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Assessing the impact of climate and air quality policies on future emissions in Korea through quantification of control and co-control effects

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A R T I C L E I N F O

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A B S T R A C T

Climate policies designed to reduce greenhouse gas (GHG) emissions can also lead to reduced air pollutants, and conversely, air pollution reduction policies can contribute to GHG reductions. We defined "control" as achieving key policy goals and "co-control" as achieving additional goals simultaneously. This study quantitatively analyzed the effects of Korea's Climate and air pollutant reduction policies using the GHGs and air pollutant Unified Information Design system for Environment (GUIDE) model, which facilitates an integrated analysis of the control and co-control effects of these policies. We incorporated the latest policies in Korea into the model and developed four scenarios to generate and evaluate future emission inventories for each scenario until 2030. The four scenarios include the baseline scenario (no additional policy), the Nationally Determined Contribution (NDC) scenario (climate policies), the Air Quality Management (AQM) scenario (air quality policies), and the NDC+AQM scenario (both policies). The analysis results from the NDC and the NDC+AQM scenarios present the reduction effects of CO_2 emissions due to climate policies and illustrate the co-control effects that reduce atmospheric pollutants such as SO_x, NO_x, and $PM_{2.5}$ as well. Moreover, through a comparative analysis of emission reduction outcomes across the four scenarios, this study shows the advantages of concurrently evaluating climate and air quality policies using the integrated model. Furthermore, by assessing the effects of policies within each emission sector, we can identify sections necessitating supplementary reduction strategies. The findings presented in this research offer valuable insights and data to inform forthcoming policy development and assessment endeavors.

1. Introduction

Asia accounts for approximately 50% of global CO_2 emissions, of which East Asian countries, such as China (30.9%), Japan (3.2%), and Korea (1.8%), account for more than 30% of global emissions (BP, 2021). In other words, East Asia holds the top spot for global CO_2 emissions. These emissions are a direct result of energy consumption in sectors such as power generation, industry, and transportation, all of which are driven by the region's high energy demand. Most energy is obtained through the combustion of fossil fuels. In this process, substantial amounts of greenhouse gases (GHGs) such as CO_2 are released into the air. GHGs and air pollutants have varying impacts and ranges. GHGs trap heat in the atmosphere, leading to global warming and climate change. They have long-term impacts which can affect the entire planet. However, air pollutants can have more immediate and local effects on human health and the environment. Consequently, there is a tendency to focus on implementing policies regarding the mitigation of visible damage caused by air pollutants, such as fine dust, rather than on addressing the effects of climate change. Although reducing air pollutants can have immediate benefits for human health and the

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environment, it is important to prioritize efforts to reduce GHGs and address long-term climate change (Amann et al., 2020).

The management of GHG emissions and air pollutant reduction policies simultaneously can be mutually beneficial and more cost-effective than managing them separately. According to data released by the Organization for Economic Co-operation and Development (OECD), reducing GHG emissions by 50% compared to 2005 levels by 2050 would decrease premature mortality due to air pollutants by an estimated 20–40% (OECD, 2009). The IPCC Fifth Assessment Report also found that the integrated management of air pollutants and GHGs is more cost-effective than independent management (IPCC, 2014), as air pollution is associated with climate change. Many short-term climate change pollutants, such as black carbon and methane, which have a local impact on the climate, are also air pollutants emitted via the burning of fossil fuels. Therefore, it is crucial to develop policies and strategies to manage air pollution and climate change simultaneously.

Analysis of the effects of policy implementation is crucial for gaining a better understanding of the policy and identifying any issues that may arise during implementation. This helps steer the policy in a more desirable direction and achieve the desired results. Methods for analyzing the effects of policies include analyzing changes in pollutant concentrations based on emission scenarios (Kim and Kang, 2020; Choi et al., 2020; Wu et al., 2019), estimating the benefits of management policies from an economic perspective (Koo et al., 2018; Hwang et al., 2018; Liu et al., 2023), and analyzing the cost-effectiveness of reduction measures (Hwang et al., 2021; Amann et al., 2011; D'Elia et al., 2018). When implementing policies, it is crucial to adjust their size and timing based on the anticipated effects, and effective budget allocation is necessary to comply with cost constraints. Cost-effectiveness analysis can be applied to this process. It enables a comprehensive examination of the process of air pollution generation and its impact as well as the performance and feedback of reduction policies.

As mentioned above, although GHGs and air pollutants differ in their emission characteristics in terms of time and space, they share the same sources, and their effects can vary depending on climate policies. Therefore, when implementing related policies, it is necessary to manage these factors to achieve synergistic effects. From a cost-effectiveness perspective, the integrated management of GHGs and air pollutants is essential for maximizing the benefits of reduction policies. To achieve this, several integrated assessment models have been developed and utilized to quantify the generation, transport, and damage of GHGs and air pollutants under various energy and policy scenarios in an integrated manner.

Korea is currently promoting policies to reduce GHG and air pollutant emissions. The 2nd Master Plan for coping with Climate Change (ME, 2019) is a representative policy among Korea's GHG reduction policies. The policy includes an energy conversion policy that prohibits the construction of new coal power plants to reduce coal power generation and increase renewable energy generation and an eco-friendly vehicle policy that promotes low-emission vehicles. The Korean Green New Deal (Relevant Ministry, 2020) constructed an eco-friendly energy infrastructure and enhanced competition in eco-friendly industries. Moreover, following the adoption of the Paris Agreement in 2015, Korea established its 2030 Nationally Determined Contributions (NDC) for GHG emission reduction and is working towards achieving the goals therein. In 2016, it developed the National Roadmap for Greenhouse Gas Reductions by 2030, established a revised roadmap in 2018, and finalized an enhanced NDC in 2021. Regarding air pollutant reduction, the Special Plan for Fine Dust Management (Relevant Ministry, 2016), the Comprehensive Plan on Fine Dust (Relevant Ministry, 2017), and the Comprehensive Plans for Fine Dust Management (Relevant Ministry, 2019) have recently been implemented, and policies are being added annually. As a result of the policies implemented thus far, the annual emissions of fine particles from coal power plants have decreased. Korea is also working on managing emission sources by strengthening emission standards, managing cap-and-trade in the workplace, and establishing an emission levy system. Efforts have also been devoted to reducing the number of diesel vehicles in operation, a major source of emissions, by encouraging the early scrapping of old diesel vehicles and promoting the use of eco-friendly vehicles.

This study aimed to analyze the effects of Korea's climate and air pollutant reduction policies using the GUIDE model (ME, 2020). We aimed to identify sectors where these policies were effective and sectors that may require additional reduction measures. The GUIDE model currently provides tools for applying various socioeconomic and energy outlook models and air pollutant reduction policies in Korea and enabling the calculation of future emissions under different scenarios. However, to apply diverse scenarios to the GUIDE model, it is essential to investigate policies according to user requirements and modify the model's data based on the analysis. To conduct this study, we surveyed and analyzed the government's planned energy and air pollutant reduction policies and created scenarios that could simultaneously examine the effects of GHG and air pollutant reduction policies. We modified the policies and technology database of the GUIDE model to apply the surveyed data and future prospect scenarios and conducted an analysis.

Another one of our primary research objectives was to evaluate the advantages of the GUIDE model as an integrated analytical tool. We began by examining how the GUIDE model analyzes the control and co-control effects of policies. Climate policies aimed at reducing greenhouse gases may result in a concurrent reduction of air pollutants, just as air pollution reduction policies can lead to a decrease in greenhouse gases. This distinction categorizes the primary objective as "control" and the supplementary objectives as "co-control." To gain insight into how the GUIDE model handles these effects, we designed four distinct scenarios: baseline, climate policy only, air quality policy only, and both policies applied. Subsequently, we compared the control and co-control effects across these scenarios. Furthermore, we aimed to present the advantages of concurrently assessing climate and air quality policies using an integrated model. The GUIDE model initiates its emission calculations by considering climate policies and subsequently incorporates reductions attributed to air quality policies. This approach eliminates redundancies in applying reduction measures to emissions that have already been reduced by climate policies. It also sought to confirm these characteristics by comparing the emission reduction outcomes across the scenarios.

2. Methodology

2.1. Research framework

The GUIDE model is an integrated assessment model capable of identifying and quantifying the impacts of the emissions and transport of GHGs and air pollutants. To estimate future emissions using this model, it is necessary to have base year emissions, projections of future activities, climate policies, air pollutant reduction policies, and scenarios that incorporate all of this information. The process of this study is illustrated in Fig. 1. In the Socio-economic & Energy model, future GHG emissions are estimated using base year energy & non-energy activity, socio-economic data, and climate policy databases (DB) as input data. Additionally, in this process, activity projection factors necessary for estimating future air pollution emissions are generated. In the air quality policy model, future air pollutant emissions are estimated by applying the activity projection factors to base-year air pollutant emissions. Subsequently, the model calculates the reduction in future air pollutant emissions by incorporating policy and technology databases that reflect air pollutant reduction policies, thus determining future emissions.

The GUIDE model developed thus far contains fundamental information on project emissions from the base year 2015–2030. For this reason, this study utilized Energy & non-energy activity data, socio-economic data, and the base year emissions inventory provided in the

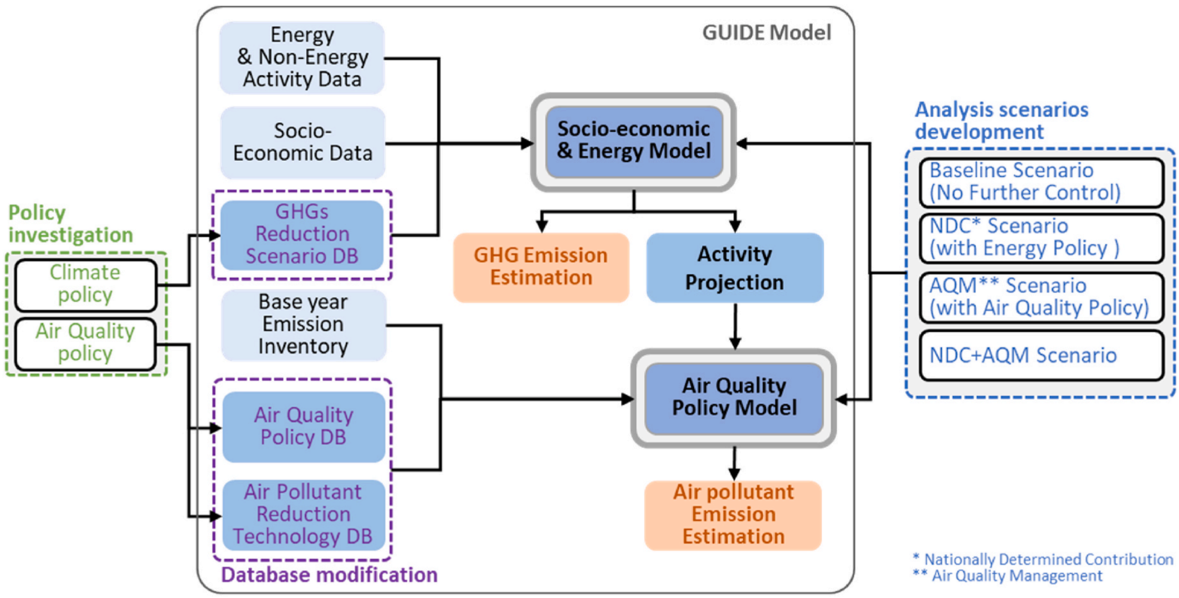

Fig. 1. Research flow.

GUIDE model. Energy activity data is based on energy consumption, while non-energy activity data is based on factors such as industrial processes, agricultural and livestock output, or waste disposal quantities. For the energy & non-energy activity data and the base year emissions inventory, the Comprehensive Regional Emissions inventory for Atmospheric Transport Experiment (CREATE) (Woo et al., 2020; ME, 2019; Kim et al., 2023a,b) was utilized. The CREATE inventory uses a detailed classification of fuels and sectors in Asian countries. It contains emission inventories for 2010 and 2015 for estimating both air pollutants and GHGs. This study used Korea's 2015 emissions inventory as the base year for the GUIDE model.

However, as there were variations in the contents of the climate and air pollutant reduction policy scenarios being evaluated, we updated the relevant DBs, such as GHG reduction scenario DB, Air Quality policy DB, and Air Pollutant Reduction Technology DB to accurately reflect the scenarios being analyzed. For this purpose, we conducted policy investigations on climate and air quality policies planned for implementation in Korea until the target year, 2030.

To analyze the control and co-control effects of climate policies, air pollutant reduction policies, and both, we created four policy scenarios (see the right side of Fig. 1). Policy scenarios can be defined as future pathways for estimating future emissions and are categorized based on whether a climate policy or an air pollutant reduction policy should be added. We applied each policy scenario to create projections of future emissions inventories by scenario until 2030 and quantitatively analyzed reduction effects.

2.2. Methodology of future emissions estimation in GUIDE model

2.2.1. Socio-economic and energy model

Fig. 1 illustrates that the initial step occurs within the "Socio-economic & energy model," where the estimation of greenhouse gas (GHG) emissions takes place. Detailed energy and non-energy activity data are provided for each emission source sector for the base year. GHG emission estimation factors, which are connected to activity data, were incorporated into the model. The future activity projection factors are determined based on socio-economic statistics, such as population, GDP, and future changes in oil prices, which are used for the estimation of future activity values. This process is embedded in the GUIDE model.

The version of the GUIDE model used in this study includes activity data for the base year 2015 and several future socio-economic projections from 2016 to 2030, obtained from a previous study (ME, 2020). Currently, future socio-economic projections are available for population, GDP, and oil prices, each falling into one of three ranges: High, Middle, and Low. However, because population and GDP must be at the same level, there are, in fact, a total of nine possible combinations. In this study, we specifically chose the middle-level socioeconomic future projection, and the values are derived from projections where population, GDP, and oil prices all align at the middle level.

In accordance with the selected socioeconomic future projections, future activities are forecasted. Subsequently, when incorporating future climate policies, the projected future activity levels are estimated. GHG emission estimation factors are applied to estimate GHG emissions corresponding to these activity levels. The GUIDE model has established a GHGs reduction scenario DB that encompasses applicable climate policies. It also features a mechanism, developed in the previous study (ME, 2020), for calculating adjustments in activity levels resulting from the implementation of these policies. Users have the flexibility to choose the climate policies they want to apply and analyze accordingly."

Furthermore, as shown in Fig. 1, the socio-economic & energy model supplies activity projection factors for the air quality policy model to predict future activity levels for air pollutant emission estimation. Since the databases for activity data, both for greenhouse gases and air pollutants, follow a consistent structure, The growth rates by year of greenhouse gas activity levels can be utilized as those of air pollutant activity levels. According to this process of the GUIDE model, future activity projections for air pollutants include the effects of the climate policy implementation. In other words, the GUIDE model is an integrated model that analyzes both climate and air quality policies simultaneously, but to be precise, it initially calculates the greenhouse gas reduction effects of climate policies before examining the impact of air quality policies. As a result, the co-control effect of climate policies on air pollutants is analyzed.

2.2.2. Air quality policy model

As shown in Fig. 1, the air quality policy model estimates future air pollutant emissions based on the base-year emission inventory for air pollutants and the activity projection factors calculated through the process described in Section 2.2.1. Subsequently, it proceeds to estimate future emissions of air pollutants resulting from the application of air quality policies.

The reduction amount for each pollutant and policy was calculated using Equation (1), which involves applying rule penetration and control efficiency to future annual baseline emissions. This equation is applied individually for each distinct activity, with the subscript 'A' representing a pollutant. Future annual baseline emissions, $Emission_A$ is calculated by multiplying the activity and emission factors found in the emission inventory.

$$Reduction_A = Emission_A \times Rule\ Penetration_A \times Control\ Efficiency_A \tag{1}$$

The Rule Penetrations (RP) for all applicable emission reduction policies are stored in the Air Quality Policy DB shown in Fig. 1, while the Control Efficiencies (CE) for all applicable emission reduction technologies are stored in the Air Pollutant Reduction Technology DB also presented in Fig. 1. The GUIDE model provides the functionality for users to apply RPs and CEs related to specific policies and technologies when analyzing air quality policies and technologies. Therefore, before conducting an effectiveness analysis for new policies or technologies, it is necessary to update these databases.

Rule penetration (RP) is a variable that represents the extent to which a policy is implemented, expressed as a ratio. It is calculated as the ratio of emissions for which the effects of the measure can be applied to the total emissions in the sector where the policy is implemented. The calculation methods for the RP vary depending on whether the policy is institution-based or quantity-based. Institution-based measures are policies that legally establish reduction targets, while quantity-based measures are policies that specify planned quantities for the application of reduction technologies. The calculation methods for RP in each case are as follows.

- RP for institution-based measure: For policies that specify sub-sectors for reduction, use the emission ratio of sub-sector. Otherwise, if no sub-sectors are specified, consider the entire sector and input 100%.
- RP for quantity-based measure: Equation (2) calculates the ratio of emissions that can be reduced through the impact of a specific policy relative to the total emissions in the sector where the policy is applied. 'Emission reduction due to a specific policy' represents the portion of emissions that decreases from the initial emissions as a result of reduced activity due to the policy.

$$Rule\ Penetration_A = \frac{Emission\ reduction\ due\ to\ \ a\ specific\ poilcy}{Total\ emissions\ of\ the\ sector} \tag{2}$$

The calculation method for CE varies depending on whether the policy involves the direct application of emission reduction technology or not. The calculation methods for CE in each case are as follows.

- CE for direct technology applied measure: Results from research paper and technical reports related to the emission reduction efficiency of technologies were employed.
- CE for indirect technology applied measure: In cases of changing emission factors before and after reduction policy implementation, Equation (3) was used. Conversely, when emission amounts changed, Equation (4) was used.

$$Control\ Efficiency_A = 1 - \left(\frac{Emission\ factor\ after\ control}{Emission\ factor\ before\ control}\right) \tag{3}$$

$$Control\ Efficiency_A = 1 - \left(\frac{Emissions\ after\ control}{Emissions\ before\ control}\right) \tag{4}$$

2.3. Policy investigation & DB modification

2.3.1. Climate policies

Nationally Determined Contributions (NDC) were used as the climate policy applied in future analysis scenarios. To achieve its 2030 GHG reduction target, Korea conducted two rounds of analysis, in 2016 and 2018, to assess the reduction potential of the relevant sectors. Based on these findings, we establish a 2030 roadmap that includes sector-specific reduction plans. The sector-specific measures outlined in Table 1 were designed to construct energy mitigation scenarios within the GUIDE model.

Policies labeled as 'Y' in Table 1 are climate policies that not only reduce greenhouse gas emissions but also lead to a reduction in air pollutant emissions. These policies typically result in reduced emissions of air pollutants due to changes in combustion amount and conditions, such as transitions in energy sources. A policy labeled as 'N' in the table is the carbon tax policy, which aims to reduce carbon emissions through economic incentives. It is difficult to measure the direct air pollutant reduction effects of this policy in GUIDE.

We also applied the 9th Basic Plan for Electricity Supply and Demand (MOTIE, 2020), as described in Section 2.2.1. As a secondary energy source, electricity is mostly produced using primary energy sources as raw materials and has a substitutive relationship with primary energy consumption. Therefore, it is important to consider activities that influence emissions. The Basic Plan for Electricity Supply and Demand is the highest-level national plan regarding electricity in Korea. The 9th Basic Plan for Electricity Supply and Demand spans 2020–2034 and includes measures to transition the power mix, restrict the operation of coal-fired power plants, reduce coal-generated power, and expand renewable and LNG-generated power. By using the difference in fuel-specific power generation between the 9th Basic Plan for Electricity Supply and Demand and the 8th Basic Plan for Electricity Supply and Demand, the 9th Basic Plan for Electricity Supply and Demand was reflected in the GUIDE model.

2.3.2. Air quality policies

Regulatory policies regarding the management of emissions, demand forecasting, and energy activity are among the most important variables

Table 1
Climate policy by sector.

Sector	Technology	Co-control* modeled in GUIDE?
Power generation sector	20% new and renewable energy generation by 2030	Y
	Decommission 10 old coal-fired power plants	Y
	Convert four coal-fired power plants to LNG fuel	Y
	Apply technologies to retrofit 10 bituminous coal-fired power plants	Y
	Improve the efficiency of new coal-fired power plants	Y
	Suspend operation of coal-fired power plants during spring	Y
Transportation (ground) sector	30% commercialization of electric buses by 2030	Y
	3 million electric passenger vehicles by 2030	Y
	Restrict to 4 million hybrids vehicles	Y
	Scenarios for improving the average fuel efficiency of new passenger cars and buses	Y
Steel sector	Fuel measures (substitute B–C oil with LNG)	Y
Petrochemical sector	Improve energy efficiency of Naphtha Cracking Center (NCC) (improve by an average of 0.5% per year until 2030)	Y
Non-metallic sector	Increase share of slag cement (1 percentage point in 2020, 4 percentage points in 2025, 6 percentage points in 2030)	Y
Residential and commercial sectors	Carbon tax (USD 30/tCO_2eq. in 2020, USD 60/tCO_2eq. in 2030)	N

Co-control*: When climate policy is implemented, it has the effect of not only achieving climate policy related goals but also reducing air pollutant emissions.

for estimating and forecasting future emissions. Air pollutant reduction policies aim to preserve or improve air quality by identifying the emission characteristics of air pollution sources and controlling emissions using policy instruments or regulatory measures. The GUIDE model applies the Revised Second Master Plan for Seoul Metropolitan Area Air Quality Management, which is based on the "Study on the Revised Second Master Plan for Metropolitan Air Quality Management, Final Report." However, as the policy targets the Seoul Metropolitan Area, an air quality policy targeting the entire country is required. Accordingly, we examined the Master Plan for Air Quality Management by Region.

The Master Plan for Air Quality Management by Region divides the country into four regions that require management to enable air quality control tailored to each region. The Master Plan for Air Quality Management by Region expands the Master Plan for Metropolitan Air Quality Management to a nationwide scale, and the implementation period spans five years, from 2019 to 2024. To apply the Master Plan for Air Quality Control by Region to the GUIDE model, we modified the Master Plan for Air Quality Management by Region based on the Seoul Capital Area policy already incorporated in the GUIDE model. The policy and technology databases for each policy were created by referring to the GUIDE model's data structure and format. Table S1 shows the Tier 3 level policy names, sectors, and air pollutants aimed to be reduced.

Table 2 includes the names of these policies and indicates whether they are capable of reducing greenhouse gases such as CO_2. As explained in Section 2.2.1 regarding the order of the analysis process of the GUIDE model, it is not possible to assess changes in greenhouse gas emissions due to air quality policies. Therefore, the last column in Table 2 is labeled "N" for all policies. Nevertheless, policies marked in gray cells are the ones that could potentially lead to a simultaneous reduction in greenhouse gas emissions due to energy transition or energy usage reduction effect. It might be worth considering whether these policies could be incorporated into future improvements of the GUIDE model.

2.4. Future scenarios development

In this study, four scenarios were developed: the baseline scenario, the NDC scenario (where only the climate policy was applied to the baseline scenario), the AQM scenario (where only the air quality policy was applied to the baseline scenario), and the NDC+AQM scenario (where both policies were applied to the baseline scenario). More detailed explanations are as follows:

- The baseline scenario was created by applying middle-level socio-economic projections to the emissions of 2015 (the base year) as described in section 2.2.1. It was assumed that future policies were applied at the same level as in the base year and that no additional climate or air pollutant reduction policies were applied.
- In the NDC scenario, climate policies were added to the baseline scenario. The climate policies applied in this study are based on the Korea NDC announced in 2018, and they are listed in Table 1. The plan's coverage extends up to 2030. In this scenario, we aimed to examine the impact of the application of climate policies on the reduction of CO_2 emissions and the reduction of air pollutants due to the co-control effects of these policies.
- The AQM scenario involved the addition of air pollutant reduction policies to the baseline scenario. These policies are listed in Table 2 and are based on the Master Plan for Air Quality Management by Region announced in 2019. Given that the plan's coverage only extends up to 2024, we have assumed that the 2024 policy control will continue until 2030. In this scenario, our objective was to investigate the impact of air pollutant reduction policies on the decrease of atmospheric pollutants.
- To develop the NDC+AQM scenario, both energy and air pollutant reduction policies were added to the baseline scenario. In this scenario, the emission reduction effects of both climate and air pollution policies can be analyzed. Furthermore, when compared to results from other scenarios, it will illustrate the advantages of concurrently evaluating the impacts of climate policies and air quality policies using the GUIDE.

Using the GUIDE model, we created four scenarios depending on the presence or absence of climate policies and air quality policies, and calculated emissions for each scenario up to the year 2030. We started by constructing the Baseline scenario, which represents emissions in 2015 without any additional climate or air quality policies. Subsequently, we developed the other three scenarios. For each scenario, we made adjustments to activity levels and policy-related parameters, including RPs and CEs, to account for the specific policies applied.

3. Results

3.1. Future emissions estimation by scenario

In Table 3, the emissions for the base year, 2015, and the projected future emissions for each scenario are presented. In the GUIDE model, future emissions are estimated on an annual basis. We have compiled the annual emissions by substance for the years 2020, 2025, and 2030 in Table 3, along with the percentage change in emissions compared to the Baseline scenario emissions, which is provided in parentheses below each value. These figures represent the reduction effects resulting from the policies implemented in each scenario.

The emissions in the Baseline scenario exhibit a decreasing trend for most substances by 2025 compared to the base year of 2015. However, there is an increase in emissions by 2030. In the Baseline scenario, it is assumed that the policies applied in the base year of 2015 continue, which is why the emissions show a decrease even without additional policies. However, the emissions increase after 2025 because the reduction policies implemented after that year are not sufficient to counteract the socio-economic emissions growth. Notably, VOC and NH_3 emissions continue to increase, in contrast to other pollutants. This indicates that the reduction policies pertaining to VOC and NH_3 that were in place until 2015 were insufficient to effectively curtail their emissions.

In the NDC scenario, climate policies have a direct impact on controlling greenhouse gas emissions, specifically CO_2 emissions. Additionally, there's a decrease in emissions of air pollutants, which can be attributed to the effects of energy transition; this is referred to as co-control effects. Examining CO_2 emissions, which is the most significantly impacted pollutant, we observe that in 2020, there was a reduction of 7.7% compared to the Baseline scenario emissions. By 2025, this reduction increased to 10.6%, and by 2030, it reached a 31.6% reduction. This indicates that the climate policies implemented in the NDC scenario became more focused as the target year of 2030 approached, and the analysis results indeed confirm the effectiveness of these policies. In South Korea's NDC (2018), the goal is to achieve a 22.3% reduction in greenhouse gas emissions by 2030 compared to the emissions in 2015. Referring to Table 3, CO_2 emissions in the base year of 2015 were 646.1 Tg/yr, while in 2030, they are projected to be 451.3 Tg/yr. This estimation demonstrates that the NDC policies have achieved a 30.2% reduction, meeting their emission reduction target.

In the AQM scenario, significant reductions in emissions of air pollutants, including SO_x, NO_x, $PM_{2.5}$, and VOC, are observed. Looking at the substance with the most significant emission reduction, SOx, we can see that in 2020, emissions show a reduction of 34.0%, in 2025, a reduction of 56.4%, and in 2030, a reduction of 54.4%. The relatively lower reduction rate in 2030 is due to the fact that South Korea's air quality policies, applied in the AQM scenario, are planned up to the year 2024. In this study, it is assumed that these policies remain the same until 2030. This implies that more stringent policies need to be established beyond 2024 to address the socioeconomic increase in emissions

Table 2
Air pollutant reduction policy by emissions sector.

Tier 1	Tier 2	Tier 3	Co-control ** modeled in GUIDE?
Control measures for emissions facilities	Strengthen air pollutant cap-and-trade	Strengthen air pollutant cap-and-trade	N
	Manage emissions facilities other than cap-and-trade	Strengthen emissions standards (excluding cap-and-trade)	N
		Manage small incinerator facilities	N
		Restrict sulfur content using fuel at workplace	N
		Restrict solid fuel use at workplace	N
		Support low NO_x burner substitution	N
		Establish VOC facility management standards	N
Control measures for everyday pollution sources	Strengthen control of everyday VOC and NO_x emissions	Restrict solvent content	N
		Expand use of water-based paints	N
		Expand use of eco-friendly printing inks and paints	N
		Manage solvents in laundromats	N
		Strengthen control of VOC sources in urban centers	N
		Install Gas station vapor recovery system (Stage II)	N
		Restrict sulfur content using fuel in boilers	N
		Convert anthracite for civilian use to clean fuel	N
		Support and mandate low NO_x boiler replacement	N
	Strengthen control of PM_{10} and $PM_{2.5}$ in everyday environments	Install prevention facilities at charcoal kilns	N
		Install prevention facilities at grilled restaurants	N
		Recycling collection	N
		Shared collection facilities in rural areas	N
		Enforce illegal burning zones	N
		Operate dust collection vehicles and vacuum cleaning vehicles	N
		Supply low-wear tires	N
		Manage fugitive dust emission workplace	N
		Manage open lots (planting grass on school grounds, etc.)	N
		Establish road design standards	N
		Reduce fugitive dust emissions at construction sites	N
Control measures for road-mobile pollution sources	Expand supply of eco-friendly vehicles	Supply electric vehicles	N
		Supply electric two-wheeled vehicles	N
		Supply electric freight vehicles	N
		Supply hydrogen fuel cell vehicles	N
	Strengthen emissions standards and post-management of production vehicles	Strengthen emissions standards for diesel vehicles	N
		Strengthen emissions standards for two-wheeled vehicles	N
	Strengthen control of vehicle exhaust emissions	Install DPF in old vehicles	N
		Install p-DPF in old vehicles	N
		Retrofit engines of old vehicles	N
		Early retirement of old vehicles	N
		Install PM-NO_x simultaneous reduction device	N
		Support SCR installation for old diesel vehicles	N
		Supply CNG buses	N
		Restrict operation of polluting vehicles in LEZs	N
Control measures for non-road mobile pollution sources	Strengthen emissions standards and post-management of production machinery	Strengthen emissions standards for construction machinery	N
		Strengthen emissions standards for agricultural machinery	N
	Strengthen control of transport machinery	Install DPF on old construction machinery	N
		Replace engines in old construction machinery	N
		Substitute electric engines in old construction machinery	N
		Use onshore power supply facilities	N
		Strengthen sulfur content standards for ship fuel oil	N
		Designated as a sulfur oxide emission regulation area	N

Co-control**: An air quality improvement policy was implemented, which not only achieved reducing air pollutant emissions but also reduced energy use and related CO_2 emissions.

Table 3
Future emissions by scenario.

Pollutants		CO_2	SO_x	NO_x	$PM_{2.5}$	VOC	NH_3
Unit		Tg/yr	Gg/yr	Gg/yr	Gg/yr	Gg/yr	Gg/yr
2015	Base year	646.1	342.1	1075.5	96.0	995.8	297.2
2020	Baseline	617.5	339.4	1046.7	94.9	1041.7	312.8
	NDC	570.0 (▾7.7%)	321.9 (▾5.2%)	1004.2 (▾4.1%)	89.4 (▾5.7%)	1039.9 (▾0.2%)	311.2 (▾0.5%)
	AQM	617.5 (0.0%)*	224.1 (▾34.0%)	842.8 (▾19.5%)	50.3 (▾47.0%)	709.4 (▾31.9%)	312.8 (▾0.0%)
	NDC+AQM	570.0 (▾7.7%)	213.2 (▾37.2%)	800.3 (▾23.5%)	49.4 (▾48.0%)	707.3 (▾32.1%)	311.2 (▾0.5%)
2025	Baseline	612.3	332.4	1038.5	94.9	1048.8	326.4
	NDC	547.4 (▾10.6%)	311.7 (▾6.2%)	969.3 (▾6.7%)	87.5 (▾7.8%)	1040.5 (▾0.8%)	321.9 (▾1.4%)
	AQM	612.3 (0.0%)	145.0 (▾56.4%)	705.9 (▾32.0%)	48.4 (▾49.0%)	702.9 (▾33.0%)	326.2 (▾0.1%)
	NDC+AQM	547.4 (▾10.6%)	130.9 (▾60.6%)	637.9 (▾38.6%)	46.2 (▾51.3%)	694.1 (▾33.8%)	321.7 (▾1.4%)
2030	Baseline	659.7	345.1	1062.1	96.1	1057.5	340.7
	NDC	451.3 (▾31.6%)	290.0 (▾16.0%)	884.8 (▾16.7%)	80.2 (▾16.6%)	1036.9 (▾1.9%)	332.6 (▾2.4%)
	AQM	659.7 (0.0%)	157.2 (▾54.4%)	722.4 (▾32.0%)	49.5 (▾48.5%)	704.4 (▾33.4%)	340.6 (▾0.0%)
	NDC+AQM	451.3 (▾31.6%)	121.6 (▾64.8%)	563.0 (▾47.0%)	44.9 (▾53.3%)	684.8 (▾35.2%)	332.4 (▾2.4%)

*The numbers within parentheses represent the reduction percentage relative to the Baseline scenario.

adequately. Particularly noteworthy is the case of NH_3, which shows nearly a 0% reduction rate, indicating that the emission reduction policies implemented after 2015 have not been sufficient.

The NDC+AQM scenario, which combines both climate and air quality policies, exhibits the characteristics of both the previously explained NDC scenario and AQM scenario in terms of emission reduction effects. It can be considered the most realistic scenario because it represents the most realistic results of the combined implementation of climate and air quality policies. However, there is a difference in the values between simply summing up the effects of the NDC scenario and AQM scenario separately and the combined NDC+AQM scenario. This difference is analyzed and explained in detail in the following section.

3.2. Analysis of control and Co-control effects

As explained earlier, in reality, both climate and air quality policies are implemented simultaneously, each demonstrating control effects and co-control effects. Determining the exact sequence of applying the effects of climate policies and air quality reduction policies in practice can be challenging. However, in the GUIDE model, the approach is to first apply climate policies, resulting in changes in activities. Then, it recalculates air pollutant emission estimates based on these changed activities and subsequently implements air quality policies. The reason for this sequence in the GUIDE model, as established in the prior study (ME, 2020), is that climate policies primarily focus on policies related to energy use, which are sensitive to socio-economic changes. In contrast, air quality policies primarily involve reduction measures and technologies for facilities that emit pollutants. Consequently, the co-control effects of climate policies on air pollutant emissions are analyzed, but the co-control effects of air quality policies on greenhouse gas emissions are not analyzed. However, this approach helps eliminate redundancies when applying air pollutant reduction measures to emissions that have already been reduced by climate policies.

First, when examining the control and co-control effects of climate policies and air quality reduction policies, the following observations can be made. Fig. 2 represents the reductions by sector for the three scenarios (NDC, AQM, and NDC+AQM). The reductions for the NDC scenario are represented by blue bars, while the AQM scenario's reductions are indicated by green bars. The reductions for the NDC+AQM scenario are marked with orange asterisks. By comparing the reductions in emissions for each pollutant, we can distinguish between control and co-control effects. Looking at the reduction in CO_2 emissions, it is evident that only the NDC scenario leads to emission reductions. Consequently, the NDC+AQM scenario shows the same reduction, indicating that CO_2 emissions are reduced due to the control effect of CO_2 climate policies. The blue bars for air pollutants represent reductions due to co-control effects from climate policies, while the green bars represent reductions due to control effects from air quality policies. Specifically, SO_x, NO_x, and $PM_{2.5}$, which are emitted from combustion processes or fuels, show significant co-control effects in sectors such as the Energy sector, Industrial combustion, and Road transport, as expected. Conversely, VOC emissions, due to their emission characteristics, are predominantly reduced by air quality policies. NH_3 emissions exhibit co-control effects in sectors such as the energy sector, industrial combustion, and road transport due to climate policies, but due to the very limited NH_3 reduction effects in air quality policies, they exhibit relatively prominent co-control effects.

Next, the reductions achieved through the simple summation of the reduction effects of climate policies and air quality policies applied independently with the integrated policy reduction effects were compared. In Fig. 2, the combined blue and green bars for each sector represent the sectoral reductions obtained through simple summation, while the orange asterisks represent the sectoral reductions obtained through the integrated analysis. Notably, sectors with significant differences are the Energy sector, Industrial combustion, and Road transport sectors, which exhibit considerable co-control effects. The extent of difference varies by sector. The detailed figures are provided in Appendix Table S2. As shown in Table 3 and in the NDC+AQM scenario, the reductions in CO_2, SO_x, NO_x, and $PM_{2.5}$ were 31.6%, 64.8%, 47.0%, and 53.3%, respectively. This shows a difference of 0.0%p, 5.6%p, 1.7%p, and 11.8%p, respectively, compared to the simple summation of pollutant-specific reduction effects from the NDC and AQM scenarios. This indicates that by separately analyzing climate policies and air quality policies, there might have been an overestimation of the reduction effects to this extent.

3.3. Analysis of reduction effects by policies

To examine the detailed effects of South Korea's climate and air quality policies, we compared the results of the most realistic policy scenario, the NDC+AQM scenario, with the baseline scenario, which does not include additional future policies. The comparison was focused on the target year, 2030. In Fig. 3, we represented sector-specific emissions in the baseline scenario, with greenhouse gases shown in red bars and air pollutants shown in black bars. This allows for a comparison of the reduction achieved in the NDC+AQM scenario compared to the baseline scenario. The reductions in the NDC+AQM scenario resulting from climate policies are represented by blue bars, while those resulting from air quality policies are represented by green bars. Additionally, we calculated the ratio of reduction in the NDC+AQM scenario compared to emissions of the baseline scenario for each sector and marked it with yellow diamonds. This ratio can serve as an indicator of whether the combined climate and air quality policies are achieving sufficient emission reductions in specific sectors. When examining the reduction effects of South Korea's planned policies by pollutant and sector, the following observations can be made.

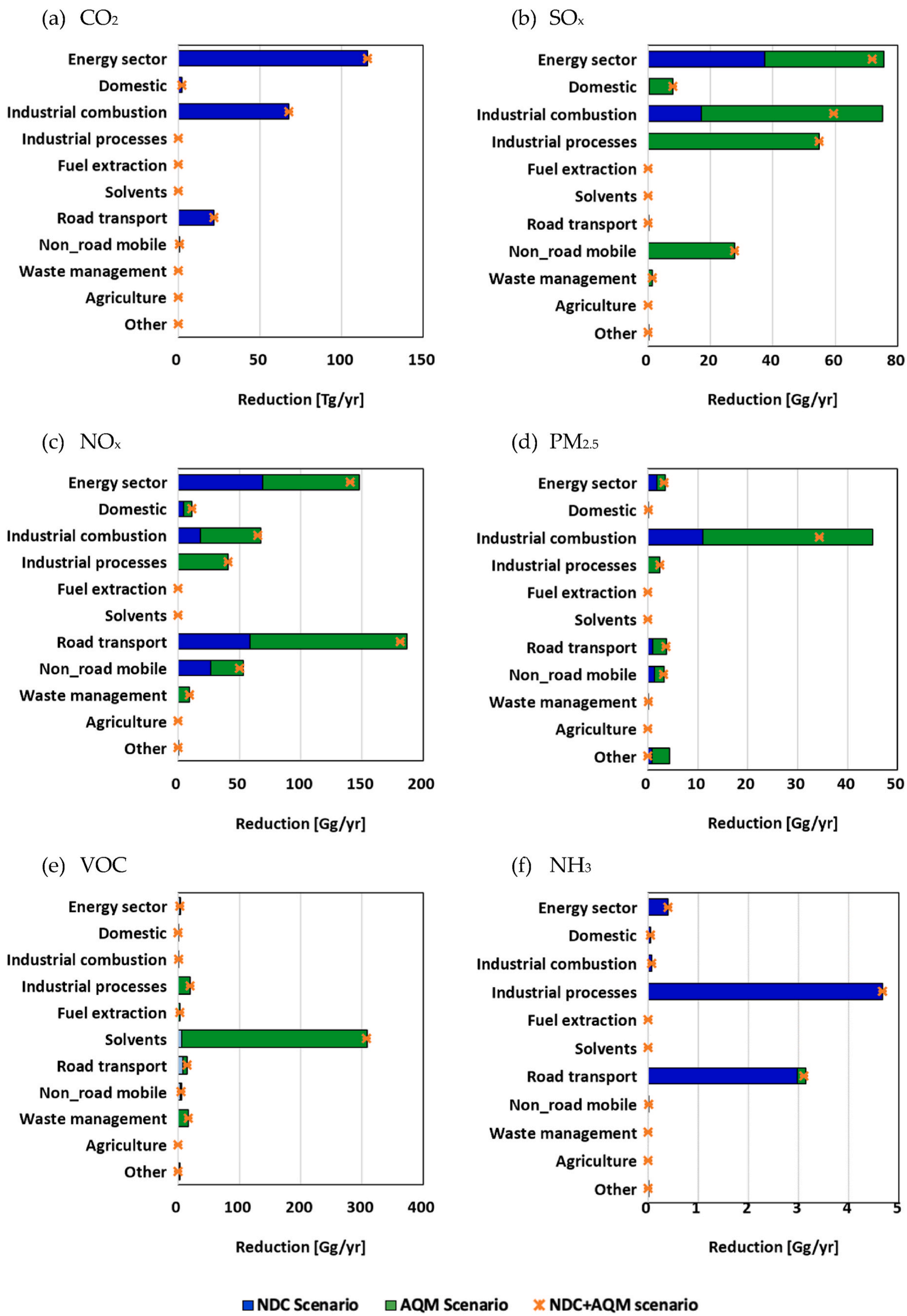

Fig. 2. Emission reductions by sector for each scenario.

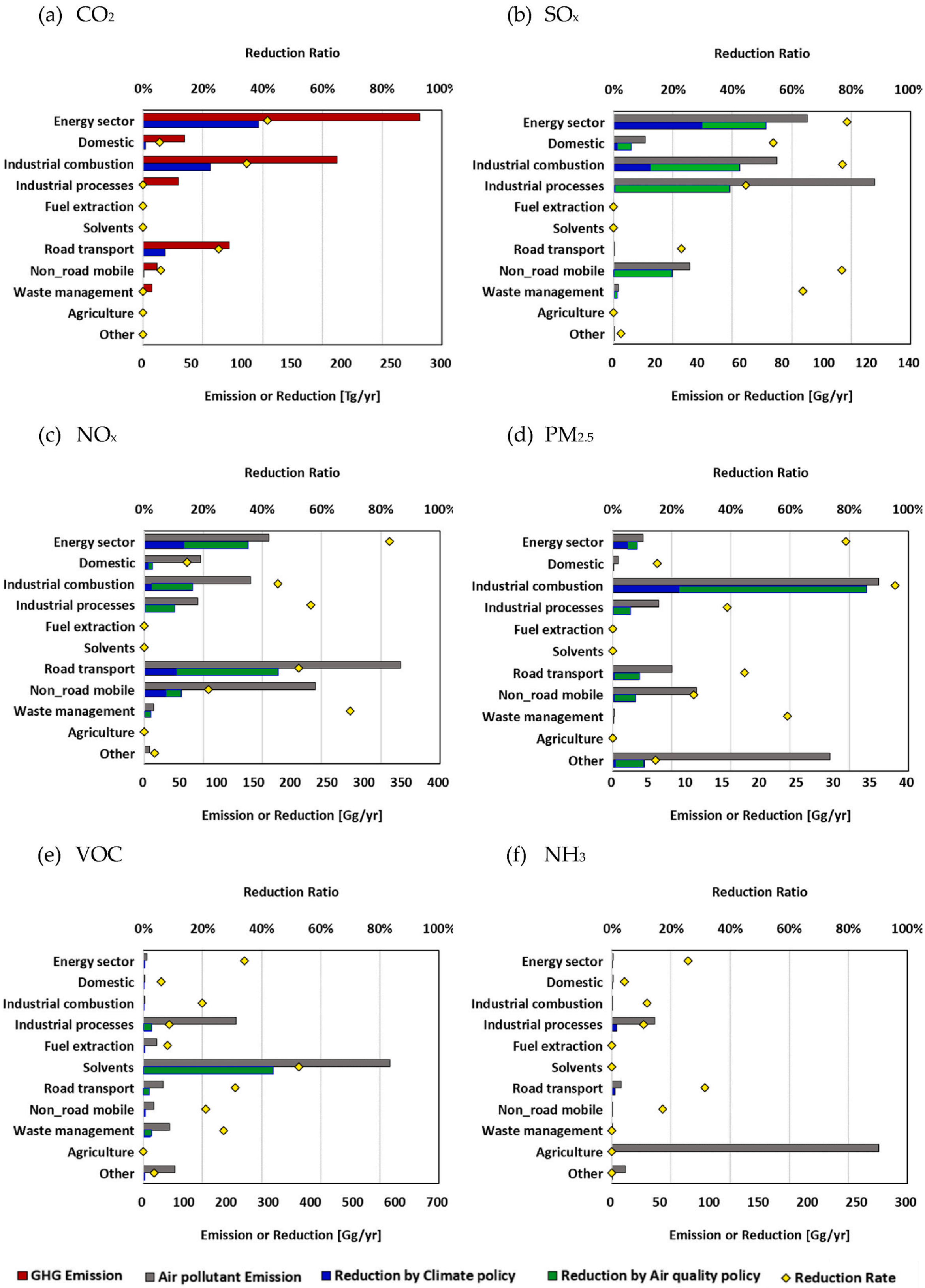

Fig. 3. Emissions in the Baseline scenario and reductions in the NDC+AQM scenario in 2030.

Firstly, when considering CO_2 emissions, we observe reduction effects from climate policies, especially in the Energy sector, Industrial combustion, and Road transport sectors, which are major emission sources. It is evident that reduction policies in these sectors contribute significantly to emissions reductions. However, in the case of the Road transport sector, reductions are approximately 10%, indicating a need for policy reinforcement. On the other hand, the Industrial processes and Waste management sectors, despite having high emissions, show almost

0% reduction rates. These results can be attributed to the fact that most of South Korea's NDC climate policies applied in GUIDE are primarily related to fuel combustion, as summarized in Table 1. Consequently, the policy effects in the two mentioned sectors were not adequately reflected. This is an aspect that will need to be considered in future improvements to the GUIDE model.

SO_x, NO_x, and $PM_{2.5}$ are pollutants that are reduced through the co-control effects of climate policies and the control effects of air quality policies. When examining the reduction rates for each of these pollutants, the following observations can be made. SO_x show an overall high reduction rate. However, it's worth noting that even though the industrial processes sector is the largest emission source, its reduction rate stands at 40%. Considering the high emissions from this sector, implementing further reduction policies could lead to more significant reductions in SO_x emissions. NO_x also demonstrates a generally high reduction rate. However, enhancing reduction rates in major emission sources such as road transport and non-road mobile sectors could result in even greater reductions in NO_x emissions. Therefore, it's essential to consider additional reduction measure for these sectors. $PM_{2.5}$ show high reduction rates in most sectors, reflecting significant policy efforts in South Korea to reduce $PM_{2.5}$ emissions. Nevertheless, the Other sector, the second-largest emission source, only achieves a 10% reduction rate. This indicates the need for policy reinforcement, particularly for fine dust emissions within this sector. Strengthening policies specific to fine dust emissions in this sector could significantly contribute to $PM_{2.5}$ reduction.

VOC emissions show few reduction effects due to climate policies but show most reductions due to air quality policies. The Solvents sector, which has the highest emissions, shows the highest reduction rate at around 50%. In contrast, the Industrial processes sector, with the next highest emissions, achieves a reduction rate of around 10%. In other sectors, some reduction effects seem to be present. However, these sectors have low emissions, and it is unlikely that they will have a significant impact on the overall reduction of VOC emissions. To achieve more substantial VOC emission reductions, it is advisable to focus on policy measures in sectors with high emissions, namely the Solvents sector and Industrial processes. Strengthening policies in these sectors can lead to more significant reductions in VOC emissions.

In Fig. 2(f), NH_3 emissions appear to have a significant reduction effect due to climate policies. However, this is misleading, as it results from the almost negligible impact of air quality policies, as indicated in Fig. 3(f). Specifically, Fig. 3(f) shows that the reduction effect of climate policies on NH_3 emissions is also very low. Of particular concern is the agriculture sector, the largest emission source, which exhibits a reduction rate close to 0%. This is a concerning issue, highlighting the urgent need for policy measures to reduce NH_3 emissions in the agriculture sector.

4. Conclusions

This study aims to analyze the impact of Korea's energy and air pollutant reduction policies using the integrated assessment model, the GUIDE. To achieve this, we investigated recent relevant Korean policies and modified the policy and technology databases in the GUIDE. Four scenarios (baseline, NDC, AQM, and NDC+AQM scenarios) were developed to examine the control and co-control effects of policy implementation. By analyzing the estimated future emissions inventories under each scenario, this study provides a quantitative analysis of the effects of Korea's climate policy, air pollutant reduction policy, integrated policies.

The emissions for the baseline scenario, analyzed under the assumption that the policies in place in the base year of 2015 remain unchanged, showed a decreasing trend for most substances until 2025, followed by an increase in 2030. This indicates that the policies applied in the base year are insufficient beyond 2025, highlighting the need for additional policies. In the NDC scenario, the influence of climate policies led to a significant reduction in CO_2 emissions from 2020 to 2030. In the AQM scenario, air pollutant emissions decreased significantly until 2025. In the NDC+AQM scenario, the combined effects of climate and air quality policies were presented. Since both policies are being implemented simultaneously in reality, this scenario was considered as a focused scenario that requires additional analysis.

In comparison to the Baseline scenario, we assessed the sector-specific reductions in three policy scenarios by the year 2030. We have confirmed that the GUIDE model, which integrates the analysis of climate policies and air quality policies, allows for a more accurate quantification of policy effects compared to the approach of separately analyzing and simply summing these policies. In the NDC+AQM scenario, the reductions in CO_2, SO_x, NO_x, and $PM_{2.5}$ had differences of 0.0%p, 5.6%p, 1.7%p, and 11.8%p, respectively, compared to simply summing the pollutant-specific reduction effects of the NDC and AQM scenarios. This indicates that when analyzing climate policies and air quality policies separately, there might have been an overestimation of the reduction effects to this extent. In other words, this emphasizes the advantage of an integrated assessment model that can consider overlapping effects between policies.

Furthermore, in this analysis, we quantified and compared the control effects and co-control effects of climate policies and air quality policies. Climate policies had a significant control effect, resulting in a notable reduction in the greenhouse gas CO_2, particularly impacting the Energy sector and Industrial combustion sectors. The co-control effects led to reductions in SO_x, NO_x, and $PM_{2.5}$ emissions in sectors associated with fuel combustion. In air quality policies, the control effects led to reductions in SO_x, NO_x, $PM_{2.5}$, and VOC emissions. However, the co-control effects on CO_2 were not analyzed. This is because the GUIDE model is structured to apply air quality policies after climate policies, making it challenging to assess the greenhouse gas effects of air quality policies. Nevertheless, some air quality policies are expected to indirectly influence greenhouse gas reductions by decreasing energy consumption. Addressing these indirect effects will be necessary in future model improvements.

The analysis of pollutant-specific and sector-specific policy effects in the NDC+AQM scenario for the year 2030, compared to the Baseline scenario, has revealed insufficient reductions, especially in major emission sectors. To enhance the reduction effects, additional policies and reduction measures are required in these sectors. Additional reduction policies should be considered for the Energy sector, Industrial combustion, and Road transport to achieve reductions in CO_2, SO_x, NO_x, and $PM_{2.5}$. Notably, pollutants such as NH_3 and VOC continue to increase in emissions as industries and society advance, yet there have been inadequate preparations for reduction policies. Consequently, it is crucial to develop and implement emission reduction policies, especially in sectors such as Industrial Processes for VOC and in Agriculture and Industrial Processes for NH_3, as they are significant emission sources.

The reason for the lower reduction effects in this study, in contrast to recent policy trends, is because the climate policies applied in this study are based on the previous NDC policy drafted in 2018, and the air quality policy is considered only until 2024. South Korea's climate policies have been adjusted for 2030 due to the 2050 carbon neutrality issue, and it is anticipated that the policy effects would be greater than what is reflected in this study. In future studies, analyzing the revised NDC policies for carbon neutrality would enable additional quantification of the effectiveness of enhanced policies. Furthermore, the analysis of the effects of new air quality policies applied after 2025 is expected to yield stronger reduction results. Nevertheless, the findings of this study can serve as valuable reference material in the policy enhancement process for emission sources with limited policy effects beyond 2025.

This study mainly concentrated on policy comparative analysis using future emission projections from the GUIDE. In our future research, we plan to broaden our analysis to include the assessment of potential health benefits related to air pollution reduction. Analyzing air pollution improvement policies from an economic perspective involves estimating the costs and benefits associated with implementing emission reduction options to improve air quality. Therefore, policy evaluations can be conducted cost-effectively. Estimating the costs and benefits of air quality improvement through economic analysis can provide valuable information for selecting policy alternatives and help policymakers make informed decisions on how to allocate resources most efficiently to reduce air pollution and improve public health. This approach could ultimately lead to more effective and targeted air pollution reduction policies that benefit both the environment and public health.

Author statement

Youjung Jang: Formal analysis, Data Curation, Writing - Original Draft, Hyejung Hu: Writing - Review & Editing, Validation, Bomi Kim: Investigation, Younha Kim: Validation, Seung-Jick Yoo: Resources, Kyungae Jang and Yoon-Kwan Kim: Software, Hyungah Jin: Resources, Jung-Hun Woo: Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Rafaj, P., Schöpp, W., Wagner, F., 2011. Cost-effective Emission Reductions to Improve Air Quality in Europe in 2020. IIASA, Laxenburg.
Amann, M., Kiesewetter, G., Schöpp, W., Klimont, Z., Winiwarter, W., Cofala, J., Rafaj, P., Höglund-Isaksson, L., Gomez-Sabriana, A., Heyes, C., Purohit, P., Borken-Kleefeld, J., Wagner, F., Sander, R., Hilde, F., Nyiri, A., Cozzi, L., Pavarini, C., 2020. Reducing global air pollution: the scope for further policy interventions. Phil. Trans. Math. Phys. Eng. Sci. https://doi.org/10.1098/rsta.2019.0331.
BP, 2021. Full Report – Statistical Review of World Energy.
Choi, Y.-J., Choi, K.-C., Lee, S., Lee, H.-J., 2020. Study on Seasonal Particulate Matter (PM) Management to Prevent High Pollution Events. The Seoul Institute.
Comprehensive Plan on Fine Dust, 2017. Relevant Ministry.
Comprehensive Plans for Fine Dust Management, 2019. Relevant Ministry.
D'Elia, I., Piersanti, A., Briganti, G., Cappelletti, A., Ciancarella, L., Peschi, E., 2018. Evaluation of mitigation measures for air quality in Italy in 2020 and 2030. Atmos. Pollut. Res. 9 (6), 977–988. https://doi.org/10.1016/j.apr.2018.03.002.
Development of Climate Pollutants Emission Inventory for East Asia(III), Final Report, 2019. Minist. Environ.
Development of the Decision Supporting System for Integrated Management of GHGs and Air Pollutants, Final Report, 2020. Minist. Environ.
Korean Green New Deal, 2020. Relevant Ministry.
Hwang, I.-C., Baek, J.-R., Jeon, E.-M., Ahn, M.-J., 2021. Cost-effective Reduction of Air Pollutants in Seoul. The Seoul Institute.
Hwang, I.-C., Kim, C., Son, W., 2018. Benefits of Management Policy of Seoul on Airborne Particulate Matter. The Seoul Institute.
IPCC, 2014. Climate Change 2015: Impacts, Adaptation & Vulnerability. Fifth Assessment Report.
Kim, S.-I., Kang, B., 2020. Analysis on Particulate Matter Policy Effects in the Power and Transport Sectors. Korea Energy Economics Institute.
Kim, J., Park, J., Hu, H., Crippa, M., Guizzardi, D., Chatani, S., Kurokawa, J., Morikawa, T., Yeo, S., Jin, H., Woo, J.-H., 2023a. Long-term Historical Trends in Air Pollutant Emissions in South Korea (2000–2018). Asian Journal of Atmospheric Environment (accepted).
Kim, S., Kim, J., Hu, H., Jang, M., Lee, J.-B., Hong, S.C., Kim, O., Woo, J.-H., 2023b. Update of the Year 2019 Modeling Emissions Inventory in China. Asian Journal of Atmospheric Environment (accepted).
Koo, Y., Shin, J., Lee, M., 2018. Cost-effectiveness analysis of policies to reduce fine dust emissions in power generation and industrial sectors. J. Ind. Econ. Business 31 (1), 347–367.
Liu, X., Guo, C., Wu, Y., Huang, C., Lu, K., Zhang, Y., Duan, L., Cheng, M., Chai, F., Mei, F., Dai, H., 2023. Evaluating cost and benefit of air pollution control policies in China: a systematic review. J. Environ. Sci. 123, 140–155. https://doi.org/10.1016/j.jes.2022.02.043.
OECD, 2009. Co-Benefits of climate change mitigation policies: literature review and new results. ECO/WKP 34, 2003.
Special Plan on Fine Dust, 2016. Relevant Ministry.
The 2nd Master Plan for Coping with Climate Change, 2019. Ministry of Environment.
The 9th Basic Plan for Electricity Supply and Demand, 2020. Ministry of Trade, Industry and Energy.
Woo, J.-H., Kim, Y., Kim, H.-K., Choi, K.-C., Eum, J.-H., Lee, J.-B., Lim, J.-H., Kim, J., Seong, M., 2020. Development of the CREATE inventory in support of integrated climate and air quality modeling for Asia. Sustainability 12 (19), 7930. https://doi.org/10.3390/su12197930.
Wu, R., Liu, F., Tong, D., Zheng, Y., Lei, Y., Hong, C., Li, M., Liu, J., Zheng, B., Bo, Y., Chen, X., Li, X., Zhang, Q., 2019. Air quality and health benefits of China's emission control policies on coal-fired power plants during 2005–2020. Environ. Res. Lett. 14, 094016.