tons of hydrogen will be produced in 2050 in all three different types, with dominance shifting from grey to blue and then green in 2035. Finally, NZ2050_Eff predicts a similar trend to that of NZ2050 with one noticeable difference, where the volume of hydrogen production in 2050 is roughly 15 percent less than in NZ2050.

2.6 Final Energy Analysis Results

Figure 9. Final Energy Consumption by Energy Source



In CurPol, final energy consumption inches up until 2035, then begins to decline. It should reach about 95 percent of the 2020 level by 2050 thanks to ever-increasing energy efficiency (Figure 9). Under this status-quo scenario, however, no significant change is expected in overall energy consumption.

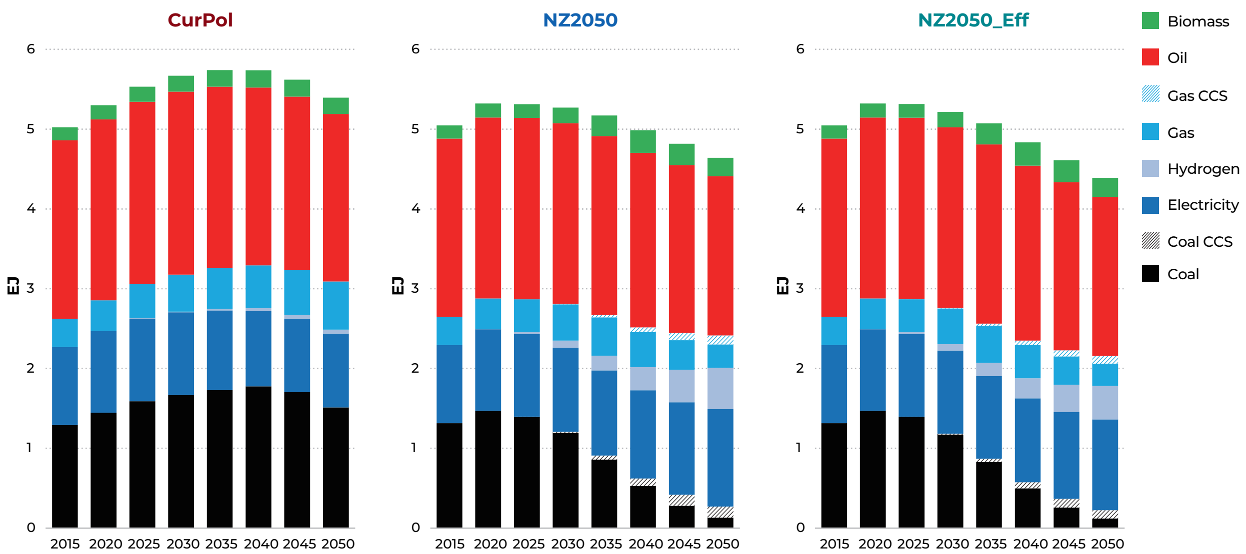
On the contrary, the NZ2050 and NZ2050_Eff scenarios envision steeper falls in final energy consumption starting in the mid-2020s, ending up at about 80 percent of the 2020 level in 2050 (Figure 9), thanks to higher energy efficiency and accelerating electrification in each economic sector.

Under the two net-zero scenarios, electricity will account for 40 percent of total final energy consumption by 2050. Consumption of coal and petroleum will steadily subside and represent about five percent and 40 percent of the total mix, respectively, by 2050, driving the decarbonization of the energy end-user sectors. The two net-zero scenarios by GCAM-KAIST 2.0 (NZ2050 and NZ2050_Eff) forecast hydrogen consumption to continue expanding, growing to represent approximately ten percent of total final energy consumption by 2050.

In particular, electrification of the energy end-user sectors accelerated by aggressive climate policies, combined with rapid decarbonization of the power sector, is expected to play an integral role in driving South Korea toward its NDC and mid- and long-term carbon neutrality targets. This understanding also implies that without decarbonization of the power sector, the country's endeavors to reduce GHG emissions would be less effective.

2.6.1 Industrial Sector Analysis Results

Figure 10. Industrial Energy Consumption by Energy Source

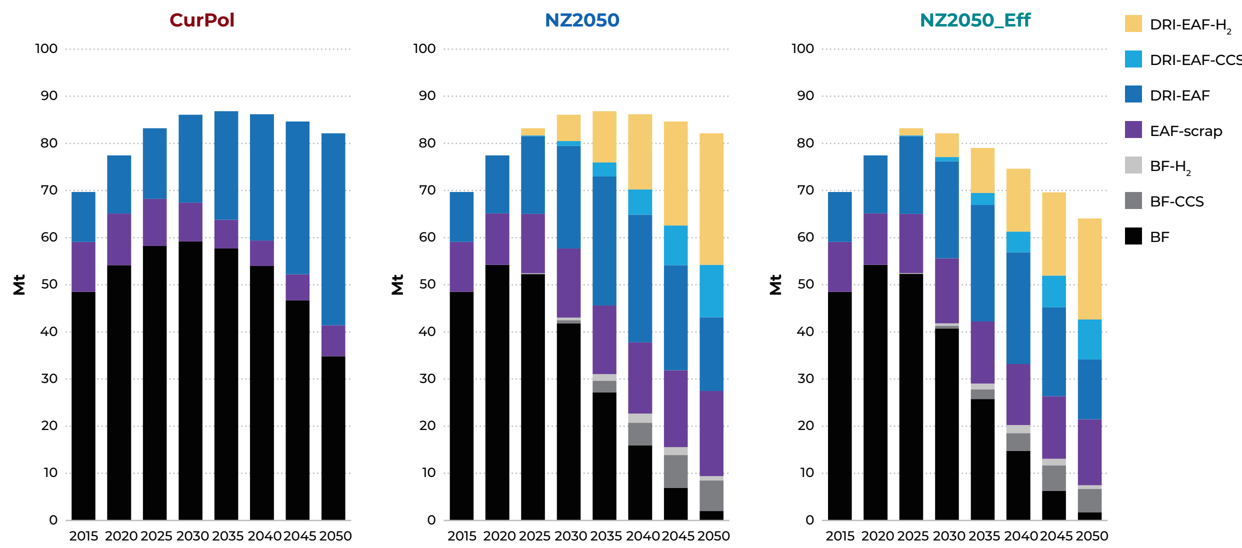


Final energy demand by the industrial sector, CurPol suggests, will rise until 2035 and then gradually decline owing to falling energy intensity in all economic activities and improved industrial equipment efficiency (Figure 10). In this scenario, hydrogen fuel consumption will more than double between 2020 and 2050, but its percentage in the entire mix will remain minuscule while the ratio of fossil fuels will stay nearly the same, resulting in insignificant GHG emissions reductions.

Under the NZ2050 scenario, on the other hand, industrial consumption of fossil fuels will plummet, and fuel will shift toward electric power and hydrogen at a rapid pace. Decarbonization happens at a slightly faster rate under the NZ2050_Eff scenario, which considers steel consumption efficiency. Both net-zero scenarios see coal being virtually phased out starting in 2030.

2.6.2 Steel Industry Analysis Results

Figure 11. Steel Production by Production Route

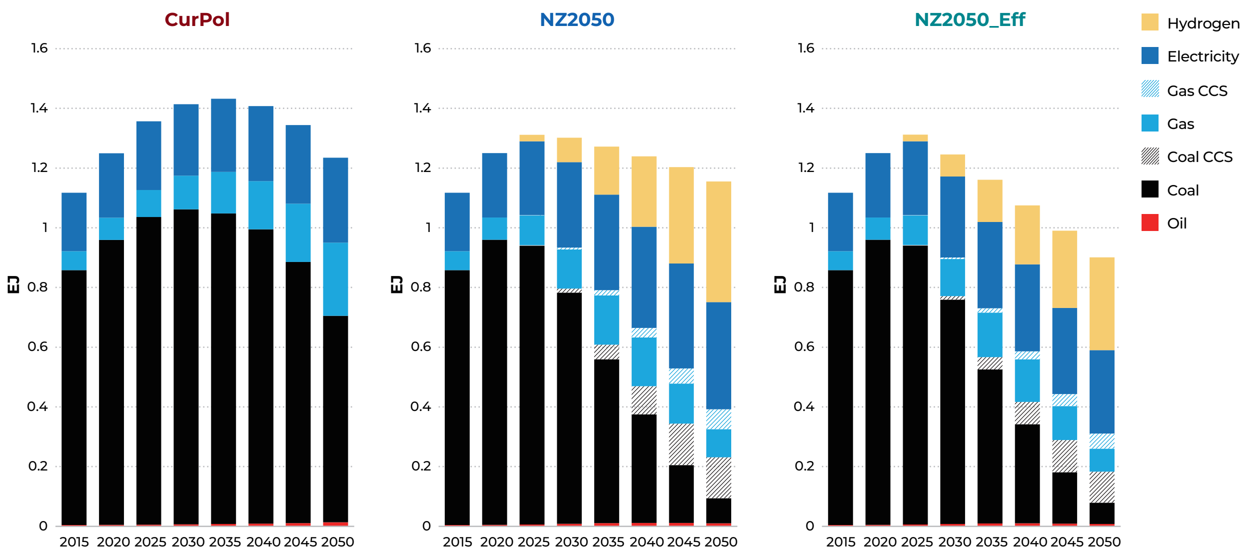


Scenario CurPol expects that steel production will increase until 2035 and then gradually decrease (Figure 11). Output by the blast furnace route (BF) will start to slowly decline in 2030 and reach about 65 percent of the 2020 level by 2050. This unambitious scenario predicts that output by the electric arc furnace route processing direct reduced iron (DRI-EAF) will more than triple between 2020 and 2050.

Under NZ2050, steel output by BF begins to decrease in 2025, five years earlier than under CurPol, and the slope gets increasingly steep, with output reaching 15 percent of the 2020 level by 2050. Around 70 percent of the meager BF output in 2050 is explained by the blast furnace route with a carbon capture and storage system (BF-CCS). Moreover, carbon pricing throughout the economy will aggressively push up the economic feasibility of the electric arc furnace route processing hydrogen-based direct reduced iron (DRI-EAF-H_2). As a result, DRI-EAF-H_2 will produce more than 30 percent of steel output in 2050 (see Appendix 4.1). On the other hand, in 2050, steel output by DRI-EAF will be 35 percent lower under NZ2050 than under CurPol, with nearly 41% of it produced by DRI-EAF-CCS. NZ2050 forecasts about three times the steel output by the electric arc furnace route processing steel scrap (EAF-scrap) in 2050 than the CurPol scenario.

As discussed earlier (see section 2.1), steel production in 2050 is 22 percent lower under scenario NZ2050_Eff (which considers both net zero-oriented climate policy and steel consumption efficiency) than under scenario NZ2050, but improvements in steel production efficiency are not expected to make a significant impact on the overall steelmaking route mix.

Figure 12. Energy Consumption by the Steel Industry by Energy Source



The CurPol scenario forecasts that total energy consumption by the steel industry will peak in 2035 and slide back down toward 2020 levels by 2050 (Figure 12). Under this scenario, the energy mix will not undergo major changes as the percentage of fossil fuels, as well as those of the other energy sources, will stay almost the same.

Under the NZ2050 scenario, however, total energy consumption by the steel industry will see a decrease of about 15 percent from 2020 by 2050, after culminating in 2025 (Figure 12). The decline is attributable to higher energy efficiency and electrification throughout the economy and the steel industry. Coal use will plummet by 80 percent from 2020 to 2050, and about 60 percent of coal consumption will involve CCS in 2050. Furthermore, consumption of environment-friendly energy sources will shoot up, with hydrogen and electricity accounting for 35 percent and 30 percent of the steel industry's total energy consumption in 2050, respectively.

The steel industry's total energy consumption will nosedive more rapidly under the NZ2050_Eff scenario to record a decline of about 30 percent from 2020 by 2050 (Figure 12). The decline is twice as big as that under NZ2050 (which does not consider the improvement of steel consumption efficiency). The energy mix will remain more or less the same, through both net zero scenarios.

3.0 Conclusion and Discussion

3.1 Ways of Decarbonizing the Steel Industry

This study developed GCAM-KAIST 2.0, an integrated analysis model for Korea, and thereby formulated several steel decarbonization scenarios for net zero 2050, exploring what each scenario would mean for the future. Through this analysis, the study derived the following takeaways and policy implications:

First, South Korea's attainment of its 2050 net-zero targets does not mean that the steel sector will be carbon-neutral.[2] In order to offset significant direct carbon dioxide emissions remaining in the steel sector, improvements in indirect emissions offset are needed.

Second, electrification of the steel sector and the increasing percentage of hydrogen in the energy consumption mix will play a key role in decarbonizing the industry. This implies that carbon neutrality requires mid- and long-term investments to augment renewable energy generation and green hydrogen production.

Third, decarbonizing the steel industry according to the country's 2050 carbon neutrality targets requires not only speedy penetration of the electric arc furnace route using hydrogen-based DRI (DRI-EAF-H_2) and the electric arc furnace route that processes DRI and is equipped with a CCS system (DRI-EAF-CCS). It also requires rapid elimination of BF without a CCS system, which will necessitate increasing units of EAF-scrap in order to meet the demand for steel.

Fourth, steel output reduction through higher steel consumption efficiency cannot make a significant dent in GHG emissions from the steel industry. However, improvement in steel consumption efficiency can still help reduce power generation and hydrogen production, which demonstrates the importance of taking into consideration steel consumption efficiency in planning investments in power generation and hydrogen production for the achievement of carbon neutrality targets.

Fifth, 2050 will see South Korea producing far more steel than other advanced countries (Figure 1), despite the remarkable differences in steel production between NZ2050_Eff (a scenario that

2 Consumption of coal and gas is expected to persist into 2050, emitting GHGs.

assumes a reduction of 22 percent in steel production in consideration of increasingly efficient steel consumption), CurPol, and NZ2050, noting that the two latter scenarios do not assume such reduction. This prediction reflects the conservative approach that this study took about the role of decarbonization of the steel industry in pulling down steel output.

3.2 Policy Recommendations

The decarbonization of the steel industry urgently calls, above all, on the South Korean government to incorporate in its climate policy goals the steel industry's GHG reduction targets that are aligned with the national 2050 carbon neutrality targets. Analysis using GCAM-KAIST 2.0 predicts that over 90 million tons CO_2eq of GHG emissions will come from steel by 2050 if the current policies are maintained (scenario CurPol), leaving the carbon neutrality targets unachieved. Setting clear GHG reduction targets for the steel industry aligned with the 2050 carbon neutrality goals, as well as investing in upgraded industry facilities, can effectively help achieve net zero by 2050 in a cost-efficient manner by encouraging reasonable investments in power generation and hydrogen production.

Net zero in steel requires reasonable GHG reduction targets and policies that encourage rapid decarbonization in power generation and hydrogen production. The upcoming tenth Power Supply Master Plan needs to consider suitable carbon neutrality targets and include an energy source mix plan aimed at facilitating electrification and renewable energy generation. In addition, renewable energy-powered green hydrogen production should be accelerated, and this effort should be backed by policy support and systematic infrastructure building. Even so, the need for a greater conversion in steelmaking routes and a conducive policy environment for the transformation remains.

Among others, R&D systems and support are required for the development and commercialization of DRI-EAF-H_2, DRI-EAF-CCS, and EAF-scrap technologies, and greater use of these routes by the steel industry. Demonstration projects for each of the forward-looking routes may be used to facilitate the adoption of new technology, and financial support for R&D may also be beneficial.

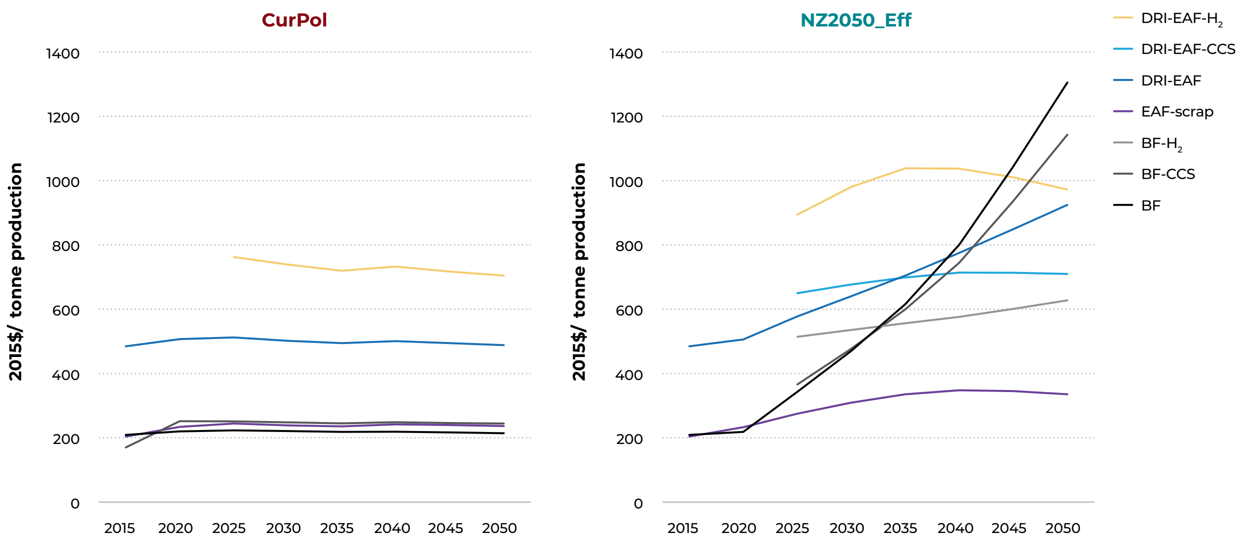
At the same time, total GHG emissions and emissions allowances should be set for the steel industry in alignment with the net-zero scenarios that this study presents.

Finally, policies are needed to encourage the improvement of the overall steel consumption efficiency and expansion of steel recycling throughout the economy. For instance, institutional support can help prolong of the lifespans of buildings, improve and optimize building designs, boost steel recycling, encourage the use of lighter building materials containing high-strength steel alloys, and encourage the improvement of steel production efficiency. Steelmakers, for their part, must facilitate closed-loop recycling in the industry. They can do so by setting targets for how much scrap should be used, how much steel should be produced using recycled steel, and what percentage of recycled steel should be contained in each steel product.

4.0 Appendix

4.1 Forecasts of Steel Production Costs by Technology

Figure 13. Cost Forecasts by Steel Production Route



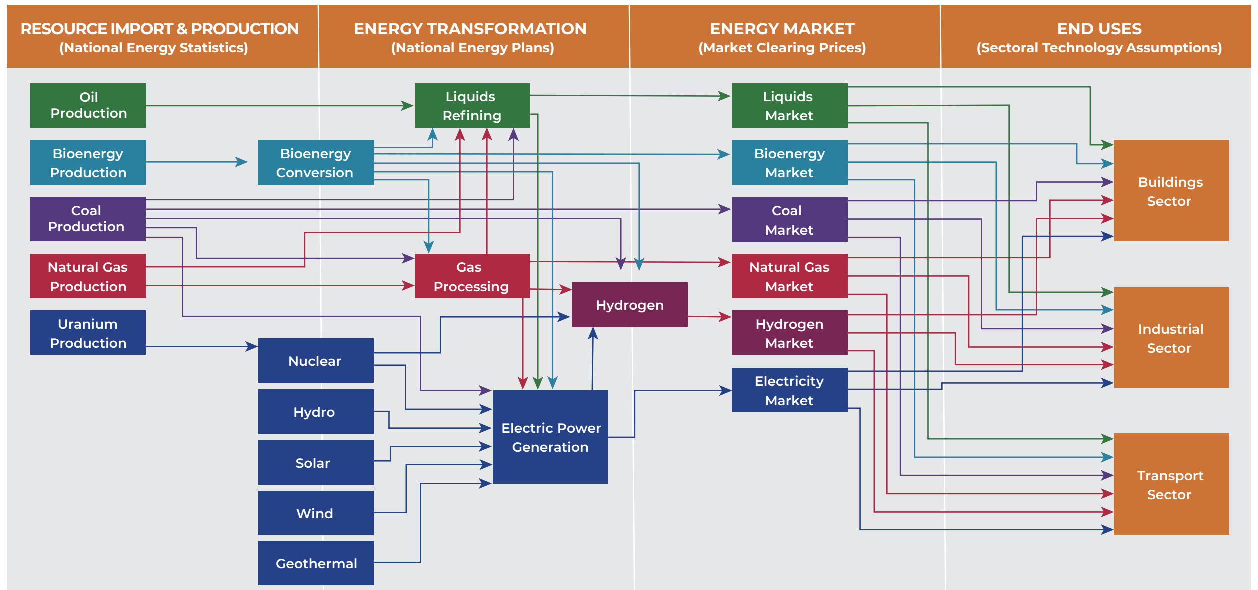
In the CurPol scenario (in which the current policies are maintained), the electric arc furnace route processing hydrogen-based direct reduced iron (DRI-EAF-H_2) cannot become economically feasible regardless of how much time passes. In contrast, in the two net-zero scenarios (NZ2050 and NZ2050_Eff), carbon pricing through the economy dramatically pushes up the unit steel production costs for the blast furnace route without a CCS system (BF) and the electric arc furnace (DRI-EAF). These net-zero scenarios predict that the unit steel production cost for DRI-EAF-H_2 will culminate in 2035 due to the use of grey hydrogen and then begin to slide gradually thanks to the increasing production of green hydrogen.

4.2 Global Change Analysis Model (GCAM)

The Global Change Analysis Model (GCAM) was developed primarily by the Joint Global Change Research Institute (JGCRI), which was launched by the Pacific Northwest National Laboratory (PNNL). The model is a representative energy-economy-environment model that has consistently been used by

major climate policy assessment studies and reports including IPCC reports. It is a partial equilibrium model *(Reference 15. Stanton et al. (2009))* and at the same time an integrated assessment model with high resolution *(Reference 13. Edmonds et al. (2012))*. In addition, being one of the five major models that were used for the development of Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs), the model is used by numerous researchers around the world.

GCAM is an analysis system that links macroeconomics and the energy system-land use-climate system and can be used to develop consistent scenarios offering a comprehensive assessment of the impact of energy and climate policies on energy and land systems from diverse perspectives. The GCAM energy system not only reflects competition between a range of fuels and technologies through the chains of primary energy production, energy transformation, and final energy consumption in individual regions but also reflects transactions in energy goods between regions. The model divides the world into 32 regions, and South Korea alone constitutes a single region.



This study built GCAM-KAIST 2.0 based on GCAM v.5.4 in consideration of South Korea's local policy and technology. With the base year set at 2015, simulations were conducted for every five years until 2100, and a logit choice model was used to represent competition between a range of technological solutions in individual technology service sectors including power supply, passenger and cargo transportation services, building air conditioning (heating and cooling) and other services for buildings, and the cement, fertilizer, and petrochemical industries. The future competitive landscape among technologies in each year was forecast in consideration of the ratio of each technology in the technology mix and its estimated cost and expected performance in that year. In the process, the unique characteristics of each region and each market were considered. All else being equal, the implementation of a carbon policy will help improve the economic feasibility of low-carbon technologies (which represent a small slice of the market), helping them chip away at the market share of carbon-intensive alternatives.

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