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Ambient Air Quality Synergies with a 2050 Carbon Neutrality Pathway in South Korea

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Abstract: South Korea is a signatory of the Paris Agreement and has announced its aim to achieve carbon neutrality by 2050. However, South Korea's current policy trajectory is not compatible with maintaining a global temperature rise below 2 °C. Climate change has not been a dominant electoral issue in South Korea, with national concerns being prioritized. A Paris-Agreement-compatible development pathway could synergistically improve ambient air quality in South Korea. This research examines the gains of a climate action pathway that would achieve 2050 carbon neutrality, compared to a business-as-usual (BAU) pathway, in South Korea. The work aims to add further evidence to the potential national gains from strong climate action across all sectors in South Korea. The paper argues that by focusing on and estimating national gains, the momentum for enhanced climate policy action can be intensified by framing robust climate action as an opportunity rather than a cost. Through a climate action pathway, South Korea could avoid 835 years of life lost (YLL) in 2030, 2237 YLL in 2040 and 3389 YLL in 2050. Through this pathway, South Korea could also cumulatively abate 5539 million tons of CO₂ equivalent (MtCO_{2e}) in greenhouse gas emissions over the 2022–2050 period.

Keywords: climate change; mitigation; South Korea; air quality; carbon neutrality



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1. Introduction

Working Group I's contribution to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), released in August 2021, has further underlined the urgency of rapidly reducing global greenhouse gas (GHG) emissions. The evidence for anthropogenic climate change has increased since the publication of the fifth assessment report (AR5), with observed changes in extreme weather events such as heatwaves and heavy precipitation [1]. The report states that global temperature increases will exceed 1.5 °C and 2 °C unless GHG emissions are massively reduced in the coming decades [1].

Under the Paris Agreement, South Korea has agreed to limit warming to no more than 2 °C, with President Moon Jae-in announcing in October 2020 that South Korea will strive to become carbon-neutral by 2050. However, South Korea's current policy trajectory and declared Nationally Determined Contribution (NDC) has been criticized as being incompatible with maintaining a global temperature rise below 2 °C [2]. In February 2021, 83% of South Korea's primary energy supply was from fossil fuels [3], meaning that a massive green transformation will be needed to decarbonize its economy. Climate change has not been a dominant issue in elections in South Korea. Other concerns, such as national air pollution levels, are consistently a higher priority for South Korean voters [4,5]. A green transition is regularly framed as a cost that should be avoided, by interest groups opposing swift reductions in GHG emissions. For example, the Federation of Korean Industries (FKI), which consists of Korea's major companies, maintains that South Korea's climate goals cannot be too ambitious, as its economy is still centered on manufacturing [6].

Mitigation of climate change can result in large health benefits [7–9]. South Korea has high levels of air pollution, with significant adverse health impacts [10–12]. The PM_{2.5} concentration levels in South Korea's capital Seoul are roughly double the levels of

other major cities in developed countries, with an air pollution mortality rate of 20.5 per 100,000 population (age-standardized) in 2016 [13]. The continued combustion of fossil fuels will keep damaging ambient air quality, resulting in higher levels of premature deaths in the future [7,14–17]. Older individuals are more vulnerable to the detrimental effects of low air quality. As shown in Figure 1, almost 60% of South Korea’s population is projected to be 50 or older in 2050 [18]. Older individuals suffer more intense detrimental impacts from exposure to air pollution. Therefore, the effects of low air quality in South Korea will worsen over time due to the steep increase in the aged population.

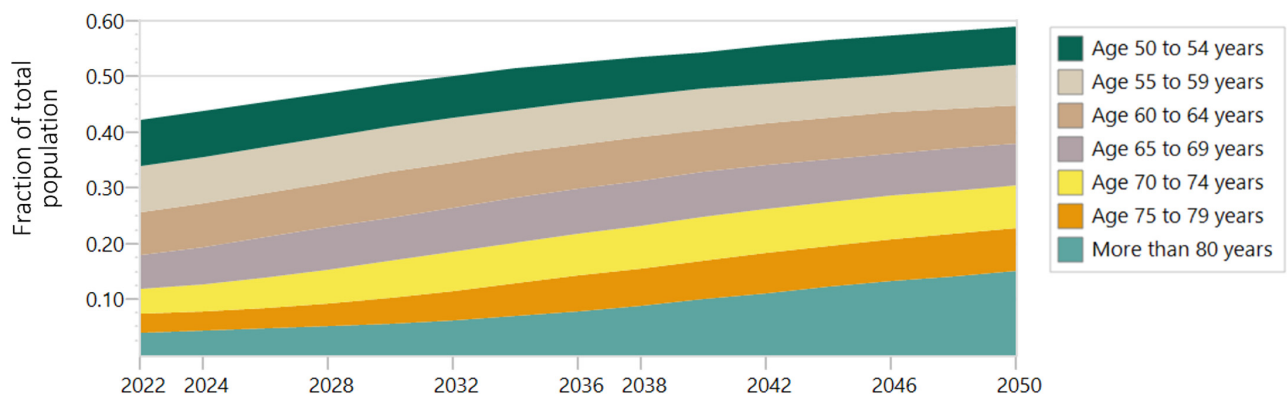


Figure 1. The predicted population of South Korea by age group from 2022–2050. South Korea’s population is projected to remain at about 51 million people for the next decade, and then decrease to about 47 million by 2050 [18].

Climate change is also predicted to have other, increasingly negative effects in South Korea [19–22]. For example, water quality in South Korea would be negatively affected by climate change [23]. A higher average temperature would increase the probability of algae blooms in water supplies [24]. Water shortages are also predicted to gradually intensify in the future, particularly in southern regions in South Korea [25]. Strong climate action would improve ambient air quality and address climate change. National benefits offset the costs of climate change mitigation [26,27], and focusing on such national positive impacts can help spur greater mitigation policy implementation [28]. The argument for a swift implementation of stronger green policies in South Korea is strengthened by emphasizing national gains.

In August 2021, South Korea enacted the Framework Act on Carbon Neutrality and Green Growth, which entailed its 2050 carbon neutrality pledge as well the target of reducing total GHG emissions by 35% by 2030, compared to 2018 levels. The South Korean government officially announced its more ambitious nationally determined contribution (NDC) at the 2021 United Nations Climate Change Conference (COP26) in November 2021. In August 2021, the Presidential Committee on Carbon Neutrality released three draft proposal scenarios for 2050 Carbon Neutrality, detailing GHG emissions by sector, but only the third scenario entails complete net zero emissions, as the first and second scenarios entail offsetting by overseas afforestation [29].

This paper aims to estimate the associated national gains from a reduced GHG emissions pathway, hereafter referred to as the ‘climate action pathway’. The work aims to provide evidence for the potential of a 2050 carbon neutrality emissions pathway to synergistically improve atmospheric air quality, and thus support the case for more ambitious climate action in South Korea. The article first outlines the methodology used to calculate the greenhouse gases (GHGs) that would be avoided, as well as those of other air pollutants, as well as its methodology for calculating some of the health benefits of the climate action pathway. The results are then outlined and analyzed. The article concludes by discussing how consideration of the additional benefits of climate action is important in the context of South Korea, and how South Korea needs to develop its overall low-carbon infrastructure.

2. Materials and Methods

This research estimates the climate change mitigation effect and associated potential positive impacts on ambient air quality from a ‘climate action pathway’. The year 2018 was selected as the baseline year of this study, as it is the base year of South Korea’s GHG emissions reduction target, part of its NDC under the Paris Agreement. The climate action pathway would meet both the 2030 35% reduction in GHG emissions compared to 2018 target, and the 3rd draft for a 2050 carbon-neutrality scenario, with a target of net zero emissions. The benefits are calculated compared to a business-as-usual (BAU) pathway. The climate action pathway assumes a linear yearly reduction in GHG emission levels from the first scenario year of 2022 to 2030, in which total emissions are reduced by 35% compared to 2018 levels. The emission reductions in each sector broadly follow the proportional reduction in South Korea’s 2050 Carbon Neutral Strategy of the Republic of Korea, released in 2020 [30], which includes details of the emission reductions needed in each sector to meet South Korea’s previous NDC of a 24% emission reduction compared to 2018 levels. To meet the 2030 target, the largest decrease in fossil fuel use and associated GHG emissions is needed in the electricity generation sector, with a 40% decrease in GHG emissions. From 2030 to 2050, a linear yearly decrease is assumed to meet the sector emissions of the 3rd draft 2050 Carbon Neutrality scenario. The 3rd draft 2050 Carbon Neutrality scenario, which results in net zero emissions, is shown in Figure 2.

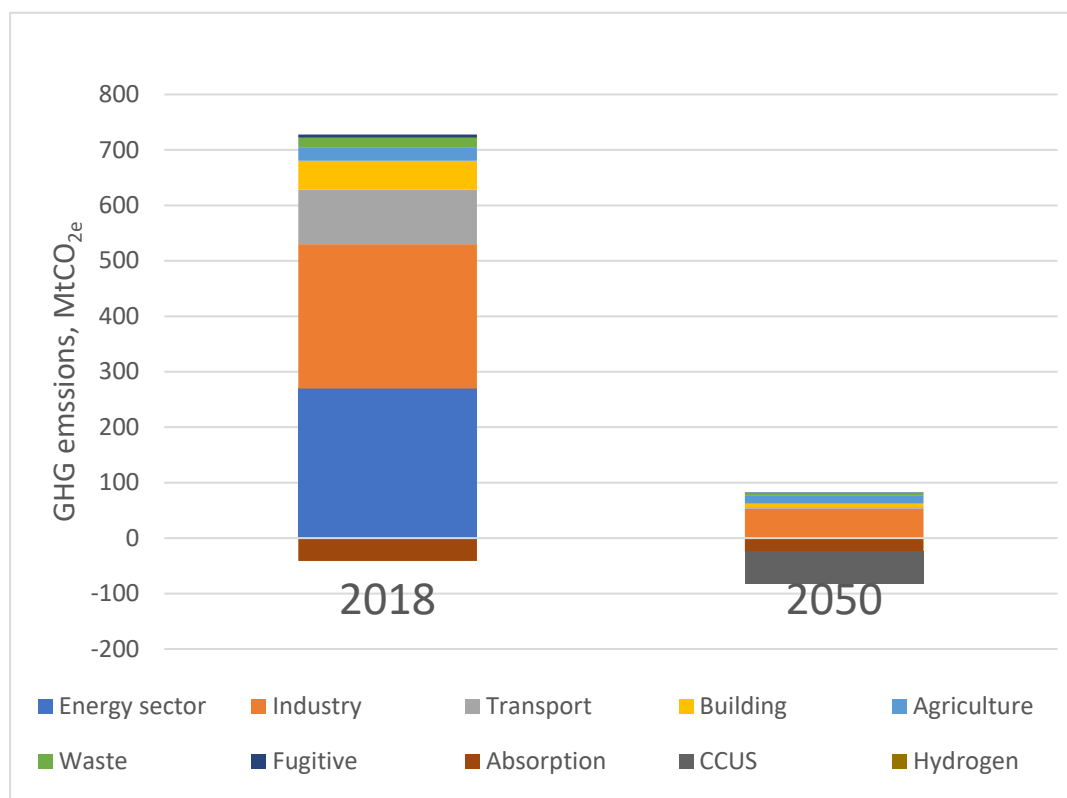


Figure 2. South Korea’s 2018 GHG emissions and 3rd draft 2050 Carbon Neutrality scenario [29]. ‘Absorption’ refers to the absorption of CO₂ by reforestation and afforestation. CCUS refers to carbon capture, utilization and storage.

The BAU pathway of this study maintains South Korea’s GHG emissions at 2018 levels. Total GHG emissions of South Korea in 2018 were 729 MtCO_{2e}. The energy, industry, transport and building sectors contributed 270, 261, 98, and 52 MtCO_{2e} of GHG emissions, respectively. This BAU pathway is consistent with South Korea’s current trajectory. The BAU pathway has about the same emission level as outlined in the Carbon Trackers modelled domestic pathway for South Korea, with the overall rating ‘highly insufficient’,

which is the rating currently held by South Korea [31]. By contrasting the gains in South Korea's climate action pathway compared to the BAU pathway, the avoided GHG emissions and some of the associated national health gains can be calculated.

The global warming impacts avoided by South Korea's abated GHG emissions through the climate action pathway are also estimated. The increase in the average global surface temperature, which would be avoided due the cumulative abated emissions, is projected. This is carried out by calculating the warming that would have been caused by the avoided GHG emissions. The degree of global surface temperature attributable per emitted thousand gigaton of carbon dioxide equivalent (1000 GtCO_{2e}) is taken from the AR6 working group 1 contribution report range of from 0.27 °C to 0.63 °C, with a best estimate of 0.45 °C [1].

For the estimation of positive air-quality impacts, the pollutant emissions avoided through the reduction in fossil fuel use in each sector in the climate action pathway, compared to the BAU, are forecasted. The avoided eight pollutants calculated are carbon monoxide (CO), nitrogen oxides (NO_x), sulphur oxides (SO_x), total suspended particles (TSP), particulate matter less than 10 µm (PM10), particulate matter less than 2.5 µm (PM2.5), volatile organic compounds (VOC), and ammonia (NH₃). The base year of 2017 was used for the quantity of emissions by sector as it is the most recent available year with complete data. The data were accessed from South Korea's National Center for Fine Dust Information [32], which is responsible for the collection and analysis of air-pollution-related data in South Korea. The total amount of pollutants, according to type and sector of origin, are shown in Table 1.

Table 1. Air pollutant emissions from fossil fuel combustion by sector in 2017 in South Korea, given in metric tons [32].

Pollutant	Energy	Industry	Transport	Waste	Agriculture
Carbon monoxide (CO)	122,020	46,013	413,607	2051	-
Nitrogen oxides (NO _x)	200,995	223,408	743,347	12,994	-
Sulphur oxides (SO _x)	98,288	179,057	35,987	2120	-
Total suspended particles (TSP)	5681	107,911	25,671	377	-
Particulate Matter < 10 µm (PM10)	4097	62,631	25,667	274	-
Particulate Matter < 2.5 µm (PM2.5)	4097	33,687	23,717	234	-
Volatile Organic Compounds (VOC)	10,583	191,523	105,327	58,405	-
Ammonia (NH ₃)	2759	43,665	4557	22	244,335

To estimate some of the potential national benefits of the climate action pathway compared to the BAU pathway, the health impacts of the reduced amount of PM2.5 emissions is forecasted. PM2.5 is particulate matter less than 2.5 µm in diameter and has major negative effects on human health. The reduction in premature mortality is calculated in units of years of life lost (YLL), which is the sum of all years, compared to the anticipated life expectancy, that were lost in each premature mortality. YLL are estimated for each premature death due to PM2.5 exposure in individuals aged thirty or older.

To evaluate some of the health benefits of the climate action pathway and the associated reduction in PM2.5 emissions, the AirQ+ tool is utilized. AirQ+ is a free software that can enable a quantification of the health effects of exposure to air pollution, developed

by the World Health Organization Regional Office for Europe [33]. This is an established methodological tool used to assess the impacts of air pollution and has been utilized in numerous studies analyzing the effects in various countries and contexts [34–36]. AirQ+ requires users to input their own data to create the health effects in the analysis of each scenario for the studied population. AirQ+ utilizes a relative risk (RR)-based methodology to calculate the health impacts of air pollution. The RR is modelled with a log-linear function. The amount of premature mortality that is attributable to PM2.5 exposure is calculated for each age group by the following formula:

$$\text{Premature mortality} = (RR - 1) / RR \cdot \sum (\text{Baseline} \cdot \text{Pop}) \quad (1)$$

where *RR* is the relative risk of all-cause (natural) mortality; *Baseline* is the total number of all all-cause (natural) deaths per 100,000; *Pop* is the population size of each age group.

The YLL avoided due to PM2.5 exposure is calculated according to:

$$\text{Years of life lost} = \sum (\text{Mortality} \cdot \text{Life_expectancy}) \quad (2)$$

where *Mortality* is the number of premature deaths in each age group attributable to PM2.5 exposure and *Life_expectancy* is the expected remaining years of life left at the time of each death, based on national life expectancy. This summation is completed for each 5-year age group aged 30 and older.

For this research's calculation of national health benefits, the base year of 2018 was selected. The COVID-19 pandemic has had a massive influence on the health sector's capacities and outcomes since 2020; therefore, this research selected a year prior to the outbreak of COVID-19 to avoid calculations being affected by the impacts of the virus. The annual average PM2.5 exposure of 27.4 µg/m³ was inputted as the baseline annual average PM2.5 exposure. The annual exposure of 2018 was 27.4 µg/m³, which is the base year of this study. There is considerable range and uncertainty regarding the conversion of tonnes of PM2.5 emissions to PM2.5 µg/m³ exposure levels. Depending on the baseline assumptions and air pollutant dispersion model that are utilized, a significant variation exists between studies [7,14–17,37–41]. The study utilizes a conservative assumption, from the lower range of each thousand tonne reduction in PM2.5 particle emissions causing a reduction in the average PM2.5 exposure level of 0.1 µg/m³. The total population and portion of population in each age group were accessed from the medium fertility variant United Nations population forecast for South Korea from 2022 to 2050 [18]. The rate of natural all-cause mortality rate in each age group aged over thirty for the base year of 2018 was retrieved from the Korean Statistical Information Service (KOSIS) [41]. The natural all-cause mortality rates for all groups are assumed to remain constant in all years in both pathways. The natural all-cause mortality rate for individuals aged over thirty years, showing relative risk (RR) values per 10 µg/m³ of PM2.5 exposure, is taken from a review of evidence on the health aspects of air pollution, conducted by the WHO Regional Office for Europe [42], primarily based on the results of a meta-analysis of 13 cohort studies by Hoek et al. (2013) [43]. The RR is 1.062 per 10 µg/m³ annual mean exposure, with a confidence interval of 1.040–1.083.

3. Results

3.1. Avoided GHG Emissions

The climate action pathway results in significant GHG emission reductions compared to the BAU pathway. The GHG emissions that are avoided in each sector are shown in Figure 3. The energy sector showed the largest decrease, followed by the industrial sector. The cumulative GHG emissions avoided over the 2022–2050 period would be 5539 million tons of CO₂ equivalent (MtCO_{2e}).

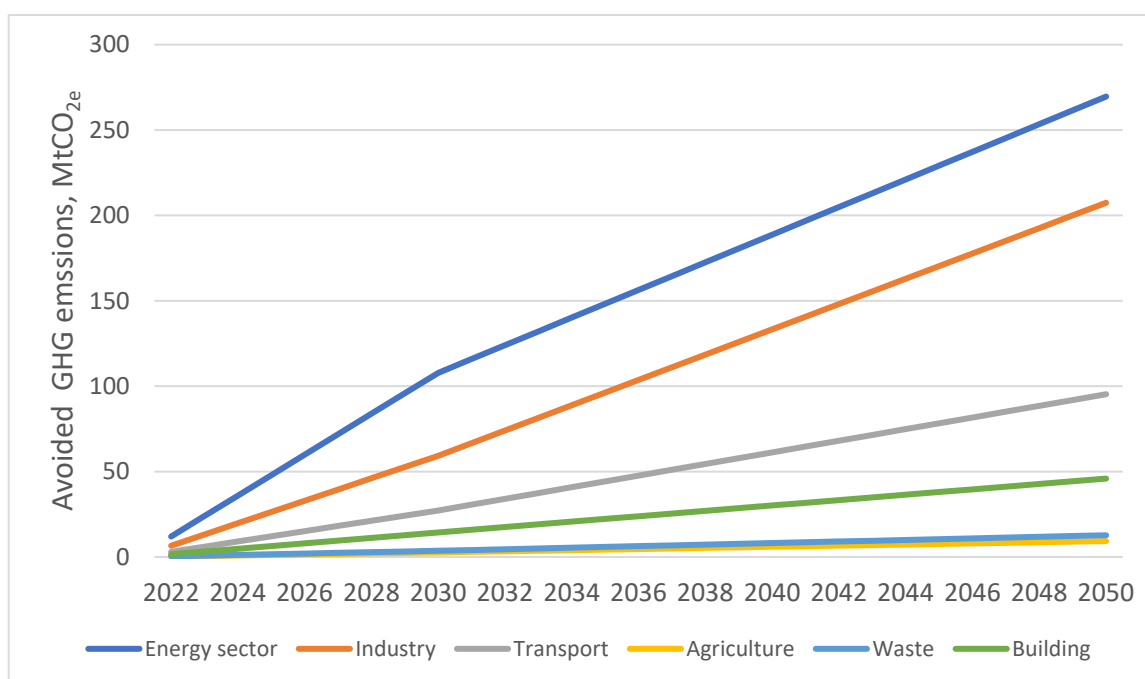


Figure 3. The avoided GHG emissions per year by each climate action pathway sector compared to the BAU pathway.

3.2. Avoided Global Warming

The cumulative amount of global warming avoided through the climate action pathway, compared to the BAU pathway, is calculated by multiplying the avoided CO₂ emissions by assumed degree of warming per thousand gigatons of CO₂ equivalent (1000 GtCO_{2e}). The values of 0.27 °C, 0.45 °C and 0.63 °C of 1000 GtCO_{2e} warming were used. This range is taken from the most recent IPCC publication, the AR6 working group 1 report [1]. The results are shown in Table 2.

Table 2. Cumulative degree of global warming avoided through climate action pathway.

Assumed Warming per 1000 GtCO _{2e} Emissions ¹	2022–2030	2022–2050
0.27 °C	0.00029 °C	0.00150 °C
0.45 °C	0.00048 °C	0.00249 °C
0.63 °C	0.00068 °C	0.00349 °C

¹ Assumed warming per 1000 GtCO_{2e} emissions taken from range in AR6 working group 1 report.

Even at the highest assumption of 0.63 °C of warming per 1000 GtCO_{2e}, the degree of global warming avoided from the climate action pathway may be interpreted as small. However, it is essential to understand this result in the context of a global movement to limit warming to less than 2 °C. It is important to recognize that South Korea's mitigation actions will not occur in isolation. South Korea's climate action, or lack of climate action, can impact the level of action that other countries will take. South Korea is vulnerable to increased global warming; the rise in temperature in South Korea has been found to be about three times higher than the average temperature rise worldwide [44], meaning that South Korea would likely experience a significantly greater warming than the global average.

3.3. Avoided Emissions of Air Pollutants and Associated Health Impacts

In the climate action pathway, compared to the BAU pathway, the associated reduction in air pollutants resulting from the decreased use of fossil fuels is calculated. As shown in Figure 4, carbon monoxide (CO), nitrous oxides (NO_x) and sulphur oxides (SO_x) emissions are predicted to decrease over time. This follows the same trend of an increase in avoided

emissions over time as the GHG emissions shown in Figure 3. In the year 2030, the avoided emissions, measured in metric tonnes of CO, NO_x and SO_x emissions, are 174,075 tons, 337,541 tons and 90,035 tonnes, respectively. The figures for these three pollutants rise to 560,455 tonnes 1,100,994 tonnes and 275,806 tonnes of avoided emissions, respectively, in 2050. Figure 4 shows these avoided emissions in thousand tonne units (kt).

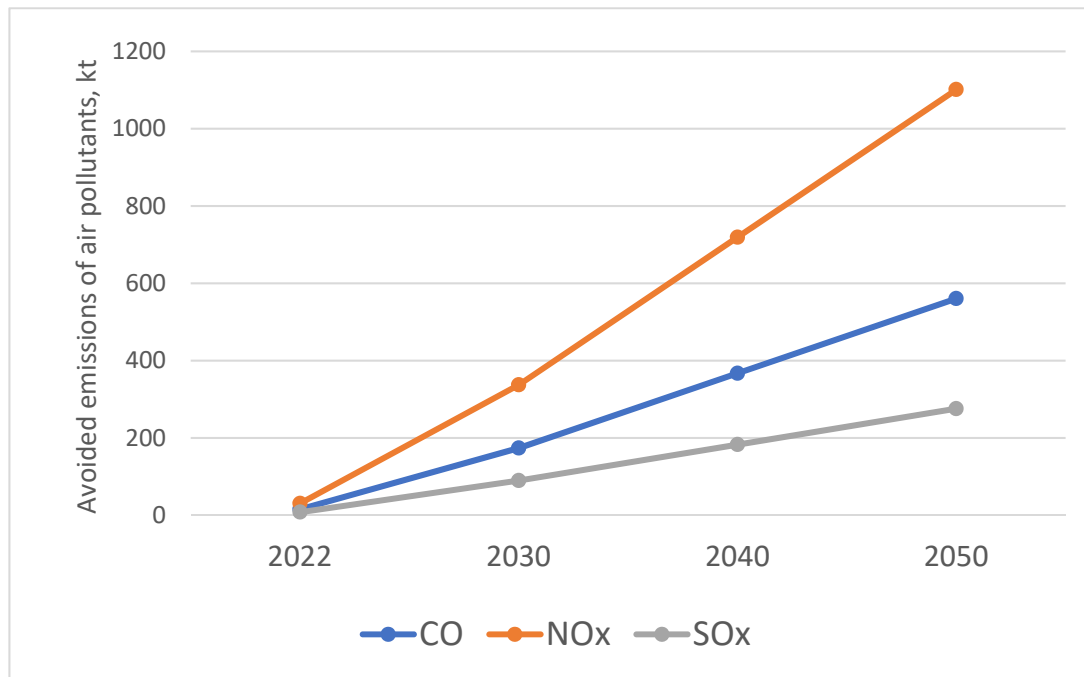


Figure 4. Avoided carbon monoxide (CO), nitrogen oxides (NO_x) and sulphur oxides (SO_x) emissions by year from the energy, industry and transport sectors in the climate action pathway compared to the BAU pathway.

In the year 2050, the achievement of net carbon neutrality would result in a massive reduction of total emitted pollutants compared to the BAU pathway. As shown in Table 3, decarbonization of the transport sector shows high potential for the reduction of CO and NO_x emissions.

Table 3. Avoided air pollutant emissions in tonnes from the 2050 climate action pathway compared to BAU pathway.

Air Pollutant	Energy	Industry	Transport
CO	122,020	36,634	401,802
NO _x	200,995	177,869	722,130
SO _x	98,288	142,558	34,960
TSP	5681	85,915	24,938
PM10	4097	49,864	24,934
PM2.5	4097	26,820	23,040
VOC	10,583	152,483	102,321

As shown in Figure 5, a green transition of the industrial sector would result in the largest reduction in PM2.5 emissions, followed by the transport sector. The avoided PM2.5 emissions in the energy sector are smaller than those in the industrial and transport sectors, but the reduction is still substantial.

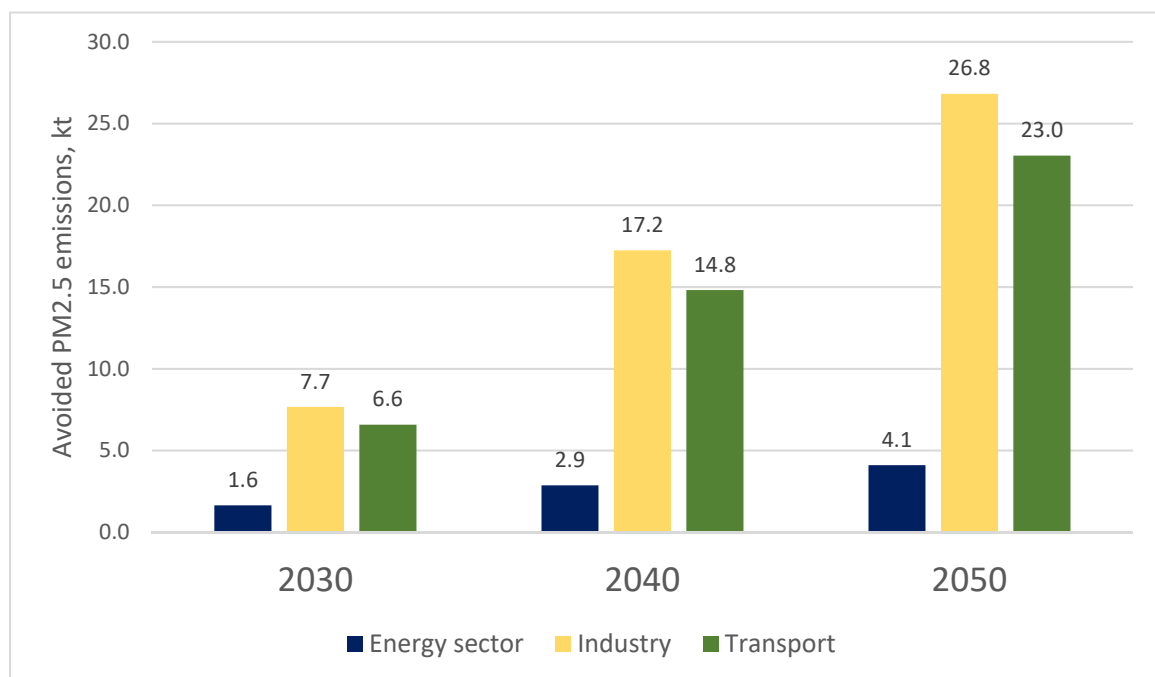


Figure 5. Total avoided thousand tonnes (kt) of PM2.5 emissions in 2030, 2040 and 2050, by climate action pathway sector, compared to the BAU pathway.

As South Korea has a rapidly aging population, the negative effects of high levels of air pollution are increasing; therefore, avoidable negative health impacts achievable through the climate pathway also rise. As shown in Figure 6, the avoided years of life lost (YLL) achieved through the climate action pathway shows a growth trend over time, increasing steeply in each subsequent decade. In 2030, the amount of YLL avoided through the climate action pathway is 835, with this figure rising to 2237 in 2040 and 3389 in 2050.

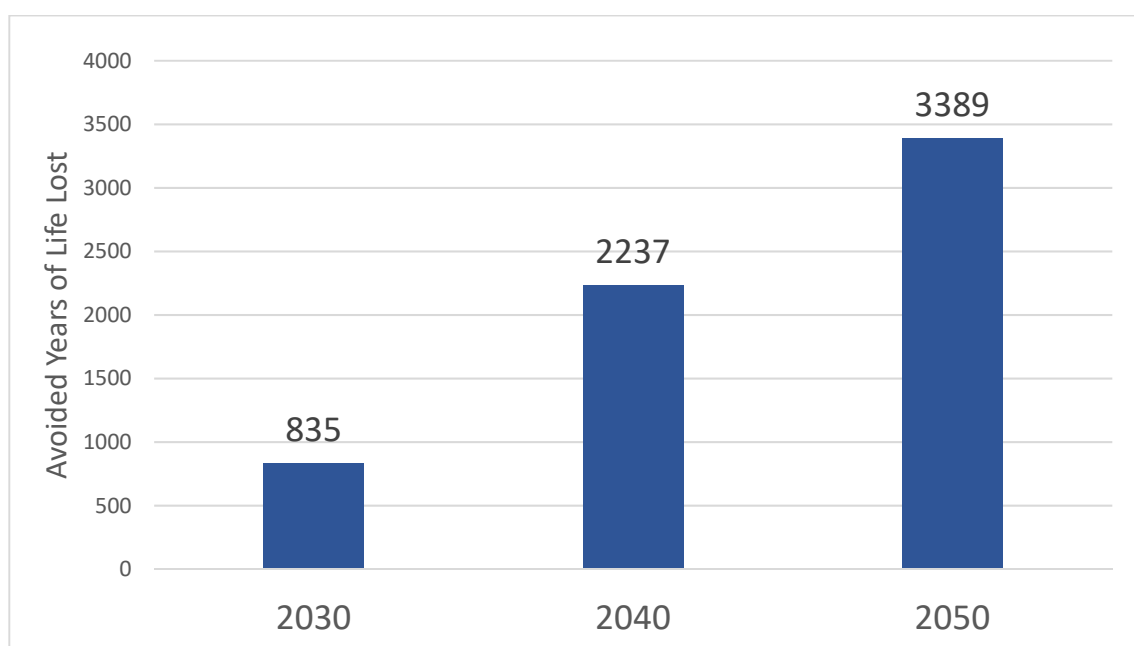


Figure 6. Total avoided years of life lost (YLL) in 2030, 2040 and 2050 compared to the BAU pathway.

4. Discussion and Conclusions

This research estimates national gains from a climate action pathway to achieve 2050 carbon neutrality, compared to a business-as-usual (BAU) pathway, to provide further evidence for the potential local benefits of strong climate action across all sectors in South Korea. The climate action pathway would meet a 35% reduction in GHG emissions in 2030, compared to 2018 target. The pathway would also meet the 2050 carbon neutrality target of net zero emissions. South Korea's current policy trajectory is not compatible with the aims of the Paris Agreement [45], and climate change is not a high priority for the South Korean electorate. The paper argues that by focusing on national gains, the momentum for enhanced climate policy action can be intensified by framing stronger climate action as an opportunity rather than a cost. Highlighting national benefits can have an influential effect on overcoming domestic opposition to a rapid green transition.

The study finds that following a climate action pathway would result in major reductions in GHG emissions, leading to a cumulative abatement of 5539 million tons of CO₂ equivalent (MtCO_{2e}) in greenhouse gas emissions over the 2022–2050 period. This would result in 0.00249 °C (with a lower bound of 0.00150 °C and a higher bound of 0.00349 °C) of global warming being avoided. These figures may seem small, but it is important to remember that South Korea's per capita emissions are relatively high, and the world has a limited carbon budget. To achieve the Paris Agreement's goal of 1.5 degrees or less of warming, the global community has only a remaining limit of 0.3 °C. There are also various national benefits to averting climate change, such as avoiding the decrease in labor productivity and higher number of injuries caused by higher temperature and humidity levels. An increased temperature would lead to algae blooms, which increase the probability of an algae outbreak in public waters in South Korea. The increase in the amount and severity of precipitation associated with global warming would also cause nonpoint water pollution, causing an overall degradation in water quality [46]. If developed, relatively wealthy countries, with relatively high levels of GHG emissions, such as South Korea, do not take action, then this discourages other countries from taking action as well. Therefore, to avoid the major negative national impacts of global warming, it is in South Korea's interest to be part of strengthened worldwide climate action.

Through the climate action pathway, there would also be major reductions in atmospheric air pollutants through the reduced use of fossil fuels, which would result in less air-pollution-related premature mortality. Compared to the BAU pathway, the climate action pathway would avoid 835 years of life lost (YLL) in 2030, 2237 YLL in 2040 and 3389 YLL in 2050. There would also be significant reductions in the amount of carbon monoxide (CO), nitrogen oxides (NO_x) and sulphur oxides (SO_x) emitted from the climate action pathway, although the calculations of the benefits of this are outside of the scope of this study. The associated decreases in mortality and morbidity caused by lower air pollution exposure would also entail positive economic impacts, such as less work time lost and the reduction in health sector expenditures. In various countries across the world, a reduction in air levels has led to major benefits [47–49]. Given the range of additional benefits, South Korea should reduce its use of fossil fuels.

In July 2020, the Green New Deal was announced as part of the Korean New Deal plan to invest 160 trillion won to create almost 2 million new jobs by 2025 and enable the green transformation of the economy. The Green New Deal outlines plans to increase South Korea's renewable energy capacity and overall low-carbon infrastructure, improve energy electricity efficiency systems and expand the number of electric and hydrogen vehicles [50]. However, more ambitious targets and stronger policy action are needed to maintain warming and keep the global temperature rise below 2 °C. A stronger legal framework needs to be established to ensure that the spending as part of the green new deal is, in fact, 'green' [51]. The current growth rate of renewable energy capacity is not sufficient to meet the ambitious climate targets, and issues such as local opposition to renewable energy sites need to be addressed [52]. The overall low-carbon infrastructure, such as improvements in energy electricity efficiency systems and the development of

hydrogen technology, requires major targeted investment [53]. To support the expanded use of electric cars, the number of charging stations need to be rapidly increased, and financial incentives will need to be improved [54].

The key limitations of this study are its simplified assumptions regarding the creation of two pathways for comparison. The BAU pathway assumes that GHG and air pollutant levels remain constant over the 2022–2050 period, but there is a huge degree of uncertainty regarding the amount and proportion of future emissions due to technological innovation, industrial development, and other economic changes. Another important uncertainty is the degree to which the underlying scientific evidence regarding the health effects from air pollution, utilized in the AirQ+ tool, is applicable to the context of South Korea. The studies from the effects of PM_{2.5} exposure and its relative risks were carried out in North America and Europe. There may be unknown differences in the impact of PM_{2.5} in South Korea compared to those regions. Another important factor in computing air pollution levels is the level of emissions from outside South Korea. South Korea is significantly impacted by emissions from other countries in the region, such as China [55,56]; thus, changes in their regional climate and air pollutant policies would also affect South Korea's levels of air pollution.

This research takes an entire-economy approach by including emissions from all sectors, but only estimates some of the effects of changes in PM_{2.5} exposure. Further study on the positive health impacts of reductions in emissions other than PM_{2.5}, such as CO, NO_x and SO_x, by implementing a climate action policy, would provide a fuller and more in-depth picture of potential national gains. Future studies may also estimate the economics benefits of reduced air pollutant emissions from a green transition by analyzing productivity loss and the other associated economics costs of air pollution.

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