2050 Carbon-Neutrality Transition Scenario

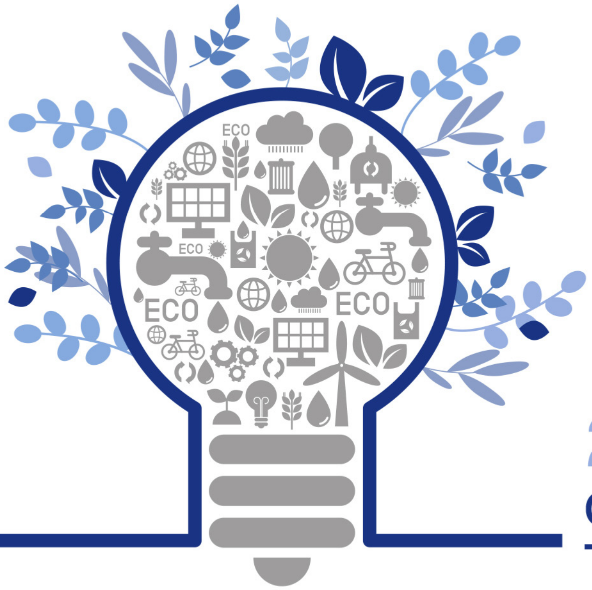
Analysis of a Korean Integrated Assessment Model

KAIST

SFO°C
Solutions for Our Climate

Supported by

This publication was produced with the financial support of the European Union's Partnership Instrument. Its contents are the sole responsibility of Solutions for Our Climate (SFOC) and do not necessarily reflect the views of the European Union.



2050 Carbon-Neutrality Transition Scenario

Analysis of a Korean Integrated Assessment Model

2050 Carbon-Neutrality Transition Scenario:
Analysis of a Korean Integrated Assessment Model

Date of Publication	May 2021
Authors	Jiyong Eom, Hanwoong Kim, Hanju Lee, Daeun Jung (KAIST), Haewon McJeon (University of Maryland), Joojin Kim, Kyungrak Kwon, Gahee Han, and Gyuri Cho (Solutions for Our Climate)
Design	INDNP Co., Ltd.
Contact	Researcher Gahee Han, Solutions for Our Climate, gahee.han@forourclimate.org

CONTENTS

Executive Summary 04

1. Introduction 06
1.1 South Korea's Nationally Determined Contribution (NDC) 06
1.2 Development of Climate Policies in Korea 06
1.3 Research Structure 08

2. Methodology and Results 09
2.1 Scenario Design and Development 09
2.2 Analysis of Korea's GHG Emissions 11
2.3 Primary Energy 15
2.4 Power Sector 17
2.5 End-Use Sector 19
2.5.1 Transport Sector 20
2.5.2 Building Sector 23
2.5.3 Industrial Sector 24
2.6 The Role of Direct Air Capture (DAC) 25

3. Conclusion and Implications 30
3.1 Directions for Achieving Carbon Neutrality 30
3.2 Policy Recommendations 31

4. Appendix 34
4.1 Korea's Socioeconomic Projections 34
4.2 Cost Outlook of Power Generation Technologies 35
4.2.1 Cost of Conventional Power Generation Technologies 35
4.2.2 Cost of Renewable Energy Power Generation Technologies 35
4.2.3 Cost of DAC 36
4.3 Cost Outlook of Technology Cost by Mode of Transport 36
4.3.1 Passenger Transport 36
4.3.2 Freight Transport 38
4.4 Flexible Resources 39
4.5 GCAM 40

5. References 42

2050 Carbon-Neutrality Transition Scenario:

Analysis of a Korean Integrated Assessment Model

Executive Summary

By signing the historic Paris Agreement in 2016, the international community agreed to commit itself to the goal of limiting global warming to below 2℃, and further to 1.5℃, compared to pre-industrial levels, to tackle climate change (UNFCCC, 2015). The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report urged the world to bring greenhouse gas (GHG) emissions down to net zero by 2050, and as of April 2021, a total of 120 countries have declared plans to achieve carbon neutrality by 2050.

The Korean government also submitted its Nationally Determined Contribution (NDC) (Ministry of Environment, 2020a) and Long-Term Low Greenhouse Gas Emission Development Strategies (LEDS) (Ministry of Environment, 2020b) to the United Nations Framework Convention on Climate Change (UNFCCC) secretariat on December 31, 2020. The Korean government further unveiled its vision for going carbon neutral to the world, announcing its "goal to achieve carbon neutrality by 2050 by combating climate change proactively with the international community"(Government of the Republic of Korea, 2020).

At a critical juncture 10 years before the NDC target year and 30 years before the target carbon neutrality year, this report examines Korea's present climate policies, projects GHG emissions, and assesses the scenarios of transitioning to carbon neutrality. Three scenarios were developed: (1) a current policy scenario which is based on government policies (the 3rd Energy Master Plan and the 9th Basic Plan for Electricity Supply and Demand) announced up to this point, (2) a scenario under which the current 2030 NDC target is achieved as set by the Korean government, and (3) a NZ2050 scenario that pursues broader socioeconomic efforts to reach net "zero" GHG emissions. This report compares and analyzes each sector's GHG reduction efforts based on the three scenarios.

2050 Carbon–Neutrality Transition Scenario

Analysis of a Korean Integrated Assessment Model

The assessment of the energy–economy–environment scenarios using a Korean Integrated Assessment Model, GCAM–KAIST1.0, found three important implications for Korea's transition to carbon neutrality.

First, electrification of the end–use demand sector linked to the decarbonization of the power sector is expected to play a significant role in Korea's attaining not only the carbon neutrality goal but also its NDC target. In particular, an early exit from coal–fired power generation and broader use of renewable energy drive down the carbon intensity of the power sector quickly, which, coupled with penetration of electric vehicles (EVs) in the transport sector and increased use of power by the industrial and building sectors, will help reduce GHG emissions dramatically in the overall economy.

Second, negative emission technologies (NETs) can be considered to offset GHG emissions that persist despite efforts to accomplish carbon neutrality. Despite the sufficient rise in carbon prices in 2050, some GHG emissions are still inevitable in each sector of the economy. To offset them, adopting and expanding NETs, bioenergy with carbon capture and storage (BECSS), land use, land–use change, and forestry (LULUCF), and direct air capture (DAC), can be considered.

Third, current climate policies now in force in Korea have been found to be insufficient to achieve not only a transition to carbon neutrality but also the current 2030 NDC target. If the country is to attain its carbon neutrality goal in the long term and its NDC target in the short term, more aggressive and extensive government policy measures are required.

1. Introduction

1.1 South Korea's Nationally Determined Contribution (NDC)

In 2015, Korea submitted its NDC, and in 2018 presented a revised roadmap to achieving the national GHG reduction target (Ministry of Environment, 2018). Additionally, in October last year, the country further announced plans to achieve carbon neutrality by 2050. Korea's current NDC target is to reduce its total GHG emissions by 24.4% below 2017 levels (709.1 MtCO2e; LULUCF excluded) by 2030, but the dominant view is that this target is incompatible with the 2050 carbon neutrality goal. Hence, the country plans to resubmit to the UN a more ambitious 2030 NDC, reflecting the determination to realize carbon neutrality by 2050 (Government of the Republic of Korea, 2021)

1.2 Development of Climate Policies in Korea

GHG emissions generated by energy use represent 87% of Korea's GHG emissions in 2017. Therefore, if the country is to achieve its NDC target, it is essential to reduce GHG emissions in the energy sector to a meaningful level. The Korean government introduced policies to accomplish GHG reductions and target demand by sector based on the 3rd Basic Energy Plan (Ministry of Trade, Industry and Energy (MOTIE), 2019). In the construction (7%) and industrial (37%) sectors (Ministry of Environment, 2020b), the 2nd Basic Plan for Green Buildings (Ministry of Land, Infrastructure and Transport (MOLIT), 2019) and the energy labeling program (Korea Energy Agency, 2015) were set forth, and in the transport sector (14%) (Ministry of Environment, 2020b), the 4th Eco-friendly Vehicle Basic Plan (MOTIE, 2021) and the Vehicle Average Fuel Economy and GHG Emissions Management Program (Ministry of Environment, 2020c). In the energy supply sector (36%) (Ministry of Environment, 2020b), the 9th Basic Plan for Electricity Supply and Demand (MOTIE, 2020a) and the 5th Renewable Energy Basic Plan (MOTIE, 2020b) were established.

The power sector, which represents 36% of the country's total GHG emissions (Ministry of Environment, 2020b), is particularly important. The incumbent government established the 9th Basic Plan for Electricity Supply and Demand, which by 2034 would close 30 (15.3 GW) of 60 coal power units and reduce nuclear power generation from 23.3 GW in 2020 to 19.4 GW. Meanwhile, by 2034, the Plan would secure 58.1 GW from gas power generation, including through the conversion of 24 coal power units, and significantly increase the installed capacity of new and renewable energy from 20.1 GW in 2020 to 77.8 GW in 2034.

The end-use energy sector, which makes up 58% of Korea's total GHG emissions as of 2017 (Ministry of Environment, 2020b), will be critical in achieving carbon neutrality by 2050. The Korean government's 3rd Basic Energy Plan aims to reduce final energy consumption by 18.6% from the base demand forecast by 2040 through reform of energy consumption structures. The Plan suggests that the building sector reduces consumption by 5.2% compared to base demand by disseminating high-efficiency equipment, improving energy efficiency in buildings, and implementing the Energy Efficiency Resource Standard (EERS). The Plan also seeks to reduce consumption in the industrial sector by 8.1% from base demand through the Korean Emissions Trading System, the GHG and Energy Target Management System, and support for enhancing the efficiency of small- and medium-sized enterprises. In the transport sector, the Plan aims to reduce consumption from base demand by 5.3% through advanced fuel efficiency and diffusion of electric and hydrogen vehicles.

For Korea to achieve not only its existing NDC target but also its 2050 carbon neutrality goal, a close examination on whether the government's climate policies are sufficient, and, if not, what additional efforts are needed in respect to the general economy, is imperative. While experts in academia, industry, and civil society are suggesting sectoral GHG reduction policies to achieve carbon neutrality, Korea has yet to see a consistent scenario assessment study based on an integrated assessment model (IAM) connected to all economic activities and consequential emissions in Korea. This report develops GHG emissions scenarios with internal consistency using a Korean IAM, GCAM-KAIST1.0, evaluates changes required of each sector to reach national emissions targets, and presents relevant implications.

1.3 Research Structure

To assess Korea's 2050 carbon neutrality policy, we analyzed mid-to long-term changes required of the energy sector, which will play a decisive role in reducing GHG emissions. To attain internal consistency and explanatory power of the GHG emissions scenarios, the study used an IAM. Specifically, taking advantage of Global Change Assessment Model (GCAM) that has continuously been used in IPCC reports, the research team developed GCAM-KAIST1.0, a model reflecting domestic energy system and policy status, and employed it for analysis. In the following, this report will (1) explain the assumptions applied to the four scenarios (CurPol, NDC, NZ2050, NZ2050_NoDAC scenarios) developed for assessment; (2) identify reduction pathways compatible with the GHG reduction target by scenario and assess reduction burden on each economic sector; (3) analyze the amount of reduction identified through analysis and the following energy system transition, first discussing the change in the energy mix of the electric power sector which plays a core role in decarbonization, then the transition in the end-use energy sector (industrial, building and transport); and (4) discuss the feasibility of the NDC target, the direction of the carbon-neutral transition, and policy alternatives based on the scenario analysis results.

2. Methodology and Results

2050
Carbon–Neutrality
Transition Scenario
Analysis of a Korean Integrated Assessment Model

2.1 Scenario Design and Development

This study foresees Korea's GHG emissions and evaluates the requirements to achieve its NDC in the short term and carbon neutrality in the long term from a techno–economic perspective. To this end, this report developed three scenarios, "Current Policy (CurPol)" "current NDC (NDC)" and "Net–zero 2050 (NZ2050)" and an additional "Net Zero 2050 without DAC (NZ2050_NoDAC)" scenario for additional sensitivity analysis. Their assumptions are as follows:

1. CurPol: This scenario reflects the energy and climate policies currently in force or confirmed to go into effect. For a mid–to long–term energy mix forecast of the power sector, the power generation facilities plan and generation outlook by 2034 specified in the 9th Basic Plan for Electricity Supply and Demand and the 5th Renewable Energy Basic Plan were reflected; for the forecast of mid–to long–term energy demand and energy demand prospect by sector, the target demand of the end–use energy sector (building, industrial and transport) specified in the 3rd Basic Energy Plan; for the forecast of diffusion of eco–friendly technologies in the transport sector, the 4th Eco–friendly Vehicle Basic Plan; and for the forecast of GHG emissions of passenger cars and trucks, management goals under the Vehicle Average Fuel Economy and GHG Emissions Management Program. Furthermore, the gross domestic product (GDP) and population outlook figures are from the Korea Institute for Industrial Economics & Trade (KEIT) and Statistics Korea while the capital expenditures (CAPEX) by power generation source are projections from Bloomberg New Energy Finance (BNEF) and National Renewable Energy Laboratory (NREL).

2. NDC: According to this policy scenario, Korea would achieve its nationally determined contribution (NDC) submitted to the UN on condition of the government's energy policy in the "current policy" scenario. In this scenario, Korea would achieve its 2030 NDC target (24.4% reduction from 2017 emission levels; the final version submitted in December 2020) through additional GHG reduction efforts in each sector of the economy and make the same level of efforts thereafter. In the model, this scenario achieves the 2030 NDC by imposing a carbon price to the "current policy" scenario and raises the carbon price at the rate of economic growth until 2050. Eventually, this scenario presumes continued cost-effective GHG reduction efforts that unify marginal abatement cost (MAC) of each sector of the economy through the imposition of a carbon price.

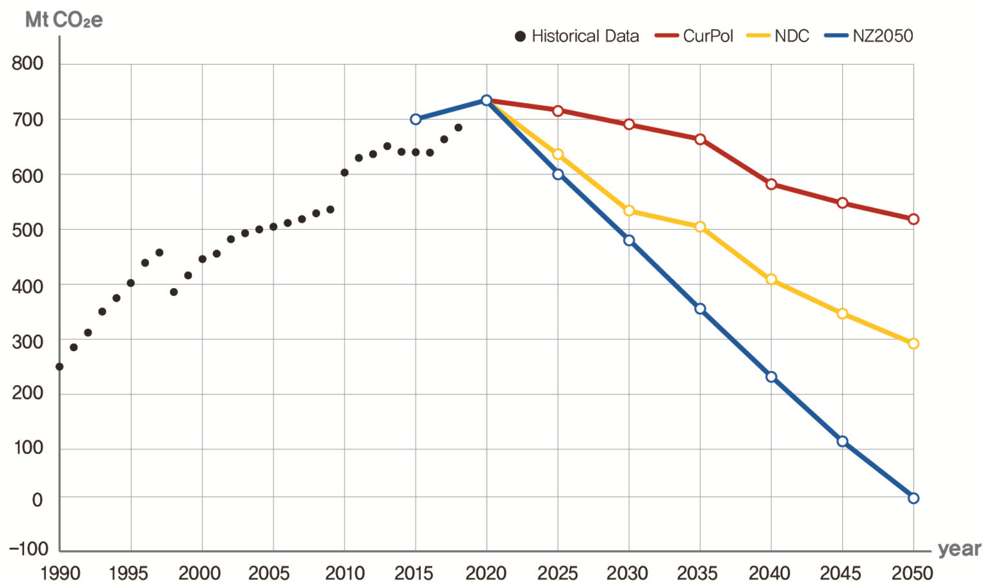
3. NZ2050: This scenario assumes the government's energy policy under the "current policy" scenario and that net-zero GHG emissions are achieved by 2050 by curtailing Korea's annual GHG emissions at a steady rate from 2025. In the model, by further imposing a carbon price to the "current policy" scenario, this scenario satisfies GHG emission limitations that linearly decline from 2025 through 2050. Eventually, this scenario presumes continued cost-effective GHG reduction efforts that unify MAC of each sector of the economy through the imposition of a carbon price.

4. NZ2050_NoDAC: While following the assumptions of the "NZ2050 scenario," this scenario cannot use DAC as it has not become economically feasible.

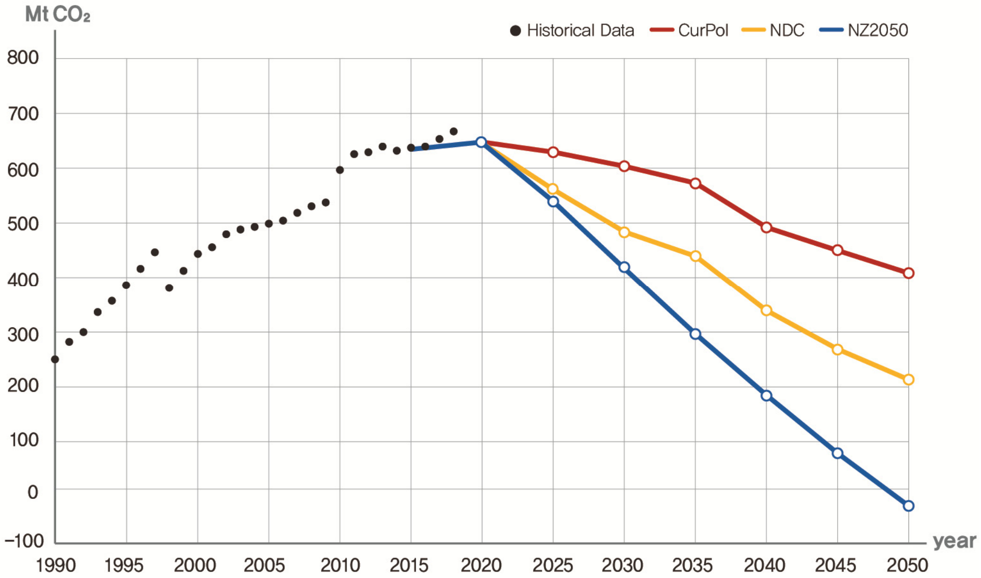
However, the emissions level in 2030 in the above NZ2050 scenario is different from the 2030 NDC target to achieve the IPCC's 1.5℃ goal. This should be understood to have been set for the convenience of analyzing the model. For reference, Climate Analytics (Climate Analytics, 2020) suggests Korea's 2030 GHG emissions level should be limited to between 290~400 million metric tons of CO2 equivalent (MtCO2e) at most to achieve the IPCC's 1.5℃ goal.

To develop quantitative scenarios with internal consistency and explainability, this study developed GCAM-KAIST1.0, a Korean model based on GCAM of Pacific Northwest National Laboratory (PNNL) in the United States. GCAM is a representative IAM that has continuously been used in IPCC reports. This assessment system describes the process of climate change caused by the GHG emissions of each country's activities of representative economic sectors; it describes the entire process with production and consumption of goods, market equilibrium through price, and inter-technology competition based on economic feasibility and fuel substitution. A brief explanation of GCAM can be found in the appendix (See Appendix 4.5). Hereinafter, this report will compare and assess Korea's total GHG emissions, primary energy, power sector, end-use energy, and energy consumption of each sector based on the above scenarios.

2.2 Analysis of Korea's GHG Emissions



〈Figure 1: Korea's GHG emissions pathway by scenario.〉



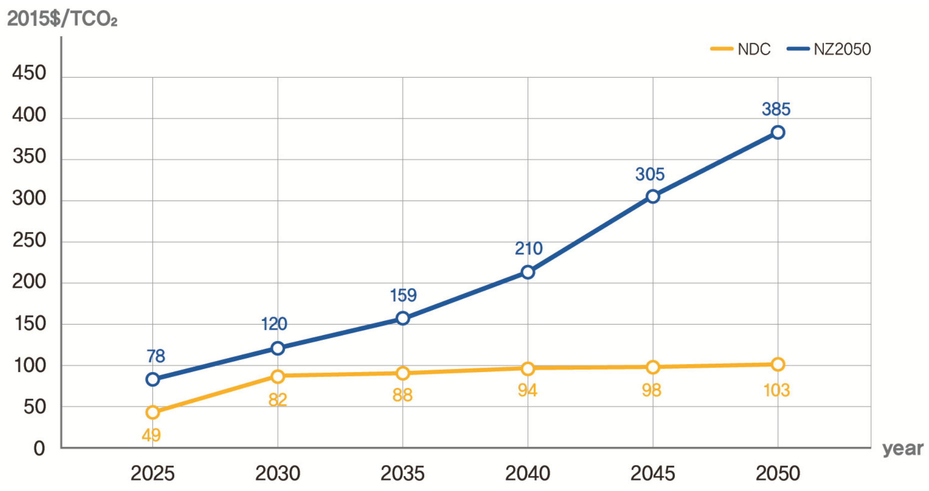
〈Figure 2: Korea's CO2 emissions by scenario.〉

The analysis of GCAM-KAIST1.0 found that if current policies continue, GHG emissions will decrease by about 30% between 2020 and 2050, and if the NDC remains as is, emissions will decline by roughly 60% by 2050, making the country unable to achieve carbon neutrality (Figures 1 and 2). In conclusion, both the CurPol scenario and the NDC scenario are quite far from reaching the 2050 carbon neutrality goal.[1)]

The above analysis of GHG and CO2 emissions by scenario leads to the following three conclusions: First, in order to achieve the NDC target as well as carbon neutrality, much more ambitious and extensive GHG reduction measures than currently in place must be prepared. To this end, it is worth considering actively expanding carbon price policies such as emissions trading schemes and carbon taxes. Second, emission levels expected in 2030, the target year of the NDC, already show a meaningful difference under the NDC scenario and the carbon-neutral scenario. If the country's effort to achieve carbon neutrality is evenly distributed over time, emissions in 2030 would be at 481 MtCO2e, which the current NDC target exceeds at 536 MtCO2e (excluding reductions abroad). Furthermore, the NDC target emissions are significantly different from the aforementioned GHG emissions level

1) The slight difference between GHG emissions in Figure 2 in past emissions largely results from the Global Warming Potential (GWP) value applied to methane gas (CH4). While Korea uses the GWP (21) for methane in the IPCC's Second Assessment Report, GCAM-KAIST1.0 uses the GWP (25) in the IPCC's Fourth Assessment Report.

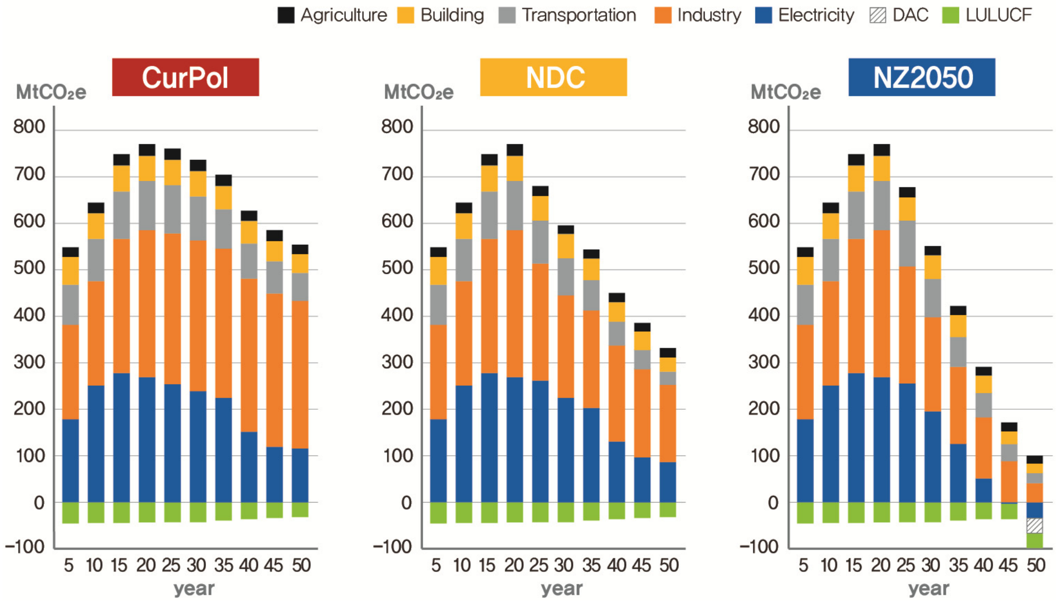
range of 290~400 MtCO2e suggested by Climate Analytics for achieving the 1.5℃ IPCC target (Climate Analytics, 2020). This indicates that the current NDC target emissions are short of making immediate and reasonable efforts to reach carbon neutrality, giving legitimacy to the Korean government's ongoing discussion on raising the NDC target. Third, if Korea is to become carbon neutral by 2050, it must achieve net-negative CO2 emissions domestically to offset non-CO2 emissions, which requires consideration of adopting NETs.



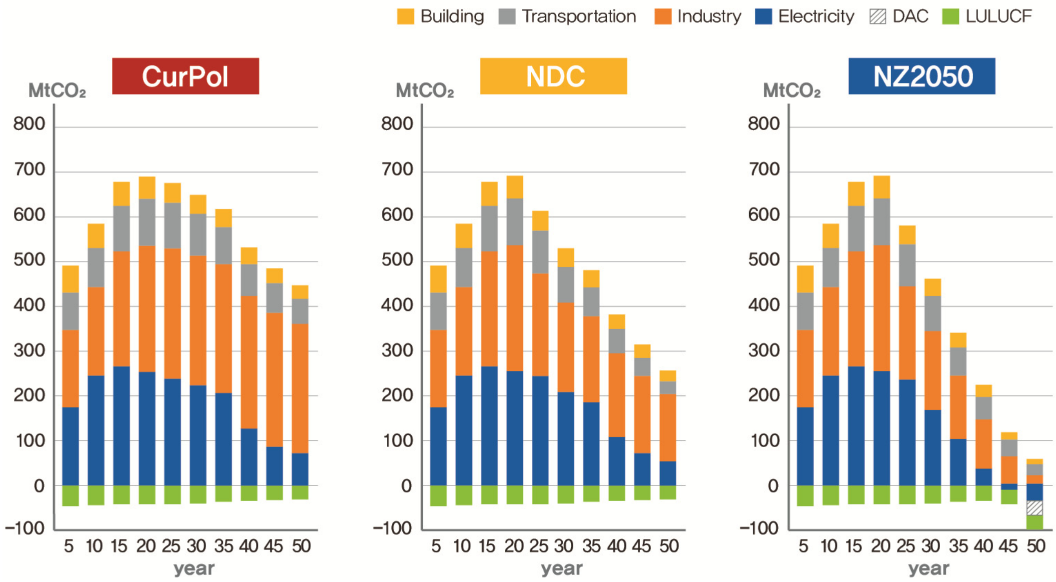
〈Figure 3: Carbon price needed for policy implementation.〉

Reduction efforts required of the economy in general to curtail GHG emissions can be evaluated with a carbon price. The carbon price when the current NDC is maintained and the carbon price required for the transition to carbon neutrality were found to be markedly different (Figure 3). The carbon price required for transition to carbon neutrality is forecast to rise roughly two to three times faster than the carbon price increase rate under the NDC scenario.[2)]

2) This report's "current policy" scenario was created by reflecting the government's energy technology dissemination plan exogenously. Thus, the carbon price in the figure can be deemed as the additional price required to achieve the NDC target and carbon neutrality on the premise that the current policy continues.



〈Figure 4: GHG emissions by sector.〉

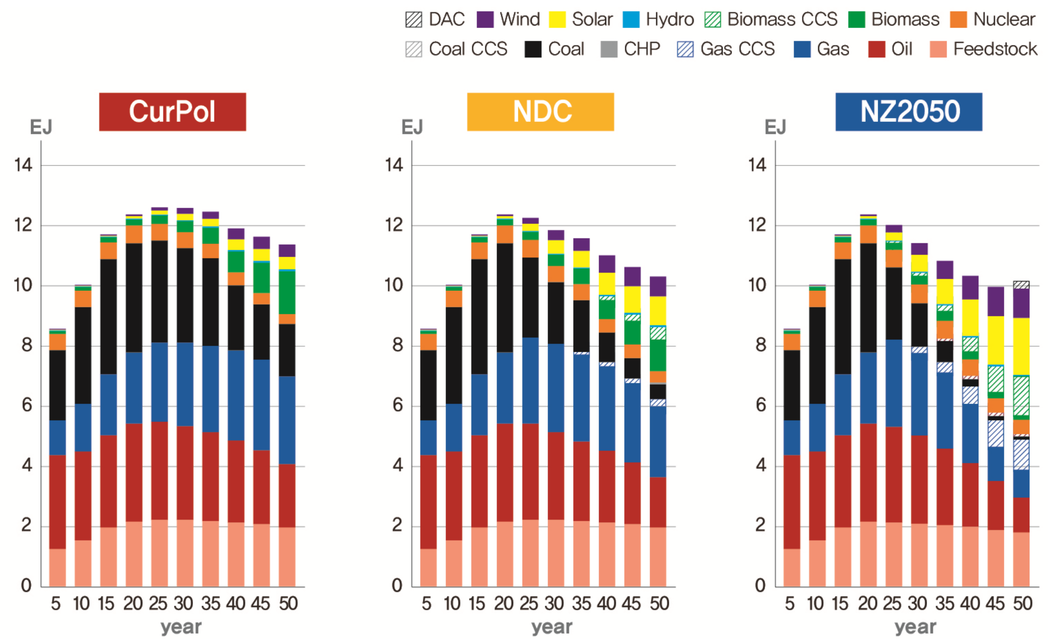


〈Figure 5: CO2 emissions by sector.〉

Korea's power, industrial, and transport sectors are expected to play a pivotal role in terms of GHG emissions and their reduction potential (Figures 4 and 5). Meanwhile, the building and agricultural sectors' contributions to GHG emissions and reduction potential are only minor.

If current policies continue, Korea's national GHG emissions are expected to peak in 2020 before declining slowly. Generally, all industries' share of GHG emissions would remain similar with exception to a decrease in GHG emissions from the power sector being offset by an increase in emissions from the industrial sector. In contrast, if the current NDC continues or carbon neutrality is pursued, a drastic GHG emissions reduction in the power, industrial, and transport sectors is predicted. Particularly, compared to the scenario of achieving the 2030 NDC target, which is considered insufficient itself, the CurPol scenario is markedly lacking. Considering these, a more radical decarbonization policy is needed to reach carbon neutrality. Also, under the NZ2050 scenario, some GHG emissions will still occur in 2050. To offset these emissions, it is necessary to consider adopting NETs such as LULUCF, BECSS and DAC.

2.3 Primary Energy



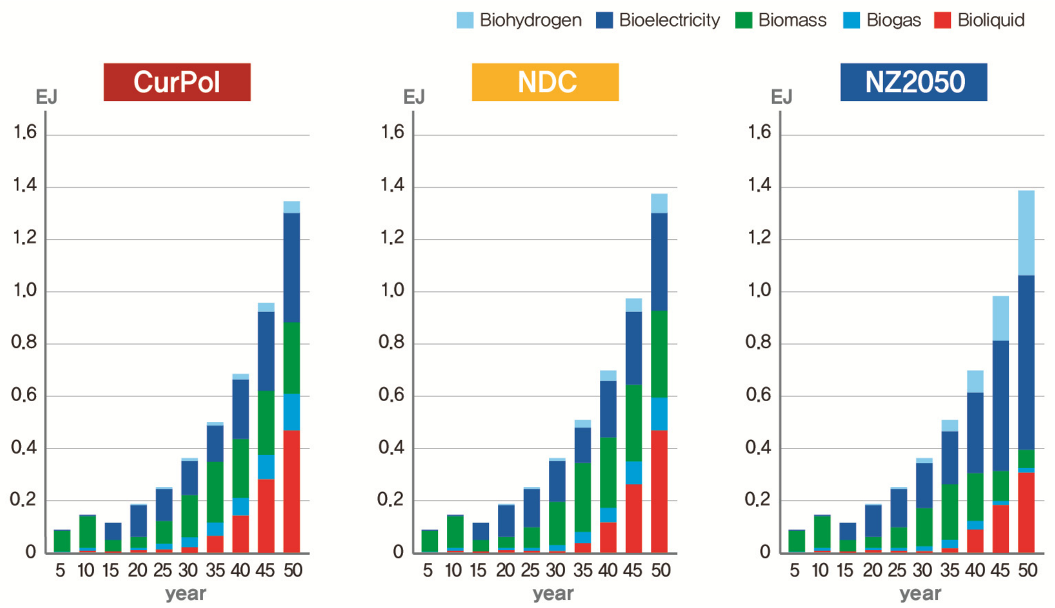
〈Figure 6: Primary energy consumption by energy source.〉

If the current policy stance is maintained, primary energy consumption would peak around 2030 before gradually diminishing (Figure 6). However, if a climate policy compatible with the NDC or carbon neutrality is put in place, the effect of a rising carbon price would be reflected in energy prices, bringing forward the time when primary energy consumption starts to decrease by about 5 years.

The composition of energy sources indicates that if the existing policy stance holds, although coal and oil consumption gradually would shrink, natural gas consumption would keep growing, leaving the share of fossil fuels in primary energy mostly unchanged (Figure 6). However, solar photovoltaics (PV), wind, and bioenergy consumption will increase in the time frame between 2020 and 2050 approximately five-, nine- and eight-fold, respectively.

Under NDC and NZ2050 scenarios, in the primary energy supply, fossil fuel consumption will dramatically drop to almost half of the level of 2020 by 2050 while solar PV, wind, and bioenergy will rapidly increase 10, 15, and seven times, respectively (Figure 6). This decarbonization trend of the energy system will be more noticeable in the NZ2050 scenario than in the NDC scenario. Specifically, in the NZ2050 scenario, after 2040, the share of natural gas and bioenergy to which carbon capture technologies do not apply would plummet.

Additionally, in the NZ2050 scenario, with the operation of DAC, of which a full-fledged adoption is expected in 2050, gas consumption will slightly rise (Figure 6).

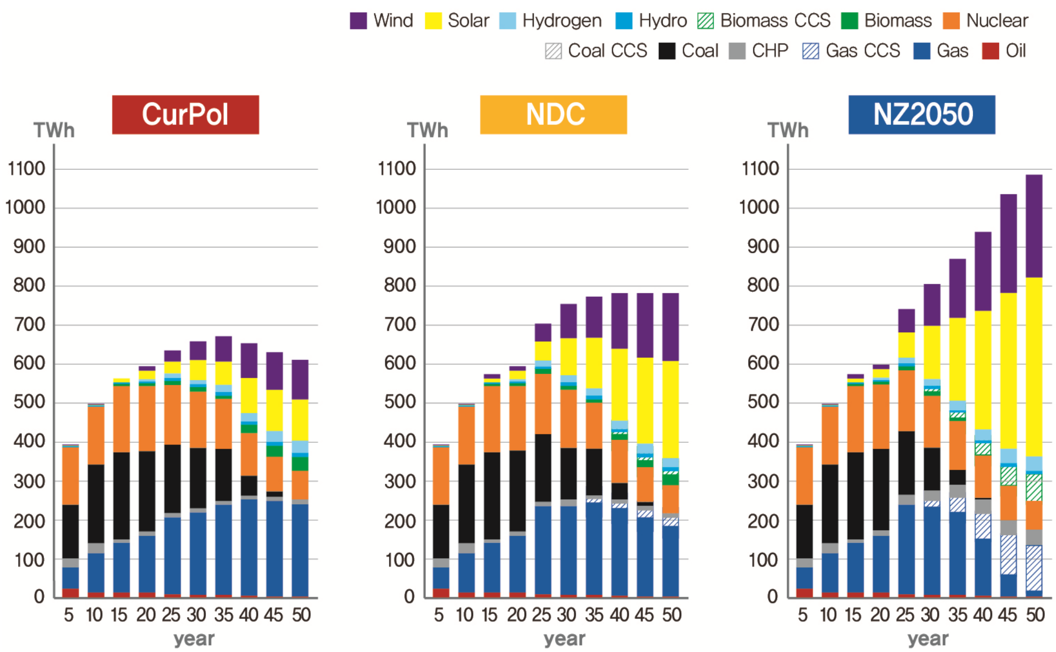


〈Figure 7: Bioenergy consumption by sector.〉

Given the limitations in raw material supply, bioenergy's share of primary energy is not expected to be large. Still, bioenergy can be converted into hydrogen, electricity, gas, and various other forms, and is expected to make some contribution to the decarbonization of the overall energy system (Figure 7). Also, in the NZ2050 scenario, the carbon price rises more sharply, prompting the shares of electric power and hydrogen sectors to grow larger than that of the transport sector.

However, it is important to note that, in accordance with IPCC guidelines, emissions from the combustion of biomass are not included in the calculation of the total emissions of the country, considering emissions from the forestry sector (LULUCF).

2.4 Power Sector



〈Figure 8: Power generation by energy source.〉

As the energy mix of the power sector reflects the power plant supply plan under the 9th Basic Plan for Electricity Supply and Demand, the shrinking share of coal power generation is noticeable (Figure 8). However, the rate at which the energy mix changes varies across different scenarios.

First, even in the CurPol scenario, the energy mix will witness a considerable change with the emissions from the power sector more than halving over the next 3 decades. If power generation facilities consistent with the 9th Basic Plan for Electricity Supply and Demand are in place, by 2035, the share of coal power generation will drop by 35% from 2020, renewables will grow by 250%, while the share of gas power generation will increase by 150%.

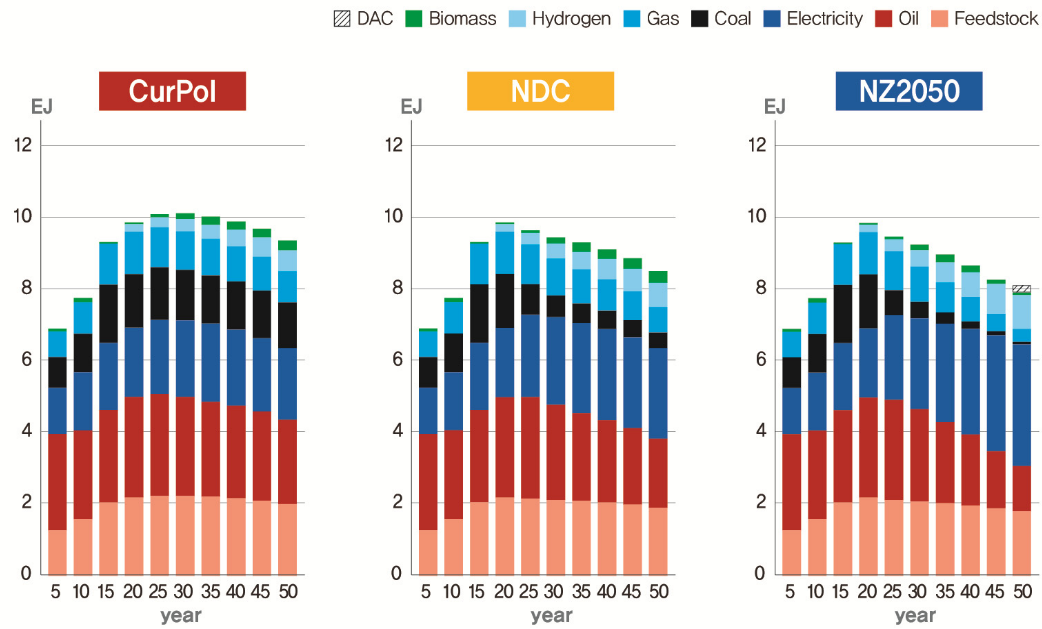
Second, if a climate policy compatible with Korea's NDC or carbon neutrality goal is implemented in earnest, coal power generation would be driven out faster, while renewable energy generation including solar PV, wind, and bioenergy would expand more substantially than under the CurPol scenario; similarly, the degree of the change would be far greater in the carbon neutrality scenario (Figure 8). In the NDC scenario, coal power generation will shrink by roughly 35% from 2020 in 2030, by more than 95% in 2045, and be completely phased out. Renewables will grow about five times the level of 2020 in 2030, and about 13 times in 2050. Under the NZ2050 scenario, by 2030, the share of coal power generation is expected to decrease, accounting for as little as 10% of the total power generation and be effectively driven out of the power market. Renewables will increase roughly seven-fold between 2020 and 2030, and some 20-fold in 2050. Accordingly, domestic power generation is forecast to grow by 30% and 80% from the present level by 2050 under the NDC and NZ2050 scenarios, respectively.

Third, decarbonization of the power sector resulting from the implementation of a climate policy greatly contributes to the curtailment of GHG emissions. Compared to the CurPol scenario, in the NDC scenario, GHG emissions from the power sector will diminish by 18% in 2030 and 68% in 2050. Likewise, compared to the CurPol scenario, in the NZ2050 scenario, GHG emissions from the power sector will drop by 31% in 2030, and 91% in 2050.

Fourth, in the course of decarbonizing the power sector, two options can be considered. One is carbon capture and storage (CCS). CCS will be adopted mainly for gas power generation starting from 2030, and its share will rise thereafter. Particularly under the NZ2050 scenario, with bioenergy generation and BECCS applied, from 2045, net-negative emissions in the power sector is expected to be possible. As a result, the cumulative CO2 capture amount of the power sector is forecast to reach 150 MtCO2e under the NDC scenario and 880 MtCO2e under the NZ2050 scenario by 2050.

Another issue that requires attention as the power sector is decarbonized is the adoption of flexible resources that can supplement the power output fluctuation of renewables. As renewables rapidly expand in the future, so will the investment in flexible resources for system stabilization. Compared to the CurPol scenario, in the NDC and carbon- neutral scenarios, flexible resource power generation is expected to increase by 150% and 250%, respectively, between 2020 and 2050 (See Appendix 4.5).

2.5 End-Use Sector



〈Figure 9: Final energy consumption by energy source.〉

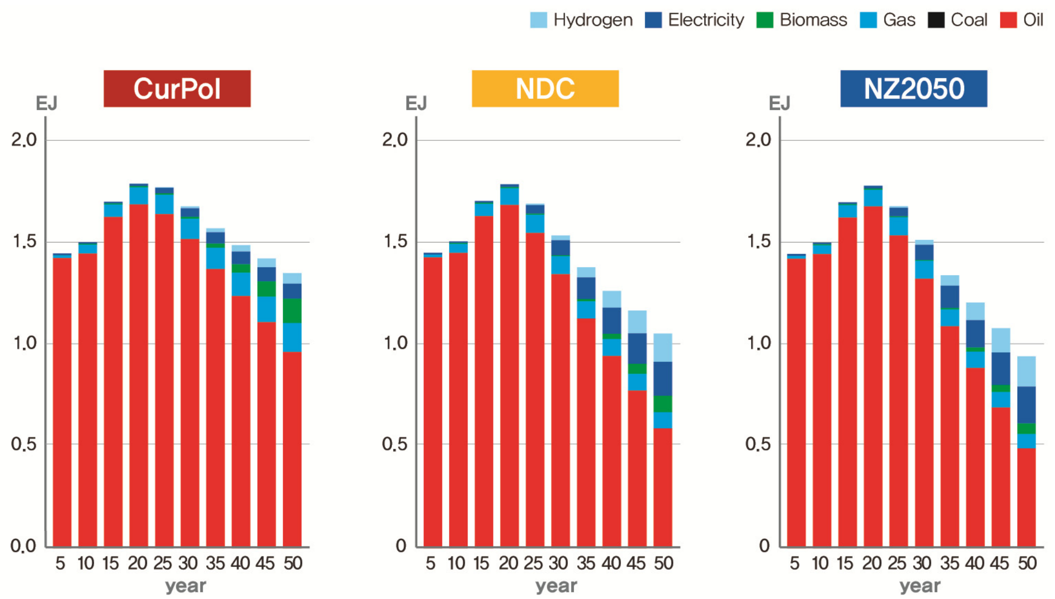
In the CurPol scenario, end-use energy consumption will show a steady growth until 2030 before it drops by roughly 5% from the level of 2020 in 2050 as energy efficiency continuously improves across the economy in general (Figure 9). Yet, the share of each energy source is forecast to remain mostly unchanged.

Meanwhile, if a climate policy compatible with the NDC or carbon neutrality is implemented, final energy consumption would start to decline from the mid-2020s with about 14% reduction from 2020 levels; from then on, the decline would accelerate, and by 2050, final energy consumption would be reduced by 20% from the level of 2020 (Figure 9). This stems from accelerated electrification in combination with improved energy efficiency in each sector of the economy. Particularly, electrification would take place even faster if the carbon-neutrality policy is pursued.

The share of electricity in final energy in 2050 is around 30% under the NDC scenario and reaches 40% under the NZ2050 scenario. At the same time, coal and oil consumption will continuously decrease. Under the NDC scenario, coal will drop by roughly 35% in 2050 compared to the level of 2020, and oil about 75%. Curtailment of coal and oil consumption will take place even faster under the NZ2050 scenario, dwindling by approximately 5% and 40%, respectively, by 2050, driving decarbonization of the end-use energy sector. The rate of dissemination of hydrogen, a new technology, increases as climate policy intensifies. Therefore, if carbon neutrality is sought after, hydrogen consumption is predicted to rise to the current level of gas consumption by 2050.

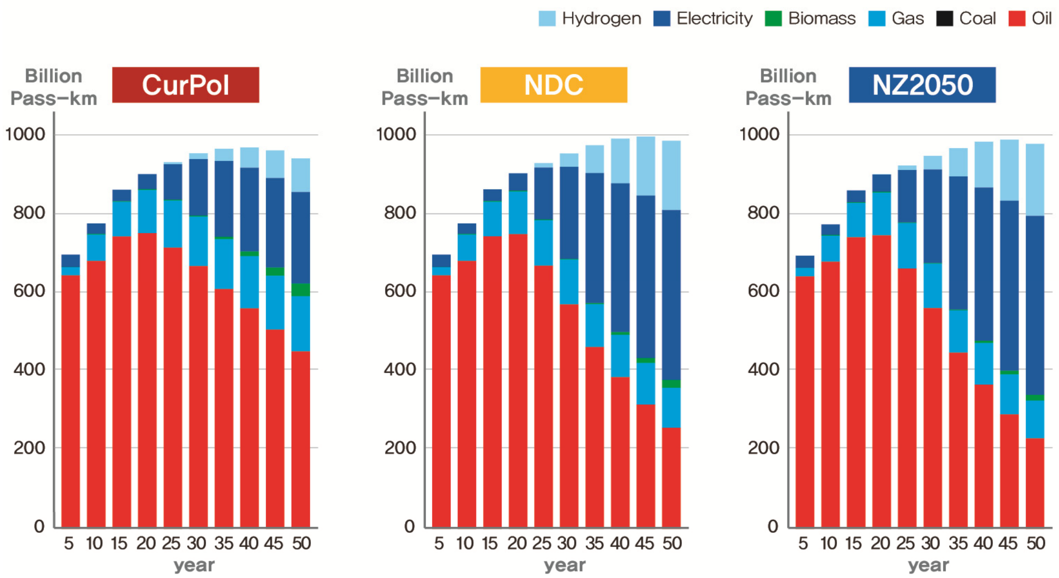
Above all, in combination with the aforementioned fast decrease of the power sector's emission intensity (decarbonization), swift electrification of the end-use energy demand sector driven by the implementation of a proactive climate policy is expected to play a crucial role in achieving not only Korea's NDC target but also the country's long-term carbon neutrality goal. However, this implies that if the electrification of end-use demand is pursued without the decarbonization of the power sector, the effect in terms of national GHG emissions reduction would be minimal.

2.5.1 Transport Sector

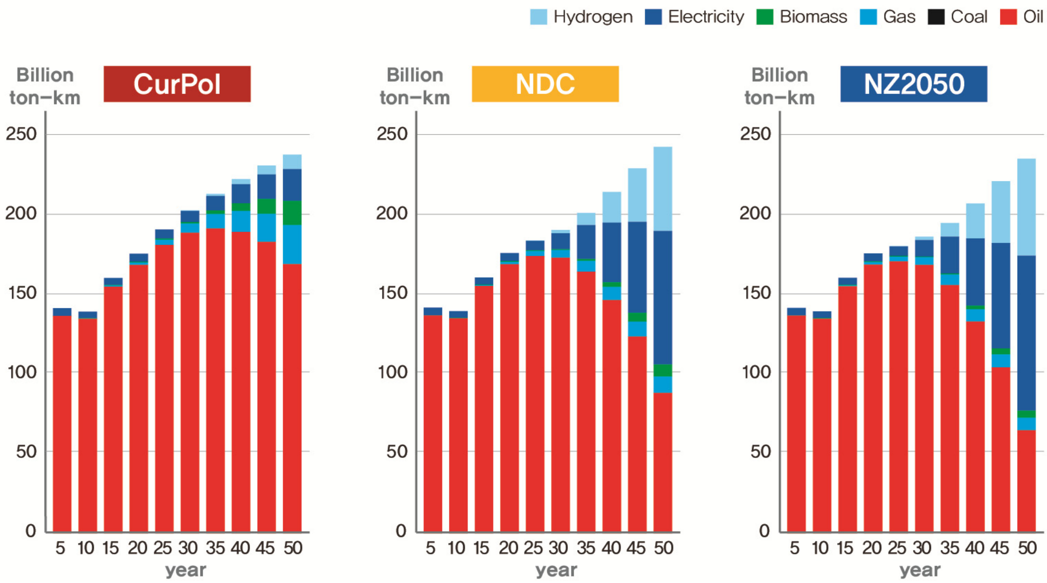


〈Figure 10: Energy consumption by source in the transport sector.〉

The transport sector's end-use energy consumption is predicted to decrease gradually due to population decline, GHG emission regulation of vehicles, and diffusion of EVs with relatively higher fuel efficiency (Figure 10). If the current policy stance holds, oil would account for around 75% of final energy consumption in 2050, but if a climate policy compatible with the NDC or carbon neutrality is implemented in earnest, oil's share would drop by 55% and 50% under respective scenarios, and electricity and hydrogen energy consumption would rise by some 30%. Compared to the CurPol scenario, end-use energy reduction would be further accelerated when NDC and carbon neutrality-compatible policies were put in place. This is attributed to the decrease in the average GHG emissions from internal combustion engine vehicles and broader deployment of electric alternatives with high energy efficiency.



〈Figure 11: Passenger transport demand by fuel (in billion passenger kilometer pkm)).〉



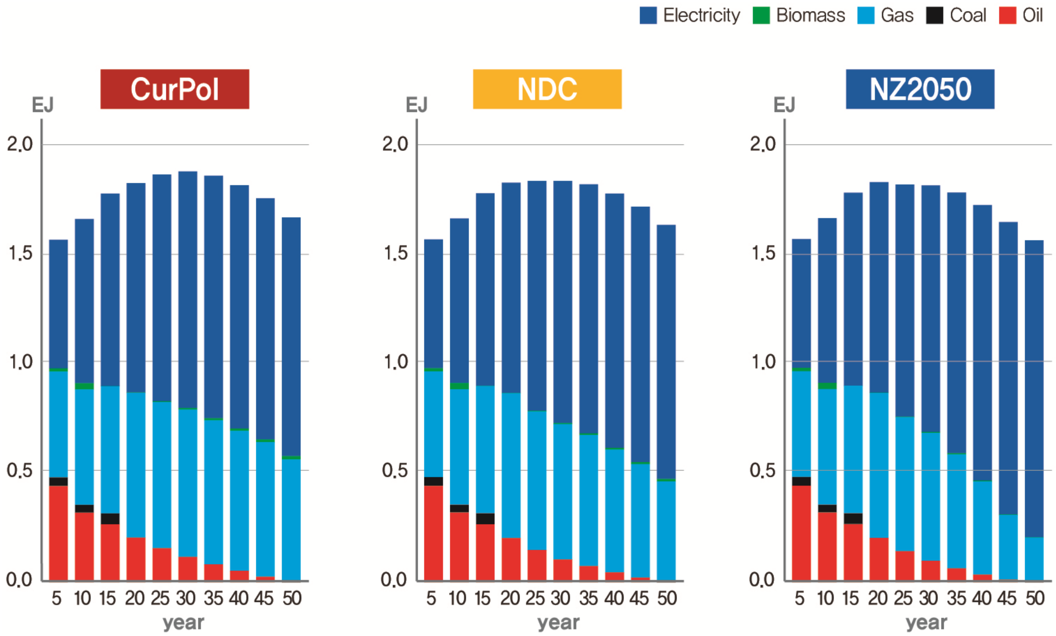
〈Figure 12: Freight transport demand by fuel (in billion metric ton-kilometer (tkm))〉

Examination of the changes in the transport sector based on passenger and freight transport (respectively in pkm and tkm) reveals structural changes more evidently (Figures 11 and 12). According to this research, as the demand for internal combustion engine vehicles, which are used to handle passenger and freight transport, are replaced with eco-friendly cars running on electricity, hydrogen, and biofuels, the transport sector's GHG emissions are expected to witness a sharp drop. This technological substitution phenomenon is predicted to accelerate as green cars achieve economic feasibility through technological advance while simultaneously carbon price drives up internal combustion engine vehicles' fuel cost.

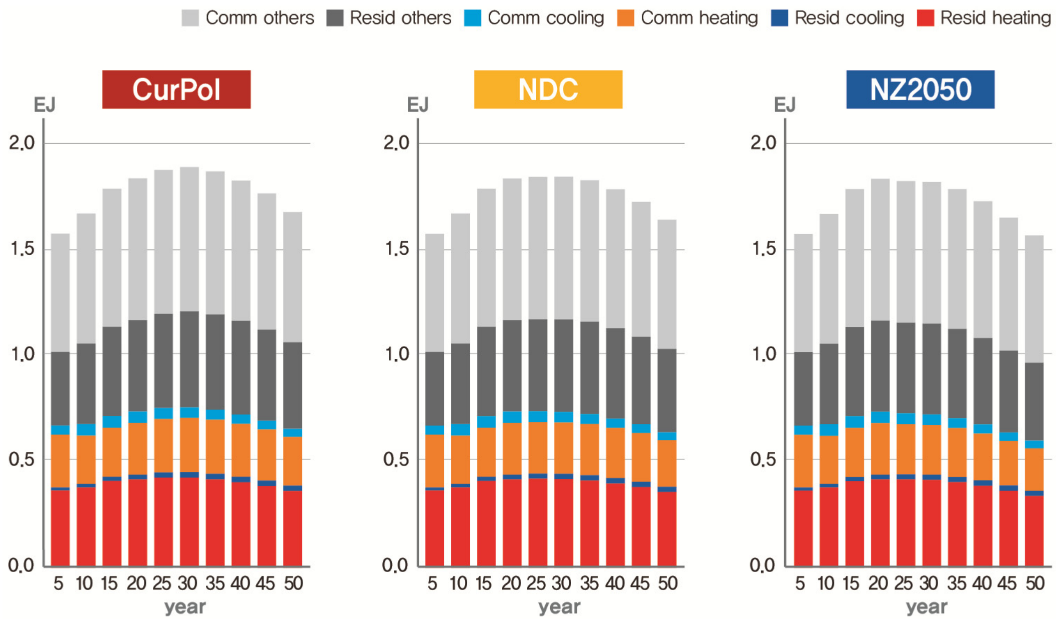
Still, decarbonization of the transport sector has limitations in two aspects. First, both passenger transport and freight transport are considered to see little GHG reduction effect through modal shift. In terms of passenger transport, buses and rail have higher energy efficiency per unit service than passenger cars, and in terms of freight transport, rail or ocean transport is more energy efficient than trucks. However, implementation of a climate policy failed to draw a meaningful shift of patterns in mode selection.

Second, since additional measures such as a ban on the sale of internal combustion engine vehicles were not reflected in the model, it is predicted that complete decarbonization through the expansion of green cars by 2050 is unlikely.

2.5.2 Building Sector



〈Figure 13: Energy consumption by source in the building sector.〉

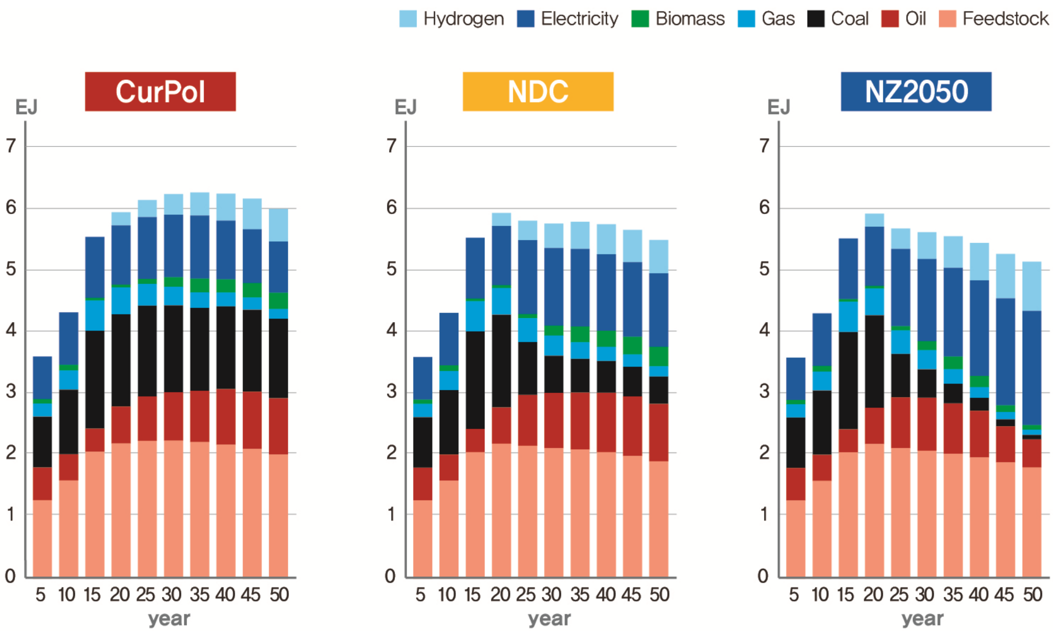


〈Figure 14: Energy consumption by service in the building sector.〉

The end-use energy demand of the building sector will gradually grow before steadily declining from 2030 (Figures 13 and 14). This results from improved insulation of buildings, higher efficiency of energy equipment, and broader dissemination of home appliances with high fuel efficiency. However, the pace at which insulation of buildings reflected in the scenarios improves is not fast enough to reduce the share of heating and air-conditioning energy in final energy consumption. This indicates that there is room for making a stronger effort to lower GHG emissions in the building sector by enforcing a more ambitious policy on insulation improvement.

Unlike in other sectors, the trend of change in energy consumption by source in the building sector is not significantly affected by implementation of a climate policy, because even under the current policy, electrification and shift away from fossil fuels are already occurring rapidly. In the CurPol scenario, the final energy consumption of power represents roughly 65% in 2050, but in the NDC scenario represents approximately 70%, and in the NZ2050 scenario represents about 85%. If an NDC and carbon neutrality-compatible policy were to be promoted, electrification would speed up slightly, but in such case, the effects of GHG emission reduction would be diminished as it would only replace gas, whose consumption stays stable, instead of replacing coal and oil which would already be exiting quickly.

2.5.3 Industrial Sector



〈Figure 15: Energy consumption by energy source in the industrial sector.〉

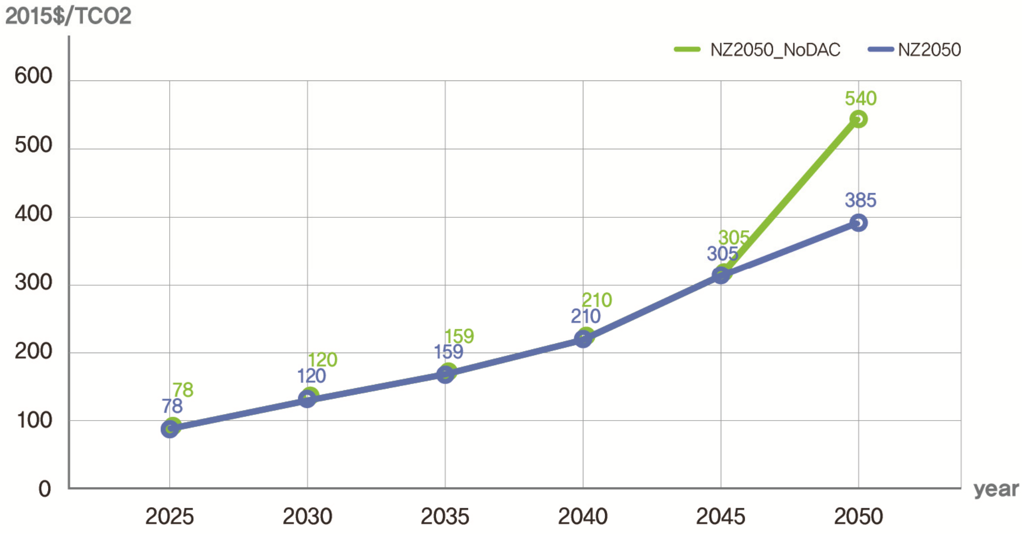
The industrial sector's end-use energy demand would, if the current policy continues, grow until 2035 before showing a modest decline due to lower energy intensity of economic activities in general and higher efficiency of industrial equipment (Figure 15). In such case, hydrogen fuel consumption will more than double between 2020 and 2050 while the proportion of fossil fuels will remain almost untouched, failing to drive down GHG emissions.

Meanwhile, an ambitious climate policy will sharply reduce fossil fuel consumption in the industrial sector, leading to a swift fuel switch to electricity and hydrogen. This change seems to take place even faster under a carbon-neutral policy. Specifically, coal is likely to be nearly absent starting from 2030 in the NZ2050 scenario.

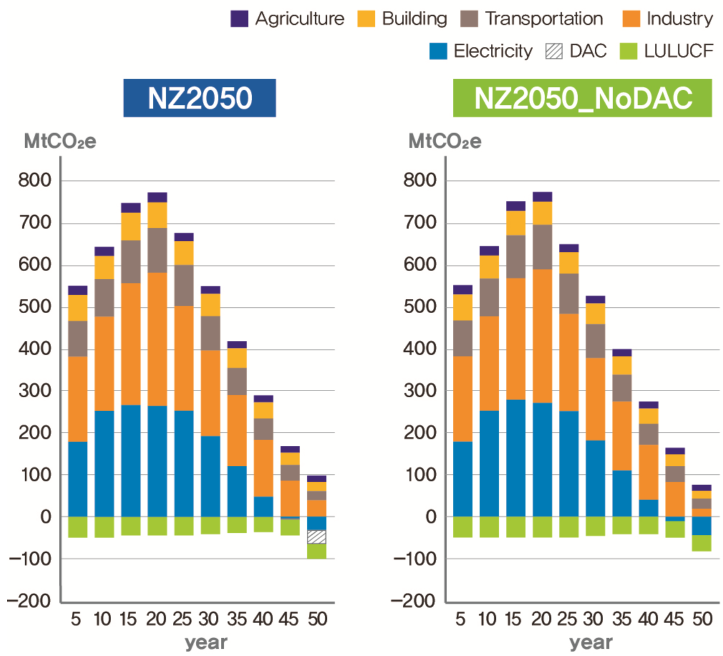
Yet, GCAM-KAIST1.0 has limitations in that the model does not address the structural shift of industries in Korea, which needs supplementation through further research in the future.

2.6 The Role of Direct Air Capture (DAC)

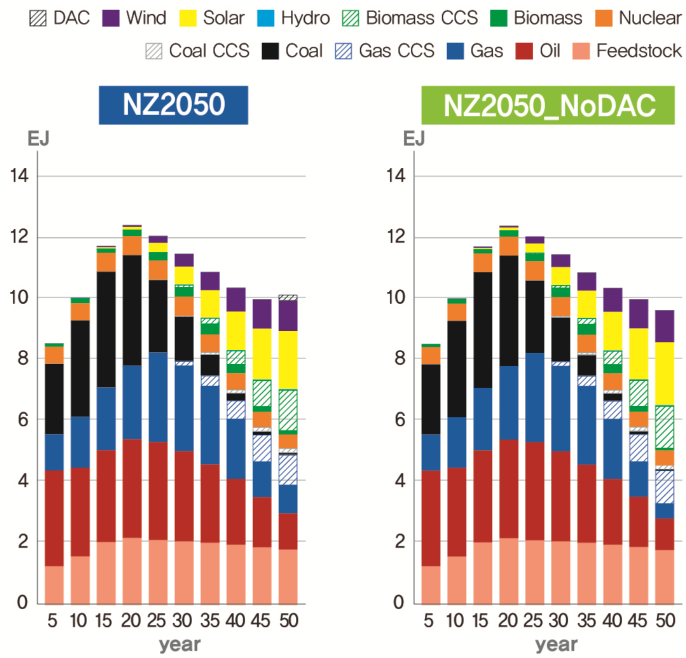
Lastly, the sensitivity related to the availability of DAC, which will play a role in achieving carbon neutrality around 2050, was analyzed. Particularly, the implications of the NZ2050 and NZ2050_NoDAC scenarios were examined in terms of carbon price for policy implementation, primary energy consumption, GHG emissions by sector, and CO2 capture.



〈Figure 16: Comparison of carbon prices depending on availability of DAC at the time of transition to carbon neutrality.〉



〈Figure 17: Comparison of GHG emissions by sector depending on availability of DAC at the time of transition to carbon neutrality.〉

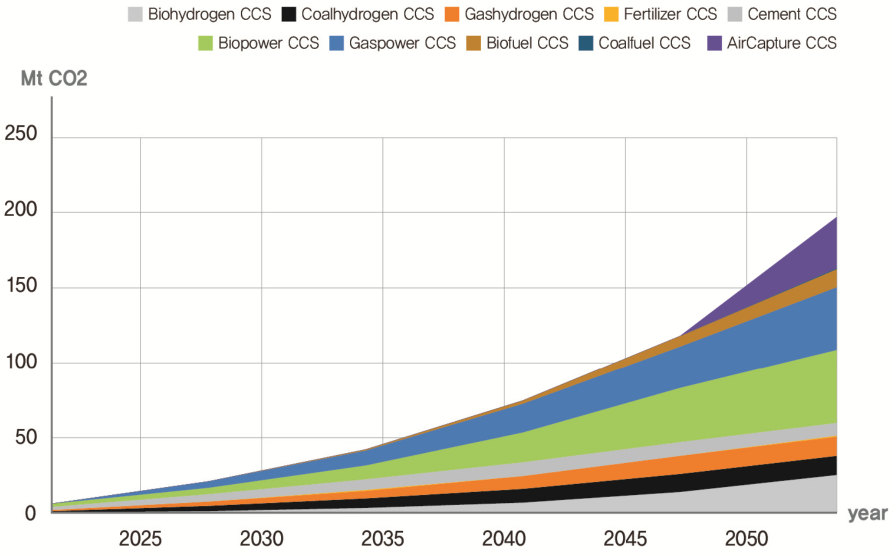


〈Figure 18: Comparison of primary energy consumption depending on availability of DAC at the time of transition to carbon neutrality.〉

If DAC failed to secure economic feasibility despite active efforts to achieve carbon neutrality, the carbon price is predicted to reach as high as USD 550 per metric ton in 2050 (Figure 16). Due to a consequential price increase effect on energy goods, under the NZ2050_NoDAC scenario, primary energy consumption is expected to decrease by 5% in 2050 compared to the NZ2050 scenario, playing a role as an additional cost factor of the Korean economy overall in the middle of the century (Figure 18). Moreover, in pursuing the 2050 carbon neutrality goal, the unavailability of DAC, a net sink technology, means that room for net-negative GHG emissions becomes inevitably smaller (Figure 17).

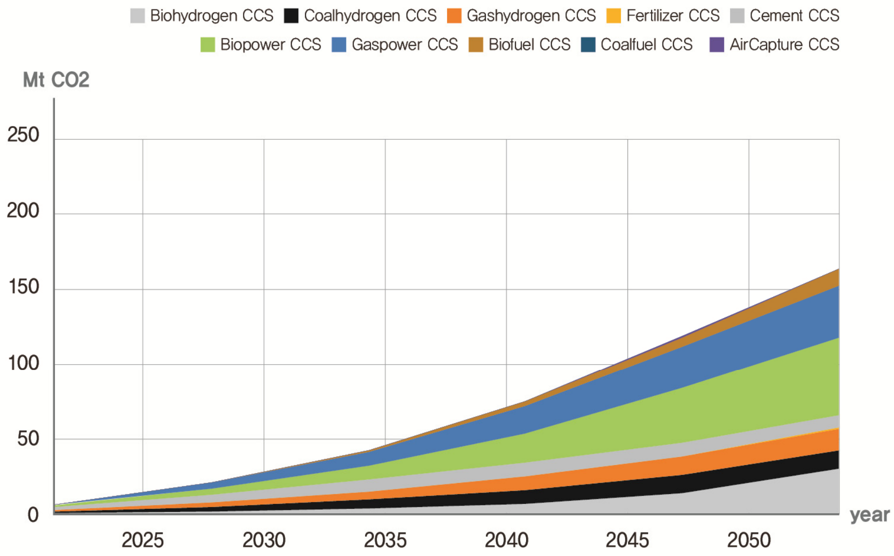
Cumulative CO_2 capture in 2050: 1.78 bn tons

NZ2050 CO_2 Capture



Cumulative CO_2 capture in 2050: 1.7 bn tons

NZ2050_NoDAC CO_2 Capture



〈Figure 19: Comparison of annual CO_2 capture depending on availability of DAC at the time of transition to carbon neutrality.〉

However, implementation of carbon neutrality based on DAC will likely aggravate the burden of CO_2 capture and storage (Figure 19). The demand for utilization of CO_2 capture and storage is expected to grow steadily in various sectors including bio-hydrogen production, bioenergy power generation, and gas power generation. In the carbon-neutral scenario, the cumulative CO_2 capture by 2050 is expected to reach approximately 1.78 billion metric tons. If DAC is not employed, the demand for CO_2 capture and storage would diminish to about 1.7 billion metric tons.

While not considered in this research, more in-depth additional studies on feasible sites for offshore geological storage of CO_2 and its potential is needed, and depending on such results, the capacity of CCS including DAC might have to be limited.

3. Conclusion and Implications

2050
Carbon-Neutrality
Transition Scenario
Analysis of a Korean Integrated Assessment Model

3.1 Directions for Achieving Carbon Neutrality

This research developed GCAM-KAIST1.0, a Korean integrated assessment model, and employed it to examine some scenarios for achievement of carbon neutrality in 2050. Based on this, the research drew the following requirements for achievement of carbon neutrality:

First, if the country is to make proportionate reductions between different time periods to achieve carbon neutrality by 2050, it is necessary to establish a clear policy goal and adopt policy means aimed at comprehensive GHG reductions across all sectors (power, building, industrial and transport) by 2050 as well as raising the 2030 NDC target.

Second, to achieve carbon neutrality in the power sector by 2050, a rapid expansion of renewables and flexible resources (such as energy storage systems (ESS)) is required. Specifically, since growth in power demand resulting from the fast electrification of the building and transport sectors is expected, a plan for stable management of the power system using pumped-storage hydroelectric power generation, ESS, demand response, etc. must be set up by considering the present energy policy stance.

Third, electrification of end-use demand associated with the decarbonization of the power sector is found to play a pivotal role in attaining carbon neutrality. In particular, the efforts to reduce GHG emissions across the economy, in general, will not only accelerate decarbonization of the power sector but also speed up electrification of the end-use demand sector and exit of fossil fuels. This means that under the NZ2050 scenario, the electricity output in 2050 should increase by 80% from the present level.

Fourth, to decarbonize Korea's energy sector, which is heavily dependent on fossil fuels, renewables must be expanded substantially, and this may require the adoption of CCS in biomass and gas power generation, partial operation of which is inevitable. According to this research, as of 2050, the capture amount will be approximately 200 million tons, and the need for CCS and how much it should be adopted must be determined based on the domestic CO2 storage potential. To reduce the required amount of CO2 geological storage, development, and diffusion of carbon capture and utilization (CCU), which uses carbon as a resource, is worth considering.

Fifth, to offset persistent GHG emissions despite active reduction efforts and achieve carbon neutrality, NETs including LULUCF, DAC and BECSS need consideration. In particular, the availability of DAC and BECCS with relatively high technological uncertainty could be an option that mitigates the economic burdens of achieving carbon neutrality. Hence, ways to make them economically feasible must be sought after through long-term research and development and

3.2 Policy Recommendations

In the course of promoting carbon neutrality by 2050, the most urgent task is to raise the 2030 NDC target significantly. The current reduction target of 24.4% from emissions in 2017 is inconsistent with international reduction efforts to reach the IPCC's 1.5℃ goal. As the 2030 NDC target is closely related to setting a cap under the Korean Emissions Trading System in force since 2015, if the NDC target was raised, an immediate reduction effect can be expected.

Particularly, large business places that fall under the energy-heavy business categories are mostly included in the industrial and building sectors under the Korean Emissions Trading System. Therefore, a rising emission permit price as a result of reduction of allowances can send a clear price signal, serving as a major driver for companies to increase investment in renewables and efficiency improvement.

Additionally, the 2030 NDC target is also connected with the GHG emission target of the transport sector. The Vehicle Average Fuel Economy and GHG Emissions

Management Program which took effect in 2012 set a long-term goal for 10 years starting from 2021. Along with an upward adjustment of the 2030 NDC target, the levels of the existing regulations must be modified substantially. In turn, the share of eco-friendly cars in car sellers' sales will grow, promoting the transport sector's transition to EVs. Additionally, adopting policies that can accelerate the adoption and spread of EVs must be positively considered; California's policy mandating sales of eco-friendly vehicles is an example.

As the results of this research indicate, to accelerate the energy transition in the power sector, a policy that brings forward the exit of coal power generation, whose economic feasibility will rapidly drop, must be established and plans for institutional supplementation such as the expansion of an incentive program for flexible resources that can resolve the fluctuation of renewables must be prepared. Furthermore, in the case of gas power generation, it must be reviewed if the gas power generation capacity under the present 9th Basic Plan for Electricity Supply and Demand is appropriate by considering various aspects such as securing of reserves, potential as a flexible resource, and GHG emissions.

The power market should also transition into a structure that can accelerate decarbonization. In this perspective, the existing variable cost-based cost evaluation system needs a drastic shift to a price-based wholesale market structure that can properly reflect the carbon price. In addition, a structure must be established that can ensure that government-controlled retail tariffs appropriately reflect environmental costs and drive changes in consumer behavior. Furthermore, there is a supply-demand instability in the electric power market resulting from the expansion of renewables, and in the long term, alleviating this instability by increasing demand response through the introduction of dynamic retail tariffs must be considered.

In terms of energy use, above all, it is necessary to strengthen the end-use energy target demand by sector specified in the 3rd Basic Energy Plan and lay the institutional foundations to ensure more financial investment for increasing energy efficiency. It is necessary to actively promote the introduction of a climate response fund to increase financial resources for existing energy efficiency programs, thus, spurring investment in energy efficiency across all sectors including building, industrial and residential. In this process, introducing additional carbon taxes through tax system reform, such as the existing Transportation · Energy · Environment Tax, to be used as funds for investment in the transition to carbon neutrality must be considered.

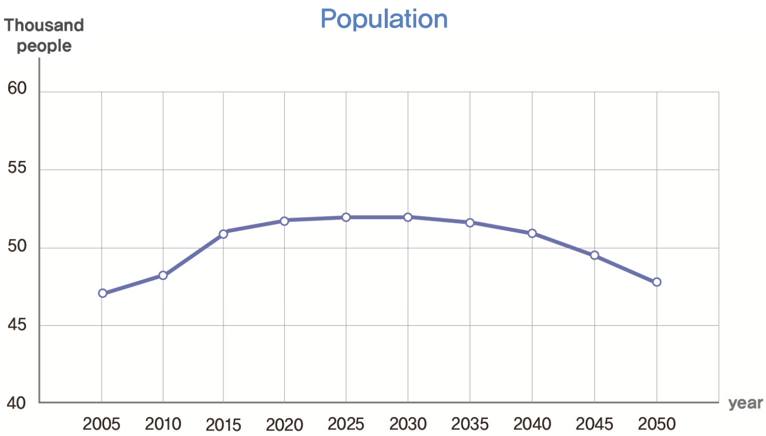
There must also be efforts to reduce CO2 emissions from biomass and gas power generation, of which some adoption is inevitable in the course of achieving carbon neutrality by 2050. Already, a variety of investments in and support for CCS in terms of R&D is taking place at the national level. Therefore, as mentioned earlier, it is necessary to review how to adopt CCS at an appropriate level from a comprehensive perspective, including the capacity and economic feasibility of offshore geological storage and opportunities for CCU. In addition, in the aspect of national strategy, long-term support of research and development of various NETs such as LULUCF, DAC, and BECSS is required.

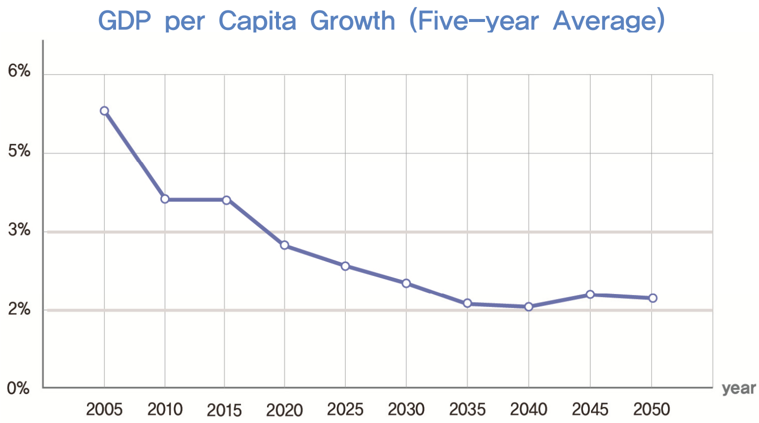
4. Appendix

2050
Carbon-Neutrality
Transition Scenario
Analysis of a Korean Integrated Assessment Model

4.1 Korea's Socioeconomic Projections

The Korean population assumption of GCAM-KAIST1.0 is based on the forecast of Statistics Korea (2019), and the economic growth rate is based on the projection of the Korea Institute for Industrial Economics & Trade (2019).





4.2 Cost Outlook of Power Generation Technologies

Power generation technology costs and forecast values for the Korean power sector used in GCAM-KAIST1.0 were prepared as follows based on the costs and forecast values of BNEF (2019) and NREL (2019).

4.2.1 Cost of Conventional Power Generation Technologies

Power Generation Technology	Unit	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Coal	2015$/kW	3,892	3,892	3,678	3,310	2,943	2,575	2,207	1,839	1,655	1,541
Combined Cycle	2015$/kW	883	883	817	817	817	817	817	817	817	817
Nuclear	2015$/kW	6,268	6,268	6,268	6,154	5,963	5,823	5,665	5,506	5,352	5,157
Oil	2015$/kW	1,195	1,059	1,059	901	864	842	828	817	809	791

4.2.2 Cost of Renewable Energy Power Generation Technologies

Power Generation Technology	Unit	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Solar Thermal	2015$/kW	5,470	5,470	5,407	3,939	3,862	3,814	3,752	3,689	3,634	3,546
ESS-linked Solar Thermal	2015$/kW	9,119	8,350	8,350	8,350	8,350	8,350	8,350	8,350	8,350	8,350
Solar PV	2015$/kW	2,453	2,453	2,453	1,269	1,144	1,019	964	905	857	809
ESS-linked Solar PV	2015$/kW	5,014	4,079	2,943	2,567	2,122	1,835	1,729	1,618	1,519	1,420
Rooftop Solar PV	2015$/kW	5,356	3,984	3,984	2,464	2,034	1,593	1,479	1,361	1,287	1,240
Biomass	2015$/kW	4,557	4,285	4,164	3,962	3,862	3,814	3,752	3,689	3,634	3,546
Onshore Wind	2015$/kW	2,023	2,023	1,659	1,523	1,387	1,247	1,188	1,129	1,070	1,008
Offshore Wind	2015$/kW	5,517	3,678	3,807	2,921	2,479	2,108	1,791	1,519	1,291	1,100
ESS-linked Wind	2015$/kW	3,369	3,285	3,285	2,818	2,361	2,064	1,953	1,843	1,732	1,618

4.2.3 Cost of DAC

To reflect the economic feasibility of DAC, GCAM-KAIST1.0 takes into consideration both the exogenously assumed technology investment cost and the energy cost (natural gas and electricity) to run the technology. The cost of DAC used in the process followed Fuhrman et al., (2020). The "NZ2050" scenario presumes low-cost DAC while the "NZ2050_NoDAC" scenario presumes high-cost DAC

Technology in 2050	Natural Gas (GJ/ tCO2)	Electricity (GJ/ tCO2)	Water (m3/ tCO2)	Non-energy Cost (2015$/ tCO2)
Low-cost DAC	5.3	1.3	4.7	180
High-cost DAC	8.1	1.8	4.7	300

4.3 Cost Outlook of Technology Cost by Mode of Transport

Modal and technological classifications applied to GCAM-KAIST1.0 basically follow UC Davis (2013), and the energy density and load factor assumptions of Korea by transport technology in Eom et al., (2010) and Eom et al., (2012) were applied. Technology cost by transport mode reflected cost reduction trends by technology applied by Begero et al., (2021) based on technology costs compatible with Korea's reality.

4.3.1 Passenger Transport

Scenario	Transport Mode	Transport Technology	Unit	2015	2030	2050
NZ2050/ NDC	Compact Car	BEV	2015$/pass-km	0.30	0.20	0.15
NZ2050/ NDC	Large Car	BEV	2015$/pass-km	0.55	0.38	0.28
NZ2050/ NDC	Light Truck and SUV	BEV	2015$/pass-km	0.59	0.40	0.30
NZ2050/ NDC	Subcompact Car	BEV	2015$/pass-km	0.24	0.17	0.12
NZ2050/ NDC	Compact Car	FCEV	2015$/pass-km	0.28	0.22	0.16

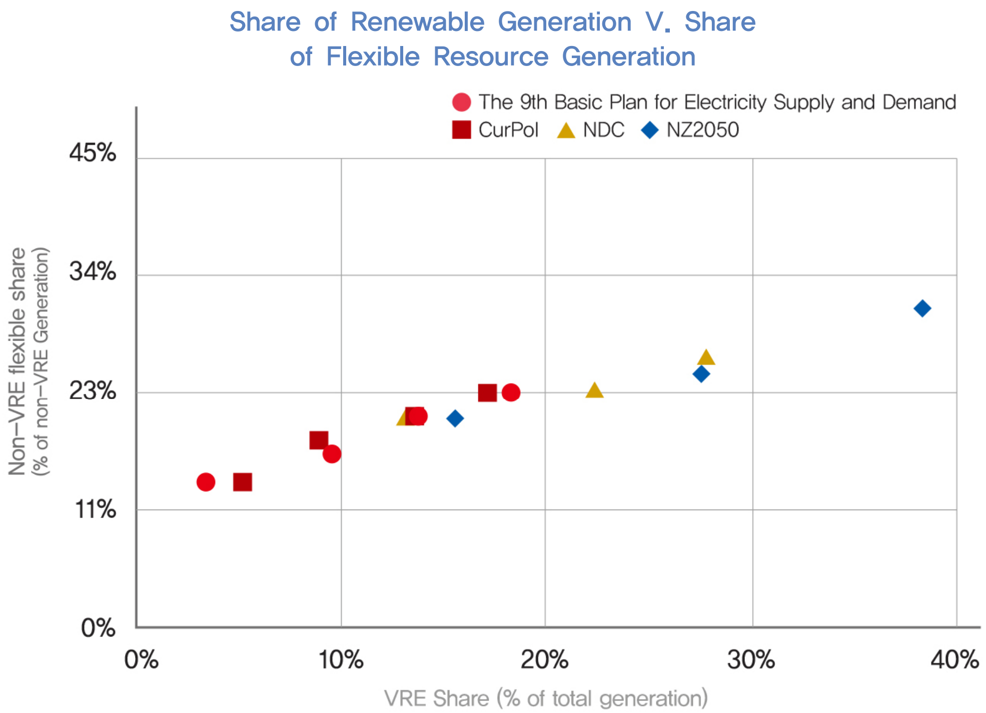
Scenario	Transport Mode	Transport Technology	Unit	2015	2030	2050
NZ2050/ NDC	Large Car	FCEV	2015$/pass-km	0.52	0.39	0.29
NZ2050/ NDC	Light Truck and SUV	FCEV	2015$/pass-km	0.56	0.42	0.31
NZ2050/ NDC	Subcompact Car	FCEV	2015$/pass-km	0.22	0.18	0.13
NZ2050/ NDC	Compact Car	Hybrid Liquids	2015$/pass-km	0.23	0.24	0.24
NZ2050/ NDC	Large Car	Hybrid Liquids	2015$/pass-km	0.41	0.43	0.43
NZ2050/ NDC	Light Truck and SUV	Hybrid Liquids	2015$/pass-km	0.43	0.45	0.46
NZ2050/ NDC	Subcompact Car	Hybrid Liquids	2015$/pass-km	0.17	0.17	0.17
NZ2050/ NDC	Compact Car	Liquids	2015$/pass-km	0.22	0.23	0.23
NZ2050/ NDC	Large Car	Liquids	2015$/pass-km	0.40	0.43	0.43
NZ2050/ NDC	Light Truck and SUV	Liquids	2015$/pass-km	0.41	0.44	0.45
NZ2050/ NDC	Subcompact Car	Liquids	2015$/pass-km	0.16	0.17	0.17
NZ2050/ NDC	Compact Car	Natural Gas	2015$/pass-km	0.26	0.27	0.27
NZ2050/ NDC	Large Car	Natural Gas	2015$/pass-km	0.45	0.49	0.49
NZ2050/ NDC	Light Truck and SUV	Natural Gas	2015$/pass-km	0.47	0.50	0.50
NZ2050/ NDC	Subcompact Car	Natural Gas	2015$/pass-km	0.19	0.20	0.20
CurPol	Compact Car	BEV	2015$/pass-km	0.31	0.24	0.21
CurPol	Large Car	BEV	2015$/pass-km	0.57	0.44	0.39
CurPol	Light Truck and SUV	BEV	2015$/pass-km	0.61	0.47	0.42
CurPol	Subcompact Car	BEV	2015$/pass-km	0.25	0.19	0.17
CurPol	Compact Car	FCEV	2015$/pass-km	0.29	0.25	0.21
CurPol	Large Car	FCEV	2015$/pass-km	0.54	0.45	0.39
CurPol	Light Truck and SUV	FCEV	2015$/pass-km	0.58	0.49	0.42
CurPol	Subcompact Car	FCEV	2015$/pass-km	0.23	0.20	0.17
CurPol	Compact Car	Hybrid Liquids	2015$/pass-km	0.23	0.23	0.23

Scenario	Transport Mode	Transport Technology	Unit	2015	2030	2050
CurPol	Large Car	Hybrid Liquids	2015$/pass-km	0.41	0.42	0.42
CurPol	Light Truck and SUV	Hybrid Liquids	2015$/pass-km	0.43	0.44	0.44
CurPol	Subcompact Car	Hybrid Liquids	2015$/pass-km	0.17	0.16	0.16
CurPol	Compact Car	Liquids	2015$/pass-km	0.22	0.22	0.22
CurPol	Large Car	Liquids	2015$/pass-km	0.40	0.41	0.41
CurPol	Light Truck and SUV	Liquids	2015$/pass-km	0.41	0.42	0.43
CurPol	Subcompact Car	Liquids	2015$/pass-km	0.16	0.16	0.16
CurPol	Compact Car	Natural Gas	2015$/pass-km	0.26	0.27	0.27
CurPol	Large Car	Natural Gas	2015$/pass-km	0.45	0.47	0.48
CurPol	Light Truck and SUV	Natural Gas	2015$/pass-km	0.46	0.48	0.49
CurPol	Subcompact Car	Natural Gas	2015$/pass-km	0.19	0.20	0.20

4.3.2 Freight Transport

시나리오	수송수단	수송기술	단위	2015	2030	2050
NZ2050/ NDC	Truck	BEV	2015$/ton-km	0.65	0.45	0.33
NZ2050/ NDC	Truck	FCEV	2015$/ton-km	0.62	0.47	0.35
NZ2050/ NDC	Truck	Liquids	2015$/ton-km	0.36	0.38	0.38
NZ2050/ NDC	Truck	Natural Gas	2015$/ton-km	0.44	0.45	0.45
CurPol	Truck	BEV	2015$/ton-km	0.68	0.52	0.46
CurPol	Truck	FCEV	2015$/ton-km	0.64	0.54	0.47
CurPol	Truck	Liquids	2015$/ton-km	0.36	0.37	0.37
CurPol	Truck	Natural Gas	2015$/ton-km	0.44	0.44	0.43

4.4 Flexible Resources

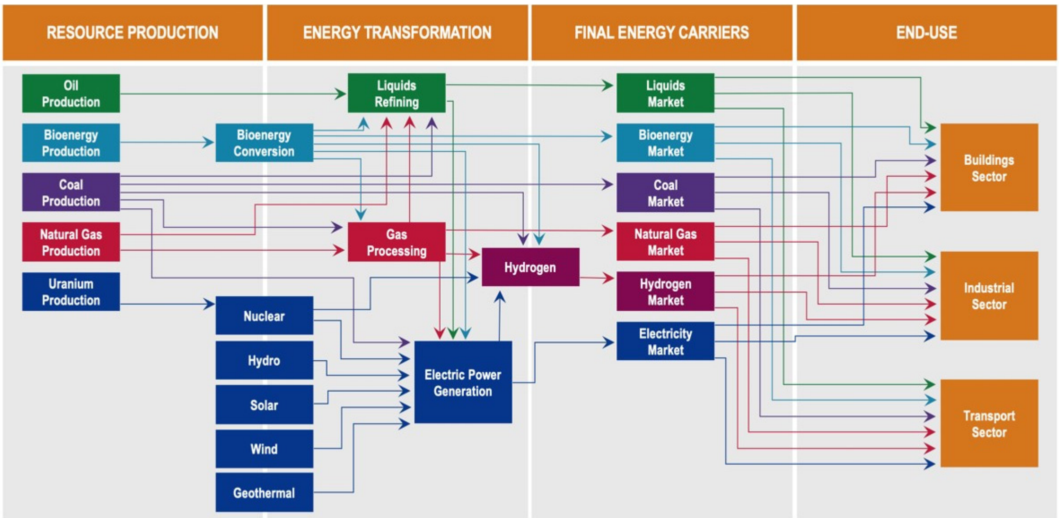


The above figure is graph that depicts the share of renewable generation versus the share of flexible resource generation under the three scenarios (CurPol, NDC, and NZ2050) evaluated in this report. Johnson et al. (2017) has also drawn the relationship between a rising share of variable renewable generation and the share of flexible resource generation needed accordingly. In each scenario, the trends were displayed in diagram form on a five-year increment between 2020 and 2035. Renewable generation was calculated by adding up the generation from solar PV and wind, both variable renewable energy resources, and flexible resources were calculated by adding up 50% of gas generation by year and output of ESS. Non-renewable generation refers to the generation excluding variable renewables (solar PV and wind) from total generation. As described in the figure, all three scenarios were found to generally meet the flexible resource requirements reflected in the 9th Basic Plan for Electricity Supply and Demand.

4.5 GCAM

Global Change Analysis Model (GCAM) was developed by U.S.-based PNNL/JGCRI and is a representative energy-economy-environment model which has been routinely used in major climate policy evaluation studies including IPCC reports. GCAM is a partial equilibrium model (Stanton et al., 2009) and a high-resolution IAM (Edmonds et al., 2012). It is also one of the five representative models used for the development of Representative Concentration Pathways (RCP) and Shared Socioeconomic Pathways (SSP), which is used by many researchers in various countries.

GCAM is an assessment system that links macroeconomics to energy systems, land use, and climate systems, and can be used to develop a consistent scenario that allows an integrated assessment of the impact of energy and climate policies on each energy and land system from various perspectives. GCAM's energy system reflects competition among fuels and technologies from primary energy production, energy transportation, and end-use energy consumption by region and transaction of energy goods between regions. GCAM divides the world into 32 different regions, and Korea is classified as one single region out of the 32 regions.



Based on GCAM v.5.2, this research developed a Korean IAM (GCAM-KAIST1.0) by reflecting Korea's present policies and technologies. The period from 2010 as the base year until 2100 was simulated on a five-year basis, and competition among various technological alternatives was expressed based on a logit choice model in each technological service area, such as power supply, passenger and freight transport services, building heating and air-conditioning services and other services, and industries, such as cement, fertilizer, and petrochemicals. Future technological competition is determined by the share and cost of each technology in the base year and its performance outlook, and in the process, unique behavioral characteristics of the region and market are reflected. If all conditions remain the same, and a carbon policy is implemented, the share of low-carbon technologies increases as the economic feasibility of existing low-carbon technologies with low market share improves relatively more than that of carbon-intensive technologies.

5. References

2050
Carbon-Neutrality
Transition Scenario
Analysis of a Korean Integrated Assessment Model

국토교통부(2019). “제2차 녹색건축물 기본계획(2020~2024)”.

대한민국 정부(2020). “대한민국 탄소중립선언”.
https://www.korea.kr/archive/speechView.do?newsId=132032791

대한민국 정부(2021). “기후정상회의(화상) 발언”.
https://www.korea.kr/archive/speechView.do?newsId=132033147&call_from=rsslink

산업연구원(2018). “장기(2040년) 산업구조 전망 분석”.

산업통상자원부(2019). “제3차 에너지기본계획”.

산업통상자원부(2020a). “제9차 전력수급기본계획(2020~2034)”.

산업통상자원부(2020b). “제5차 신 · 재생에너지 기술개발 및 이용 · 보급 기본계획”.

산업통상자원부(2021). “제4차 친환경자동차 기본계획(2021-2025)”.

통계청(2019). “장래인구특별추계 : 2017~2067년”.
http://kostat.go.kr/portal/korea/kor_nw/1/2/6/index.board?bmode=read&aSeq=373873

한국에너지공단(2015). “에너지라벨링제도 이해”.

환경부(2018). “2030년 국가 온실가스 감축목표 달성을 위한 기본 로드맵 수정안”.

환경부(2020a). “2030 국가 온실가스 감축목표(NDC)”.

환경부(2020b). “지속가능한 녹색사회 실현을 위한 대한민국 2050 탄소중립 전략”.

환경부(2020c). “2021～2030년 자동차 온실가스 · 연비 기준 행정예고”.
http://www.me.go.kr/home/web/board/read.do?pagerOffset=50&maxPageItems=10&maxIndexPages=10&searchKey=&searchValue=&menuId=286&orgCd=&boardId=1393630&boardMasterId=1&boardCategoryId=39&decorator=

Bergero, C. and Binsted, M. “An integrated assessment of a low coal low nuclear future energy system for Taiwan”. Energy and Climate Change. Volume 2. 100022.

BNEF(2019). “New Energy Outlook 2019”.
https://about.bnef.com/new-energy-outlook/

Climate Analytics(2020). “탈탄소 사회로의 전환 : 파리협정에 따른 한국의 과학 기반 배출 감축 경로”.

Eom, J. and Schipper, L.(2010) “Trends in passenger transport energy use in South Korea”. Energy Policy 38, 3598-3607.

Eom, J., and Schipper, L.(2012) “We keep on truckin’: Trends in freight energy use and carbon emissions in 11 IEA countries”. Energy Policy 45, 327-341.

Fuhrman, J. and McJeon, H.(2020). “Food-energy-water implications of negative emissions technologies in a +1.5℃ future”. Nat. Clim. Chang. 10, 920-927.
https://doi.org/10.1038/s41558-020-0876-z

Johnson, N. and Strubegger, M.(2017). “A reduced-form approach for representing the impacts of wind and solar PV deployment on the structure and operation of the electricity system”. Energy Economics. Volume 64. Pages 651-664.

NREL(2019). “Annual Technology Baseline : Electricity”.
https://atb.nrel.gov/electricity/2019/

UC Davis(2013). “Transportation Module of Global Change Assessment Model (GCAM) : Model Documentation Version 1.0”.

UNFCCC(2015). “Paris Agreement”.

2050 Carbon-Neutrality Transition Scenario

Analysis of a Korean Integrated Assessment Model

KAIST

SFOC
Solutions for Our Climate