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Solutions for Our Climate (SFOC) is a nonprofit organization established in 2016 to address the social and environmental impacts of climate change. We conduct research on solutions for reducing greenhouse gas emissions and expanding renewables, and coordinate campaigns with both domestic and international organizations to address the climate crisis.

Bridge to Death:
Air Quality And Health Impacts of Fossil Gas Power

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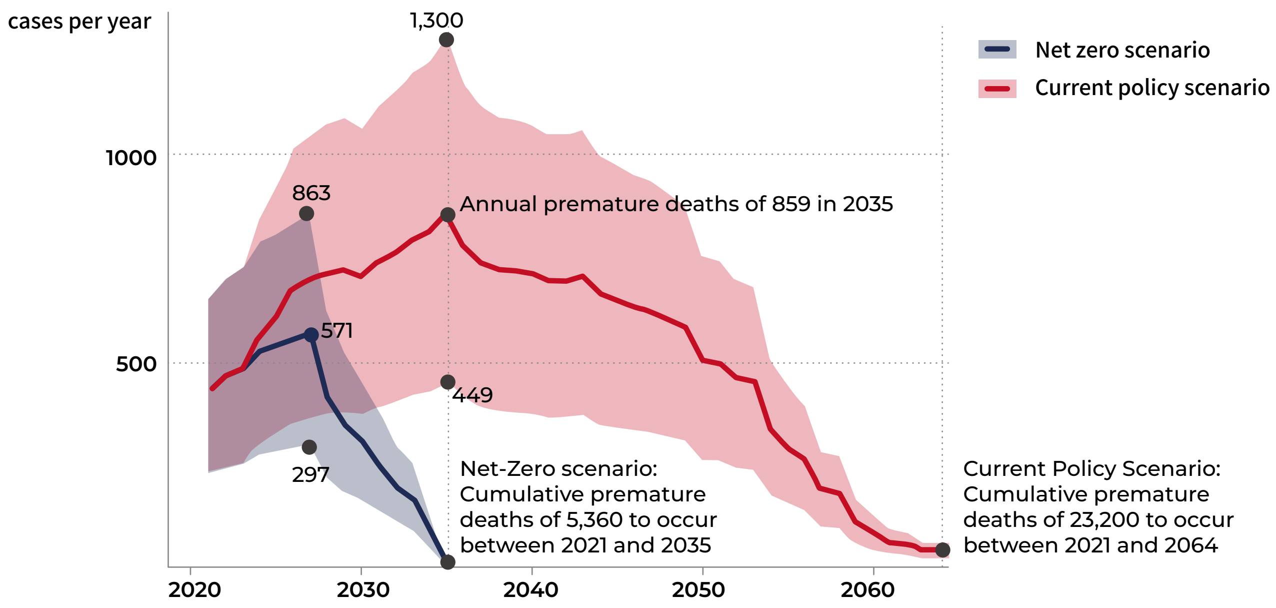
Contents

Executive Summary

A total of 99 natural gas-fired power units (41.3GW; hereinafter, "gas plants") are currently online in South Korea, among which 71 are combined cycle power units[1] (33.8GW) and 28 are combined heat and power units[2] (7.4GW).[3] Gas power's role as a bridge in energy transition is widely accepted in South Korea, and the country's 9th Basic Plan for Long-term Electricity Supply and Demand, finalized in December 2020, targets the installed capacity of gas-fired power generation to reach 59.1GW by 2034. In particular, 24 (12.7GW) out of the 30 coal fired power units scheduled for decommissioning by 2034 are planned to be converted into gas power plants[4]. Such plans, however, go against the recommendations[5] of the International Energy Agency (IEA) that clearly state that the power sector in advanced economies must be decarbonized by 2035 to meet the 2050 net-zero[6] goal, and are especially problematic as gas power generation significantly contributes to air pollution.

In this report, Solutions for Our Climate (SFOC) analyzed the air pollution from gas plants and the associated health impacts under the current policy and explored the health benefits from an accelerated phase out of gas power by 2035. We modelled the dispersion of air pollutants emitted from all existing and new (both under construction and in pipeline) gas power plants as laid out in the 9th Basic Plan for Long-term Electricity Supply and Demand and quantified the resulting health impacts. For the health impacts estimation, we compared the two following scenarios: a **"Current Policy" scenario** that follows the capacity development of the 9th Basic Plan for Long-term Electricity Supply and Demand and a 30-year-lifetime based on the Lifetime Management Guidelines, and a **"Net-Zero" scenario** that assumes withdrawal of the plans to build new plants currently in pipeline and a gas power phase-out by 2035.

The health benefits of following the Net-Zero scenario over the Current Policy scenario is substantial. Under the Current Policy scenario, gas power generation is estimated to cause up to 859 premature deaths per year and 23,200 premature deaths until 2064. On the contrary, premature deaths under the Net-Zero scenario would accumulate to a significantly lower number of 5,360 until 2035. In other words, 17,840 premature deaths can be avoided by withdrawing the plans to construct the plants in pipeline and phasing out all gas plants by 2035.



Cumulative premature deaths	Central	Low	High
Current Policy scenario	23,200	12,100	35,000
Net-zero scenario	5,360	2,800	8,070

Figure 1. Premature deaths due to gas plants under the two scenarios

Regions with higher population density and large number of power plants, such as Gyeonggi-do and Seoul, were found to experience the most cases of premature deaths caused by air pollution from gas plants. Among the modelled pollutants, nitrogen dioxide (NO_2) was identified as the main cause behind premature death.

To reduce the health damages from gas power generation, we propose the following policy decisions: First, the Korean government should withdraw all plans to build new gas plants that are currently in pipeline. The gas plants in pipeline according to the 9th Basic Plan for Long-term Electricity Supply and Demand amount to a total of 35 new gas power units (21.3GW), including 24 units (12.7GW) converted from coal plants, 3 combined cycle units (3.3GW), and 8 combined heat and power units (3.9GW). Withdrawing the plans for these plants and phasing out gas by 2035 can prevent 17,840 premature deaths.

Second, air pollution from gas plants should be managed and monitored rigorously and the

1. A combined cycle power plant produces electricity by using both a gas turbine and a steam turbine to increase energy efficiency (Korea Midland Power, "Principle of combined cycle power generation").
2. A combined heat and power plant recovers exhaust heat from electricity generation and produces heat energy that can be used for air-conditioning and/or heating. (KONETIC. "Technology of combined heat and power generation")
3. Electric Power Statistics Information System. "Power generation facilities by unit"
4. Ministry of Trade, Industry and Energy, (2020). "Announcement of the 9th Basic Plan for Long-term Electricity Supply and Demand (2020-2034)".
5. IEA, (2021). "Net Zero by 2050 – A Roadmap for the Global Energy Sector"
6. A state where the GHG emissions are practically "zero" because the amounts of GHGs emissions and absorptions are balanced.

emissions standards should be enhanced. Although air pollution from gas plants increases during their frequent startup and shutdown processes, these non-steady state operations currently are exempt from emissions standards, leaving excess amounts to be unregulated. At the same time, the geographical proximity of gas plants to densely populated areas can lead to serious health impacts. To reduce such health damages, stronger emission standards are necessary to limit nitrogen dioxide (NO_2), the biggest cause of premature deaths, and air pollutants emitted during non-steady state operation.

Lastly, we advise the Korean government to withdraw policies that facilitate financing for gas power plants. Of all, including gas power in K-Taxonomy's "green economic activities" category would be the most inappropriate. Doing so would not only encourage the expansion of gas power generation, but also justify systemic gas power financing. K-Taxonomy should instead contribute to its fundamental environmental purposes, such as climate change actions and pollutions reduction.

I. Introduction

As the international community accelerates coal phase-out and energy transition to limit global temperature rise, the role of natural gas (hereinafter, "gas") as a bridge fuel is being heavily disputed. Despite being a type of fossil fuel combustion, gas power generation has historically been recognized as a "clean" energy with lower greenhouse gas emissions and air pollution. Accordingly, the installed capacity of gas plants around the world continues to increase, with 40GW added in 2020 alone.[7]

However, gas-fired power generation contributes to a considerable amount of GHGs directly through fuel combustion and also in the course of extracting and transporting the fuel to power plants. In addition, fossil gas combustion causes air pollution including nitrogen oxides and fine particles. Air pollution is a serious threat to public health that increases the prevalence of non-communicable diseases such as ischemic heart disease, stroke, chronic obstructive pulmonary disease, asthma, and cancer. In the efforts to better address such threats, the World Health Organization (WHO) significantly strengthened the Air Quality Guideline[8] in 2021, for the first time in 16 years.[9]

Health impacts caused by air pollution from gas power plants can be serious, in particular due to recurrent incomplete combustions that are typical of frequent startups and shutdowns to meet peak demands and their geographical proximity to densely populated areas. Nonetheless, research on the health impacts from gas power generation at a country-level scale is limited. This study thus aims to pioneer such an analysis in the South Korean setting and open a global discussion on gas power.

This study used the atmospheric dispersion model, CALPUFF, to i) estimate and analyze the health benefits from an early retirement of gas plants and ii) critically review the legitimacy of the plans to build new gas plants, given the associated health threats. Premature deaths in this analysis refers to deaths caused by air pollution related diseases that would not have appeared in the absence of the harmful air pollutants emitted from the gas plants.

7. IEA, (2020). "2020 Global overview: Capacity, supply and emissions"
8. The Air Quality Guidelines recommend the standards of particulate matters, ozone, nitrogen dioxide, sulfur dioxide, and carbon monoxide to stay below the levels that are harmful to human body.
9. WHO, (2021). "New WHO Global Air Quality Guidelines aim to save millions of lives from air pollution".

II. Current Status of Gas Power Plants in South Korea

1. Current status and outlook of gas-fired power generation

In South Korea, a total of 99 natural gas-fired power units (41.3GW) are currently in operation, 71 of which are combined cycle power plants (33.8GW) and 28 combined heat and power plants (7.4GW).[10] The majority is located in the Seoul Metropolitan Area, which includes Gyeonggi-do (43%) and Incheon (21%), where power demands are particularly high. Chungcheongnam-do (9%), Ulsan (6%), and Jeollanam-do (6%) are notable host regions as well.

South Korea plans to add a significant capacity of new plants, and by 2034, gas power is projected to reach 59.1GW. Currently, 5 units (2.6GW) are under construction in Gyeonggi-do, Gyeongsangnam-do, and Chungcheongnam-do and 35 units (18.7GW) are in pipeline for Gyeongsangnam-do, Ulsan, Gyeongsangbuk-do, Chungcheongbuk-do, Seoul, Sejong Special Self-Governing City, Jeollanam-do, Gyeonggi-do, and more.[11] In particular, 24 (12.7GW) out of 30 coal fired power units scheduled to retire by 2034 are planned to be converted into gas power plants.[12]

	Number of gas power units	Installed capacity (GW)
2020	99	41.3
2034	118	59.1

Table 1. Gas power expansion under the 9th Basic Plan for Long-term Electricity Supply and Demand

10. Ministry of Trade, Industry and Energy, (2020). "Announcement of the 9th Basic Plan for Long-term Electricity Supply and Demand (2020-2034)," p. 35.
11. Korea Power Exchange, (2021). "Power Plant Construction Status in Q2 2021"
12. Ministry of Trade, Industry and Energy, (2020). "Announcement of the 9th Basic Plan for Long-term Electricity Supply and Demand (2020-2034)".

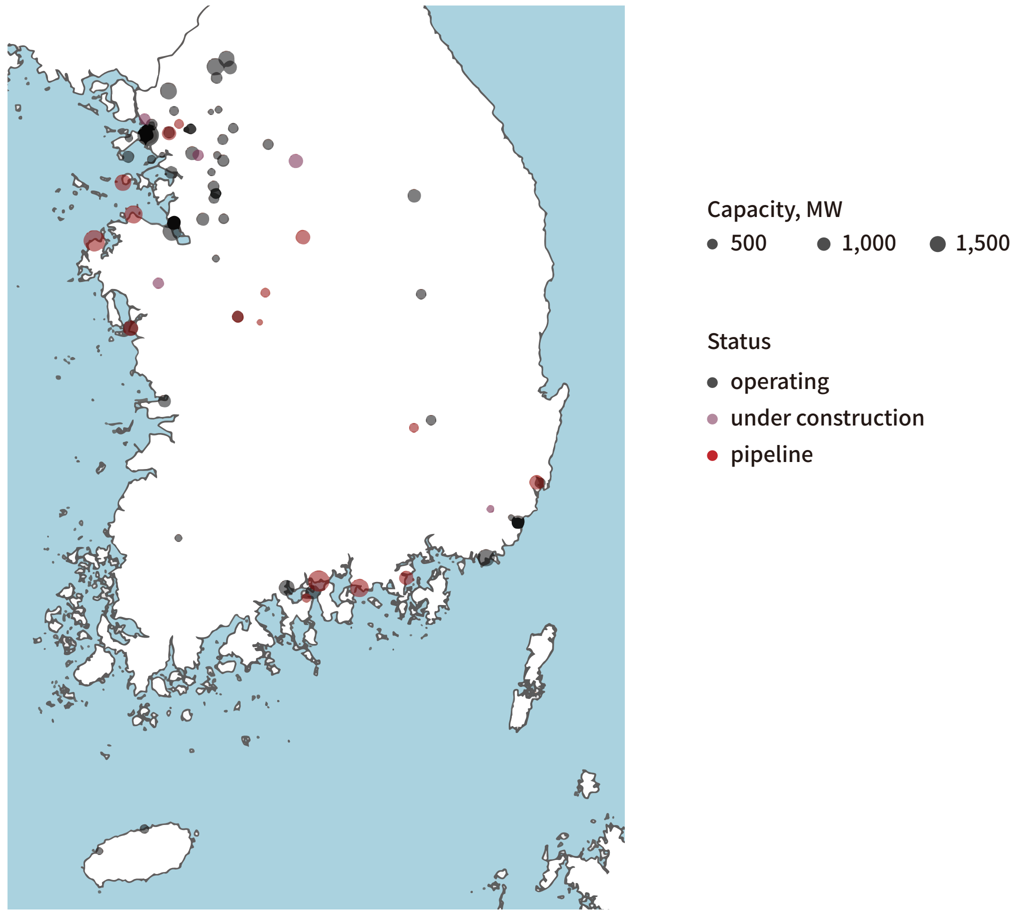


Figure 2. Distribution of gas plants[13]

According to KEPCO statistics, gas accounted for 26.4% of South Korea's total power generation in 2020, after coal (35.6%) and nuclear (29.0%).[14] The country's Nationally Determined Contributions (NDC) for 2030 and the 2050 Carbon Neutrality Scenario released last October foresee gas to account for as much as 19.5% of the total power generation in 2030,[15] and even in 2050, the target year for achieving its carbon neutrality goals, South Korea may still depend on gas to a certain degree. One of the two scenarios produced by the 2050 Carbon Neutrality Commission assigns 5% (61.0TWh) of the total generation in 2050 to gas, which would equate 20.7 million tons of GHGs emissions.[16]

13. The locations of power plants in pipeline are marked on the candidate sites that are being considered as of October 2021. The final construction sites may vary depending on future decisions.
14. KEPCO Statistics, (May 28, 2021). "2021 KEPCO Statistics (Vol. 90)".
15. 2050 Carbon Neutrality Commission, (2021). "2030 Enhanced NDC Target (Draft)".
16. 2050 Carbon Neutrality Commission, (2021). "2050 Carbon Neutrality Scenario (Final Version)".

2. Air pollution from gas-fired power generation

Gas-fired power generation, which produces electricity from the energy gained through fossil fuel combustion, inevitably emits carbon dioxide as well as air pollution, including nitrogen oxides. Carbon emissions from gas power generation is as much as 60 percent of that from coal power. The Korea Energy Economics Institute's analysis on the carbon emissions by fuel source show that coal, oil, and gas-fired power generations each emit 888 tons/GWh, 733 tons/GWh, and 499 tons/GWh, respectively.[17]

Gas power is also a significant source of air pollution, even though it is considered relatively clean compared to other conventional fossil fuel generation. According to the Ministry of Trade, Industry and Energy data, air pollution from gas power generation (0.171kg/MWh) amounts to a third of that from coal power (0.561kg/MWh).[18]

The operational and technological characteristics of gas plants are key factors behind air pollution. Gas plants are frequently turned on and off as they are mainly operated to meet peak demands. The average number of startups per unit was 148 in 2019 and 166 in 2020, meaning that gas plants tend to start up approximately once every two days. Startups and shutdowns cause incomplete combustion, which produces greater amounts of air pollution than in a steady state operation. Additionally, the temperature of the emissions is lower during startups and shutdowns, which causes the efficiency of selective catalytic reduction (SCR) devices to decline, and more air pollutants escape into the atmosphere. During this process, a large amount of carbon monoxide, an unregulated air pollutant, is emitted as well.[19, 20] However, air pollution produced during starting up and shutting down (up to five hours) is exempted from emissions regulations.

Nitrogen oxides (NO_x), main air pollutants from gas plants, cause respiratory diseases such as asthma and chronic bronchitis. NO_x also is a major source of particulate matter ($PM_{2.5}$) and contributes to the associated health problems as well. Particulate matter's small sizes (less than 10 μm or 2.5 μm in diameters) allow them to penetrate into lung alveoli, where gas exchanges occur in human body, and some can even get into bloodstream. Exposure to fine particles above a certain concentration level may cause irregular heartbeats, myocardial infarction, dyspnea, asthma, and the like, and in severe cases, can lead to premature deaths from heart and lung diseases.[21]

The Korean Ministry of Environment regulates emissions facilities under Article 15 of the Enforcement Decree of the Clean Air Conservation Act to prevent air pollution from causing damages to public health and the environment. The emissions standards of air pollution from gas power plants (nitrogen oxides, sulfur oxides, particulate matter, and mercury) are determined based on the installation year of the facilities (Table 2).

Installation year / Emissions Standard	Prior to 2001.6.30	Prior to 2014.12.31	Prior to 2019.12.31	As of 2020.1.1
SO_x (ppm)	20(15)	20(15)	15(15)	10(15)
NO_x (ppm)	40(15)	25(15)	20(15)	10(15)
TSP (ppm)	10(15)			
Hg (mg/Sm³)	0.1			

Table 2. Emissions standards of air pollution from gas power plants[22]
Total suspended particles (TSP) are particulate matters with the size of 10□ or less. Fine particles with the size of 10□ or less and the size of 2.5□ or less are referred to as PM_{10} and $PM_{2.5}$, respectively.

17. Korea Energy Economics Institute, (2017). "The Effects and Outlook of the Global Regulations on Coal"
18. Ministry of Trade, Industry and Energy, (Mar. 5, 2019). "[Statement in Response to Sedaily news article] Air pollution from LNG-fired power generation is only a third of coal-fired power generation"
19. Ji-Hoon Lee (April 7, 2019). "[Exclusive] The Betrayal of "Eco-Friendly" LNG-fired Power Plants... Turns Out They Emit Toxic Substances in Large Amounts". Hankyung Securities.
20. Based on the data that the Ministry of Trade, Industry and Energy and the Korea Power Exchange submitted to the National Assembly.
21. EPA (2002). "Overview of the Human Health and Environmental Effects of Power Generation: Focus on Sulfur Dioxide (SO_2), Nitrogen Oxides (NO_x) and Mercury (Hg)".
22. Article 15 of the Enforced Decree of the Clean Air Conservation Act, Attachment Table 8.

III. Methodology

This report quantified and assessed the air pollution from gas power plants in South Korea and the resulting impacts on air quality and human health. Using the atmospheric dispersion modeling system, we first estimated the contributions of the gas plants in operation, under construction, and in pipeline on the concentrations of near-surface air pollution. Based on the results, population data and widely used health impact assessment methods[23, 24, 25] were applied to estimate health damages from exposure to the pollutants.

Estimation of the health damages caused by gas power plants was carried out based on the comparative analysis of two scenarios that assume different timelines of phasing out the existing plants and the fate of new plants, which result in diverging estimates on air pollution and health impacts. The first scenario (**Current Policy scenario**) assumed gas power generation capacities to approach 59.1GW by 2034 and that units are retired once they reach the 30-year[26] lifespan. The last gas power unit would retire in 2064 under the Current Policy scenario. The second scenario (**Net-Zero scenario**) assumed that all gas power plants are phased out by 2035, following the International Energy Agency (IEA)'s recommendation that urges the net emissions from power sector to be reduced to zero by 2035. In this scenario, all plans to build new plants currently in pipeline are withdrawn, and all plants that are currently in operation or under construction as of October 2021 are phased out by 2035, starting with the oldest units and in the order of the construction years. The developments of the installed capacity under the two scenarios are described below (Figure 3).

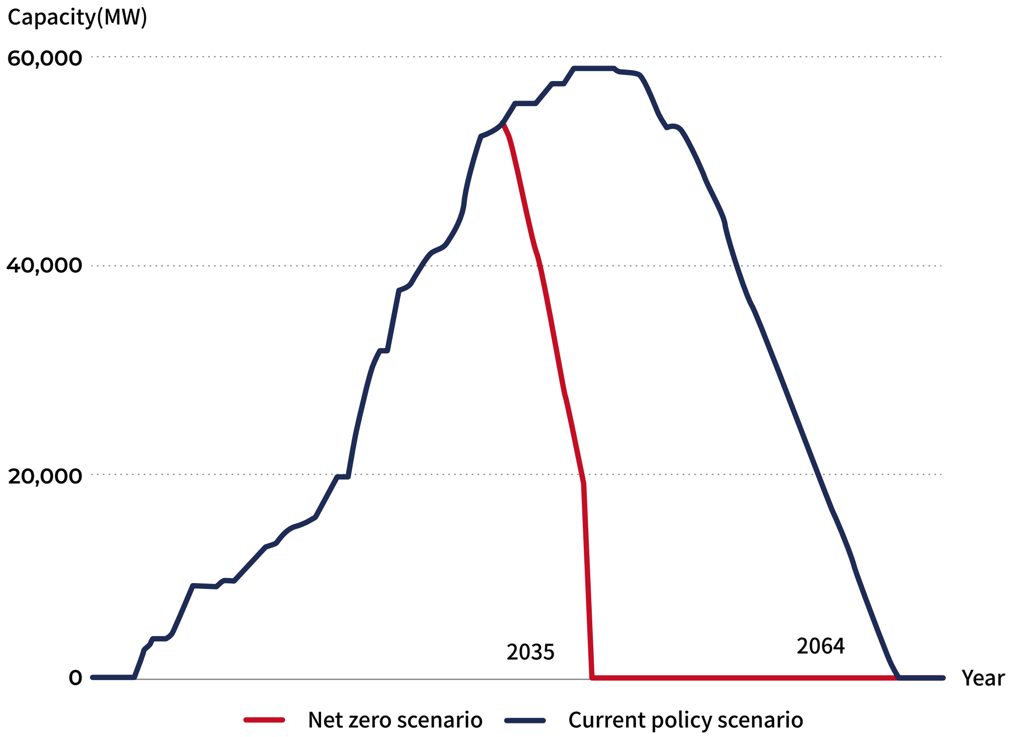


Figure 3. Operating gas power capacity by year under the two scenarios

The data on air pollutant emissions, power generation, and the general generation facilities information of each power plant were retrieved from the materials that the government agencies and power plant operators provided to the National Assembly of the Republic of Korea. Further details of the methodology and the dataset can be found in the appendix.

23. Anenberg, S.C., Horowitz, L.W., Tong, D.Q. and West, J.J. (2010) An estimate of the global burden of anthropogenic ozone and fine particulate matter on premature human mortality using atmospheric modeling. Environmental health perspectives. 1 September 2010. DOI:10.1289/ehp.0901220

24. Koplitz, S.N. et al. (2017) Burden of Disease from Rising Coal-Fired Power Plant Emissions in Southeast Asia. Environ. Sci. Technol. 51(3): 1467-1476 DOI: 10.1021/acs.est.6b03731

25. Krewski, D. et al. (2009) Extended Follow-Up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air

26. KOSPO, "Guidelines on Lifetime Management of Power Generation Facilities" (4th amendment, January 2021).

IV. Results and Analysis

1. Air pollution estimates

Assuming that all gas plants in the Current Policy scenario operate simultaneously, their emissions are estimated to cause the annual average near-surface concentration of nitrogen dioxide (NO_2) to increase by maximum 0.47ppb and particulate matter ($PM_{2.5}$) by 0.08ug/m3. Accordingly, the maximum one-hour concentration of nitrogen dioxide (NO_2) would increase by 47.55ppb (max), and that of fine particles for 24 hours would shoot up by a maximum of 0.73ug/m3.

The results show that if the new power plants currently in pipeline are constructed, the annual mean concentration of nitrogen dioxide (NO_2) and particulate matter ($PM_{2.5}$) would increase by up to 0.06ppb and 0.01ug/m3, respectively. The maximum one-hour concentration of nitrogen dioxide (NO_2) is also estimated to increase by 0.002ppb (max) and that of particulate matters for 24 hours would go up by a maximum of 0.06ug/m3 (see Appendix B).

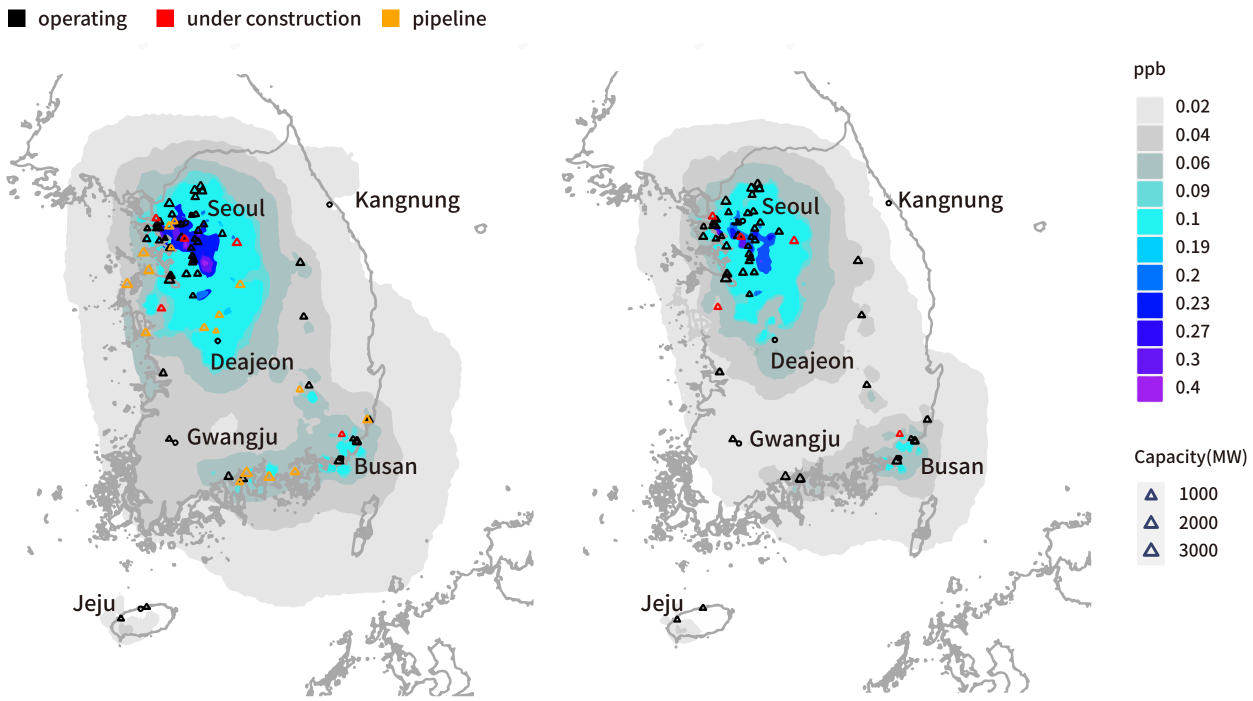


Figure 4. Comparison of the annual mean NO_2 concentration under the Current Policy scenario and the Net-Zero scenario

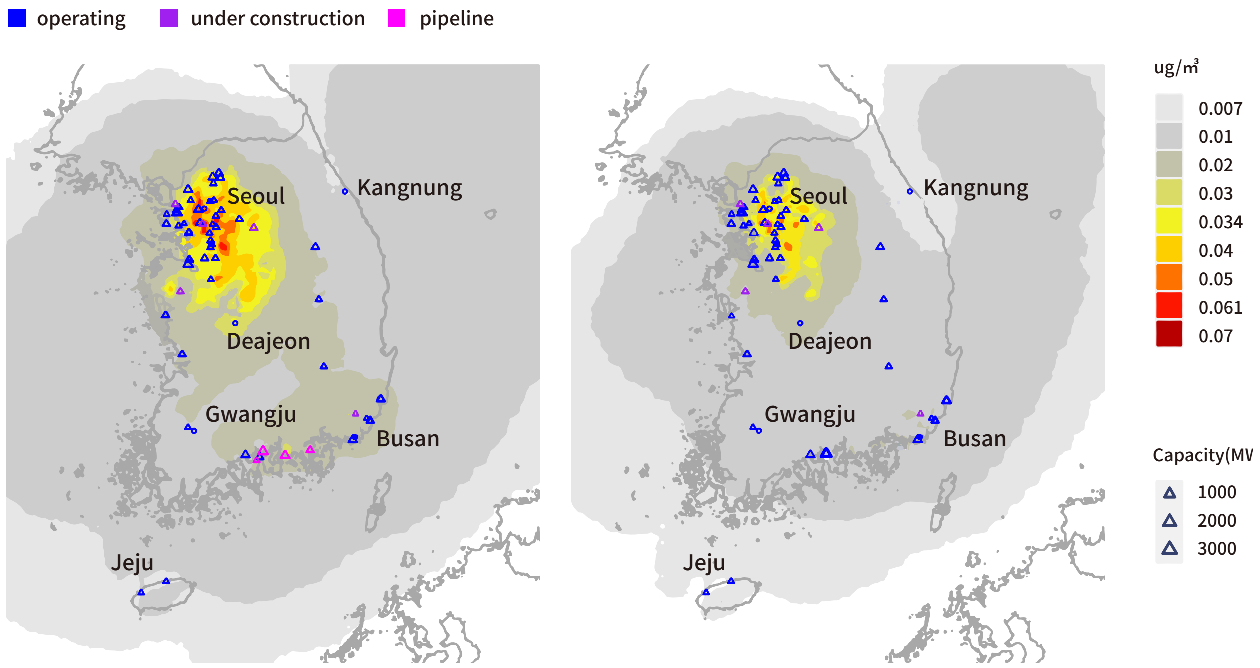


Figure 5. Comparison of the annual mean particulate matter ($PM_{2.5}$) concentration under the Current Policy scenario and the Net-Zero scenario

2. Health impacts estimates

A. Annual health impacts

Our analysis found that under the Current Policy Scenario, the annual number of premature deaths caused by air pollution from gas plants would reach 859 (low estimate of 449 and high estimate of 1,300. Table 3) in 2035, the year when the construction of all plants in pipeline are scheduled to be completed. Since afterwards, the number of premature deaths is estimated to decrease until 2064, when all gas plants are assumed to have retired.

Current Policy Scenario (2035)		
Central	Low	High
859	449	1,300

Table 3. Annual premature deaths due to gas plants under the Current Policy scenario (peak year)

The health impacts caused by gas power plants in South Korea spill over to its neighboring countries. While approximately 87 percent of the annual premature deaths occur in South Korea, the remaining impacts (approximately 13 percent) strike North Korea, Japan, and China.

Country	Current Policy Scenario (2035)		
	Central	Low	High
South Korea	761	395	1,150
North Korea	37	19	60
Japan	34	19	48
China	27	16	41

Table 4. Annual premature deaths due to gas plants by country under the Current Policy scenario (peak year)

Among the modelled pollutants, nitrogen dioxide (NO_2) was found to have the strongest effects on the number of premature deaths.

Pollutant	Cause	Current Policy Scenario (2035)		
		Central	Low	High
Total premature deaths		859	449	1,300
Premature deaths caused by NO_2		739	359	1,140
Premature deaths caused by $PM_{2.5}$		120	90	153
$PM_{2.5}$	Chronic obstructive pulmonary disease	10	4	19
$PM_{2.5}$	Diabetes	1	0	3
$PM_{2.5}$	Ischaemic heart disease	22	16	28
$PM_{2.5}$	Lower respiratory infections	27	8	50
$PM_{2.5}$	Lung cancer	18	9	30
$PM_{2.5}$	Stroke	23	9	42

Table 5. Annual premature deaths due to gas plants by major disease under the Current Policy Scenario (peak year)[27]

Aside from premature deaths, new cases of asthma and premature birth are estimated to increase, and healthy life expectancy[28] is likely to be shortened due to diabetes, stroke, and respiratory diseases.

27. This table does not show premature deaths caused by other diseases, and thus the aggregate number of premature deaths from the listed major diseases does not match the total number of premature deaths.

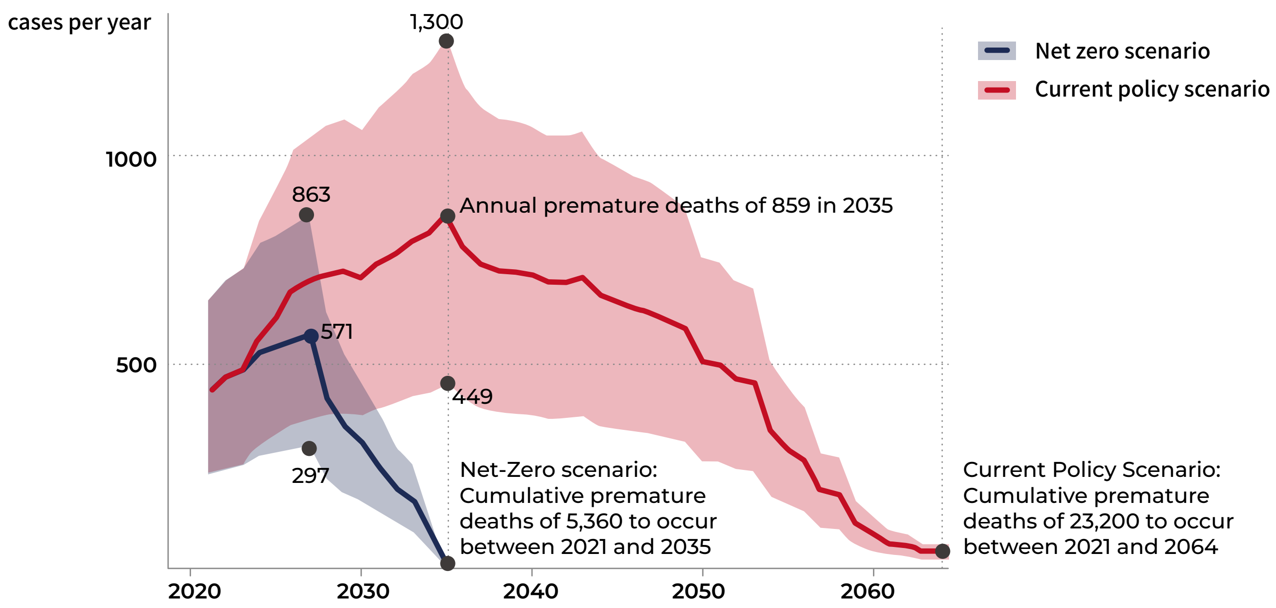
28. The World Health Organization defines healthy life expectancy as 'Average number of years that a person can expect to live in "full health" by taking into account years lived in less than full health due to disease and/or injury.' (WHO, THE GLOBAL HEALTH OBSERVATORY, "Healthy life expectancy (HALE) at birth")

Pollutant	Cause	Current Policy Scenario (2035)		
		Central	Low	High
$PM_{2.5}$	Asthma emergency room visits, adults	30	20	40
$PM_{2.5}$	Asthma emergency room visits, children	9	5	13
$PM_{2.5}$	New cases of asthma in children	302	66	184
$PM_{2.5}$	Preterm births	17	8	18
$PM_{2.5}$	Work absence (sick leave days)	60,600	51,500	69,500
$PM_{2.5}$	Years lived with disability because of chronic obstructive pulmonary disease	84	30	157
$PM_{2.5}$	Years lived with disability because of diabetes	33	8	89
$PM_{2.5}$	Years lived with disability because of stroke	118	39	238

Table 6. Annual health impacts due to gas plants under the Current Policy Scenario (peak year)

B. Cumulative health impacts

Under the Current Policy scenario, cumulative premature deaths from gas power generation are estimated to reach 23,200 (low 12,100, high 35,000) until 2064. On the other hand, under the Net-Zero scenario, the cumulative number of premature deaths reaches 5,360 (low 2,800, high 8,070) until 2035. This means 17,840 premature deaths (low 4,030, high 32,200) can be prevented by withdrawing the plans to build new plants in pipeline and phasing out all gas power plants by 2035.



Cumulative premature deaths	Central	Low	High
Current Policy scenario	23,200	12,100	35,000
Net-zero scenario	5,360	2,800	8,070

Figure 6. Premature deaths due to gas plants under the two scenarios

The cumulative number of premature deaths by country is shown in Table 7 below. The country affected most severely by South Korea's gas power plants is North Korea (1,000, central), followed by Japan (830) and China (701). The health damage in all 4 countries can be decreased by approximately 75 percent if South Korea phases out all of its gas plants by 2035.

Country	Current Policy Scenario			Net zero Scenario		
	Central	Low	High	Central	Low	High
South Korea	20,700	10,700	31,100	4,730	2,450	7,130
North Korea	1,000	513	1,620	267	136	435
Japan	830	479	1,180	212	122	302
China	701	403	1,070	150	86	228

Table 7. Cumulative premature deaths due to gas plants by country under the two scenarios

Pollutant	Cause	Current Policy Scenario			Net Zero Scenario		
		Central	Low	High	Central	Low	High
Total premature deaths		23,200	12,100	35,000	5,360	2,800	8,070
Premature deaths caused by NO_2		20,000	9,690	30,900	4,620	2,240	7,150
Premature deaths caused by $PM_{2.5}$		3,240	2,430	4,140	736	553	941
$PM_{2.5}$	Chronic obstructive pulmonary disease	275	99	523	63	23	120
$PM_{2.5}$	Diabetes	33	10	75	7	2	17
$PM_{2.5}$	Ischemic heart disease	583	425	759	133	97	173
$PM_{2.5}$	Lower respiratory infections	730	212	1,350	167	49	309
$PM_{2.5}$	Lung cancer	479	231	800	108	52	180
$PM_{2.5}$	Stroke	614	237	1,140	140	54	261

Table 8. Cumulative premature deaths due to gas power plants by cause under the two scenarios
This table does not show the number of premature deaths from other diseases, and thus the aggregate number of premature deaths from the listed major diseases does not match the total number of premature deaths.

V. Conclusion and Policy Proposal

Our analysis estimates that air pollution from gas power plants currently in operation will have caused 431 premature deaths as well as numerous new cases of respiratory diseases including asthma in the year 2021. If the number of gas plants continues to rise until 2034 according to the 9th Basic Plan for Long-term Electricity Supply and Demand, premature deaths in 2035 would increase to 859 a year.

While gas power plants' per unit air pollution is less than that from coal power plants, should the current policy stay, the cumulative number of premature death caused by gas plants is estimated to surpass that of coal plants. This likely is largely attributable to the fact that gas plants tend to be located close to densely populated areas and that the current policy allows them to remain online for 10 more years (until 2064) than coal plants (until 2054[29]). Our previous study[30] estimated that air pollution from coal power plants would result in 995 premature deaths per year and 15,000 cumulative premature deaths between 2020 and 2054. Health damages from gas power are comparable in that it is estimated to cause 859 (peak year figure) premature deaths per year and 23,200 cumulative premature deaths until 2064. Cumulative premature deaths caused by gas power plants exceed that of coal power plants.

To avoid the adversary impacts to public health, South Korea must withdraw all plans to construct additional gas power plants that currently are in pipeline. Such policy decision, in conjunction with phasing out all gas plants by 2035, can prevent 17,840 premature deaths. Based on the results on the health benefits of an accelerated gas phase-out, we recommend the following regulatory policies on gas-fired power generation:

1. Withdrawal of the plans to build new gas plants in pipeline

In the current policy environment, the installed capacity of gas-fired power generation would continue to increase until 2035, and the last gas unit would retire only in 2064. The resulting premature deaths is estimated to accumulate up to 23,200, and the number of annual premature deaths in 2035, the year when the installed capacity of gas power generation is at its peak, would reach 859.

29. South Korea recently announced that all coal power generation will be phase out by 2050. This study, however, was released one year prior to the announcement, and hence the outdated 2054 phase out year.
30. Solutions For Our Climate, (2020), "Assessment of the health benefits from an accelerated coal phase out"

South Korea should critically reevaluate such health damages and withdraw the construction plans for all new gas power plants in pipeline. With the 24 units planned to be converted from coal plants (12.7GW), 3 combined cycle power units (3.3GW), and 8 combined heat and power units (2.7GW), the number of new gas units in pipeline under the 9th Basic Plan for Long-term Electricity Supply and Demand amounts to 35 in total (18.7GW). As many as 17,840 premature deaths (approximately 75 percent) can be prevented by withdrawing the plans for new plants in pipeline and phasing out all gas power units by 2035.

2.Stronger emissions standards to limit air pollution from gas power generation

Gas plant's geographical proximity to densely populated areas contribute to its serious health impacts. To reduce such health damages, we advise that the emission standards of air pollution from gas power generation facilities be strengthened. Nitrogen dioxide (NO_2), which is responsible for 70 percent of premature deaths, should particularly be limited with additional policy measures such as tighter standards and appropriate monitoring during non-steady state operations.

During gas plant startups and shutdowns, SCR devices do not perform well and air pollution that exceeds the emission standards escape into the atmosphere. This is especially problematic because gas plants tend to operate only when electricity demands are high, resulting in frequent startups that approximates 160 times a year on average. Under Article 15 of the Enforcement Decree of the Clean Air Conservation Act, air pollution from gas-fired combined cycle power plants can exceed the emission standards for five hours during startups and for two hours immediately after shutdowns. Monitoring, however, appears to be insufficiently practiced and unable to properly track excess emissions resulting from such loose regulations. Measures to monitor, assess, and reduce the environmental and health impacts from air pollution are necessary[31].

3.End financing for gas power generation

Along with expanding gas power generation capacity, South Korea also plans to institutionally support gas power projects. The Korean government announced the "Korean New Deal" as part of its Covid-19 recovery package in July 2020 and has since been providing financial aid drawing from the "K-New Deal Fund"[32]. The "New Deal Investment Common Criteria" designates 115 items eligible for digital new deal and 85 for green new deal, and "gas turbine power generation plants (c11005)" is listed as an environmentally friendly item under the energy sector green new deal[33]. However, lifecycle analysis of liquified natural gas (LNG) has proved that the most commonly used fuel for gas power generation in South Korea contributes significantly to greenhouse gas emissions in the course of its extraction, refining, and transmission, amounting to 70 to 80% of the GHG emissions from coal power generation[34]. As discussed in this study, gas power generation also causes serious air pollution and associated health impacts, and thus does not deserve its "clean" power label. Further, the Ministry of Environment, in October 2021, released the initial draft K-taxomony, which sets the technical standards for green finance projects such as green bonds, and is going through the process of determining whether to include gas power generation under the "green economic activity" category[35]. Adding gas power to the green taxonomy risks severely compromising its fundamental purpose of providing financing only to projects that contribute to achieving environmental goals such as climate action and pollution reduction.

31. For example, the state of California had taken steps to legislate a bill to require monitoring and reporting of the emissions from gas power facility startups and shutdowns to the public and local authorities (SB-64 Fossil-fuel generation units). European Union requires large scale combustion facilities to measure and manage carbon monoxide and ammonia emissions to facilitate monitoring and adapting to the impacts of energy demand fluctuations (Kim et al., 2020, Research on Improving the Management of Air Pollutants Emitted from LNG Cogeneration Facilities).

32. Ministry of Economy and Finance, (2020). "The Korean New Deal: National Strategy for a Great Transformation"

33. Secretariat of the Finance Policy Council for Innovation and Growth, (2021). "New Deal Investment Common Criteria Implementation Manual"

34. Solutions For Our Climate, (2021). "Fueling the Climate Crisis_South Korea's Public Financing for Oil and Gas"

35. Institute for Energy Economics and Financial Analysis, (November 4th, 2021), "Accepting gas as sustainable will hurt South Korea's green finance credentials"

Appendix

Appendix A. Assessing the health impacts of existing and planned gas-fired power plants in South Korea: Methodology

The study follows the "impact pathway" approach, the most common approach for studying the health impacts of air pollutant emissions. The approach tracks air pollution from emissions from the studied sources, to the dispersion and chemical transformation of emissions, to resulting pollution levels in different locations, to population exposure, resulting increase in the risk of different health outcomes and finally to the total health impacts on the population-level.

A. Emissions

First, the study of the health impacts of gas-fired power plants requires detailed information on the location, operation and emissions of the plants.

For operating plants, annual NO_x emissions data was available for 2019 and 2020. For new plants and operating plants without measured emissions data, annual NO_x emissions E were calculated using the equation

$$E = SFGV * CAP / EFF * CF * FGC,$$

where SFGV is specific flue gas volume (Nm3/GJ thermal input), taken from Graham et al (2012), CAP is electric capacity, EFF is thermal efficiency, CF is the annual average capacity factor and FGC is pollutant concentration in flue gas.

To project the FGC, we assumed that all plants follow South Korea's emissions standards for NO_x (10 ppm for new plants). In order to consistently meet emissions standards, plants have to be designed with a significantly lower average pollutant concentration in the flue gas than required by the standard, to leave margin for fluctuations. We calculated the average ratio of average flue gas concentrations to emission limits for the existing plants and applied this to new plants. In other words, we are assuming that new plants will emit significantly less than the maximum allowed by emissions standards during normal operation.

During startup, shutdown and partial load operation, the SCR devices don't work due to the low flue gas temperature, and emissions can exceed standards. Emissions during these times were calculated assuming the SCR devices are 85% efficient and flue gas output is proportional to power generation. The latter assumption is conservative as plant thermal efficiency is lower at these times. The definitions used for non-steady-state operation modes are shown in Table 11, and are stricter than the durations allowed by South Korean regulation which permits five hours of operation without SCR for startup and two hours for shutdown.

The uplift for operation without SCR was only applied to units that have SCR installed according to data compiled by SFOC, or that had flue gas NO_x concentrations below the low end of the values for units without SCR (the threshold calculated from the data was 15 ppm).

SO_2 and $PM_{2.5}$ emissions from fossil gas burning are much lower than allowed by the South Korean emissions standards. For these pollutants, we used the average emission factors per unit of fuel input for South Korean gas-fired power plants from the REAS emissions inventory (Kurokawa et al 2013; see Table 9).

Variable	Value	Unit
CO_2 emissions	33.6	Mt
CO_2 emission factor	56.1	tCO_2/TJ
Fuel input	598	10^3TJ
$PM_{2.5}$ emissions	31.7	t
SO_2 emissions	69.0	t
$PM_{2.5}$ emissions	53.1	10^{-6}kg/GJ
SO_2 emissions	115	10^{-6}kg/GJ

Table 9. Emission factors for SO_2 and $PM_{2.5}$

To account for the variation in emissions rates throughout the year, we developed an hourly emissions dataset for all emissions sources for 2020. For most operating plants, we had hourly power generation either on the unit-level or plant level for 2020. We assumed that fuel input is proportional to electric output, and the amount of pollutants in untreated flue gas is proportional to fuel input.

The hourly emissions profiles were used to scale annual average emissions rates so that emissions during the course of the year, including non-steady state operation, matched the reported annual totals. For plants that didn't have data on annual total emissions, mainly plants that are not yet in operation, we assumed that the plants meet the 10 ppm standard for NO_x concentration in flue gas, except during non-steady state operation.

The CALPUFF atmospheric dispersion model used for the study includes a detailed model for plume rise from power plant stacks, requiring information on stack height, inner diameter, flue gas temperature and release velocity for each modeled stack. This was based on the data that the plant operators submitted to a member of the National Assembly.

To fill in missing data, we developed default values based on available data. Plants were divided into small and large (corresponding to generating capacity less than 300MWe and larger), and into electricity-only and CHP plants. For each of these four categories, we calculated the median capacity factor, thermal efficiency, stack height, inner diameter, flue gas temperature and release velocity, and applied these to all plants with missing data (Table 10). We also calculated the averaged hourly power generation profiles for each category. For new electricity-only plants, we did not use the default value computed from data for existing plants but assumed a thermal efficiency of 58%, based on Ibrahim&Mohammed (2015), which is above the realized efficiencies of even the newest operating plants in South Korea, based on reported power generation and LNG consumption data.

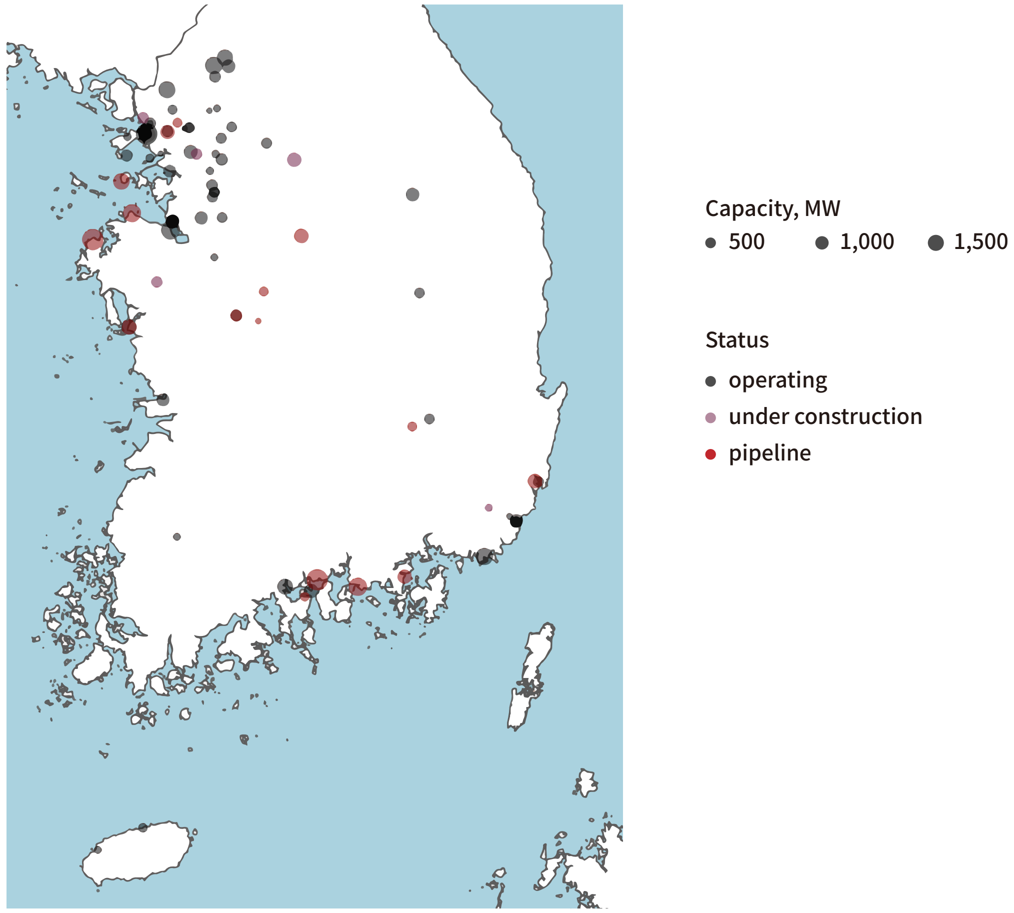


Figure 7. Map of the modeled gas-fired power plants.

type	vintage	size class	stack height	stack diameter	temperature	velocity	capacity factor	fuel-to-power efficiency[36]
electricity-only	before 2013	<=300MW	62.9	5.1	112.8	17.6	18.7%	42.6%
electricity-only	before 2013	>300MW	69.0	5.5	96.1	18.5	27.5%	44.6%
electricity-only	2013 or newer	<=300MW	100.7	4.0	87.3	12.4	41.0%	45.0%
electricity-only	2013 or newer	>300MW	107.2	7.0	112.2	39.2	47.6%	49.2%
CHP	before 2013	<=300MW	82.8	3.3	86.7	15.3	42.6%	32.5%
CHP	before 2013	>300MW	97.7	5.3	98.5	19.7	38.1%	37.4%
CHP	2013 or newer	<=300MW	117.1	2.9	75.8	23.9	35.6%	45.3%
CHP	2013 or newer	>300MW	96.2	6.1	84.7	21.8	64.1%	48.2%

Table 10. Default values by category for plants missing data.

Event	Definition	Duration of operation without SCR
Cold startup	Unit begins generation after >48 hours of zero electricity output	180 minutes
Warm startup	Unit begins generation after >8 hours of zero electricity output	120 minutes
Hot startup	Unit begins generation after up to 8 hours of zero electricity output	60 minutes
Shutdown	Unit stops generation	60 minutes
Partial operation	Unit is generating at less than 50% of rated capacity	—

Table 11. Assumptions about SCR operation during non-steady state operation (based on Bivens 2002).

36. The total thermal efficiency ("fuel-to-useful energy efficiency") of CHP plants is much higher than that of electricity-only plants, often 85% more. This column refers to the ratio of electricity generated to fuel energy input which is used to convert electric capacity to boiler thermal capacity; this ratio is generally lower for CHP plants than for electricity-only plants.

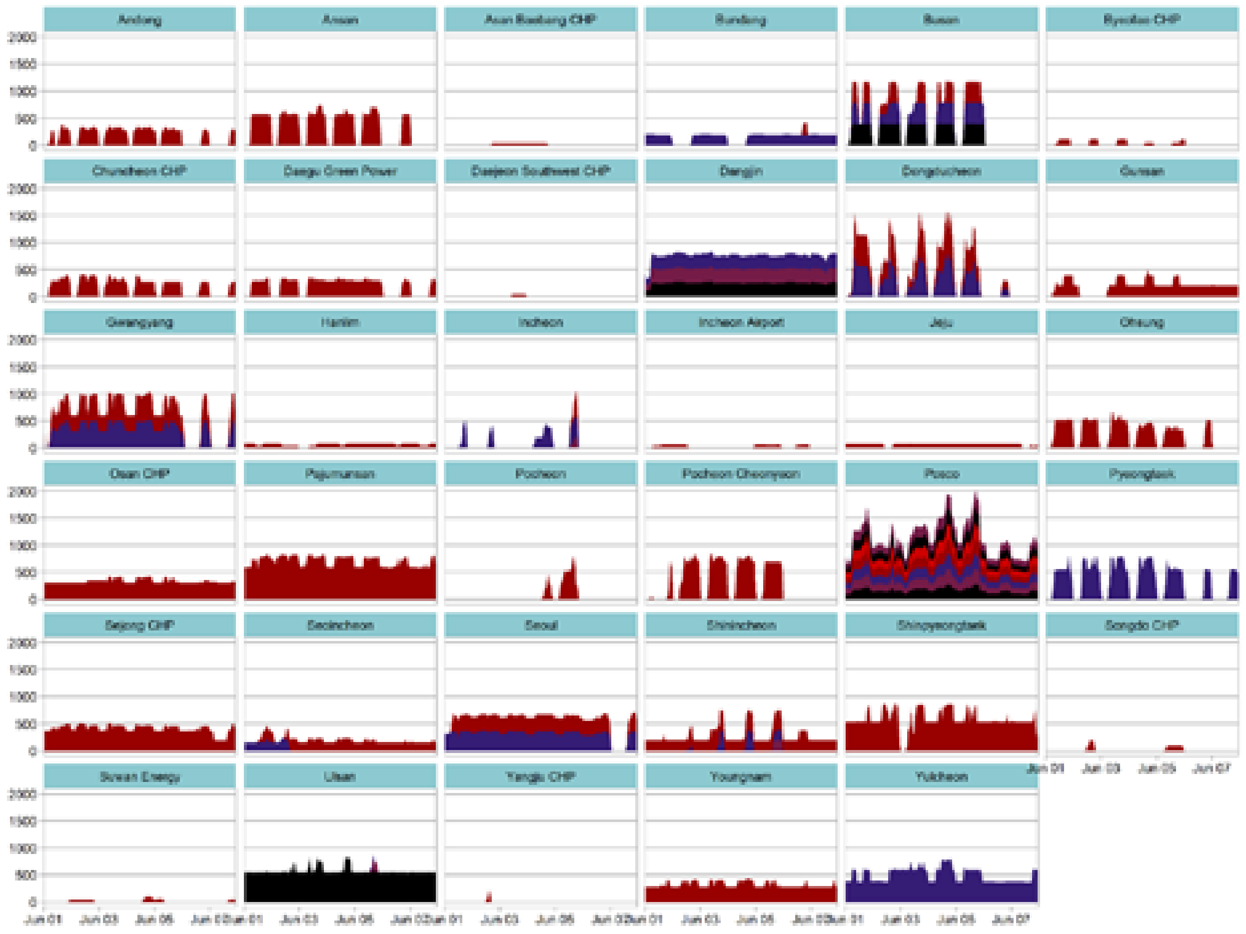


Figure 8. Gas-fired power generation by plant and unit
Example of hourly generation data used for the emissions profiles. Different colors denote different units at the same plant.

B. Future scenarios

We projected future emissions assuming that utilization and emissions of existing plants stay on 2019 level, and the utilization of new plants follows the default values developed based on 2019 data for operating plants. 2019 was chosen as the base year, rather than 2020, because there was a steep, temporary drop in gas-fired generation and emissions in 2020 related to the impacts of the COVID-19 pandemic, making 2019 a more representative base year. In the baseline scenario, the development of total gas-fired capacity until 2034 is based on South Korea's 9th Basic Plan[37], which targets 55 GW of capacity in 2030 and 59 GW in 2034. All under construction and planned plants were assumed to come online as planned, and existing capacity was assumed to retire starting from 2027 and starting from the oldest units so that the capacity targets are met. After 2034, capacity is assumed to stay at the same level until 2040, after which it starts to fall linearly so that the newest units, completed in 2034, retire in 2064.

37. Ministry of Trade, Industry and Energy (2020), "Government announces Basic Plan on Electricity demand and Supply"

We also developed a 2035 gas-fired power plant phase-out scenario, reflecting the IEA 1.5 degree scenario in which the power sector reaches zero emissions by 2035. In this scenario, all planned projects that are not yet under construction are cancelled, and plants already under construction come online as planned. Retirement years were assigned so that retirements start in 2027 and accelerate towards 2035. This leaves a time period of five years to develop replacement capacity even for the oldest units, and results in the phase-out of gas-fired capacity over a period of eight years (Figure 9).

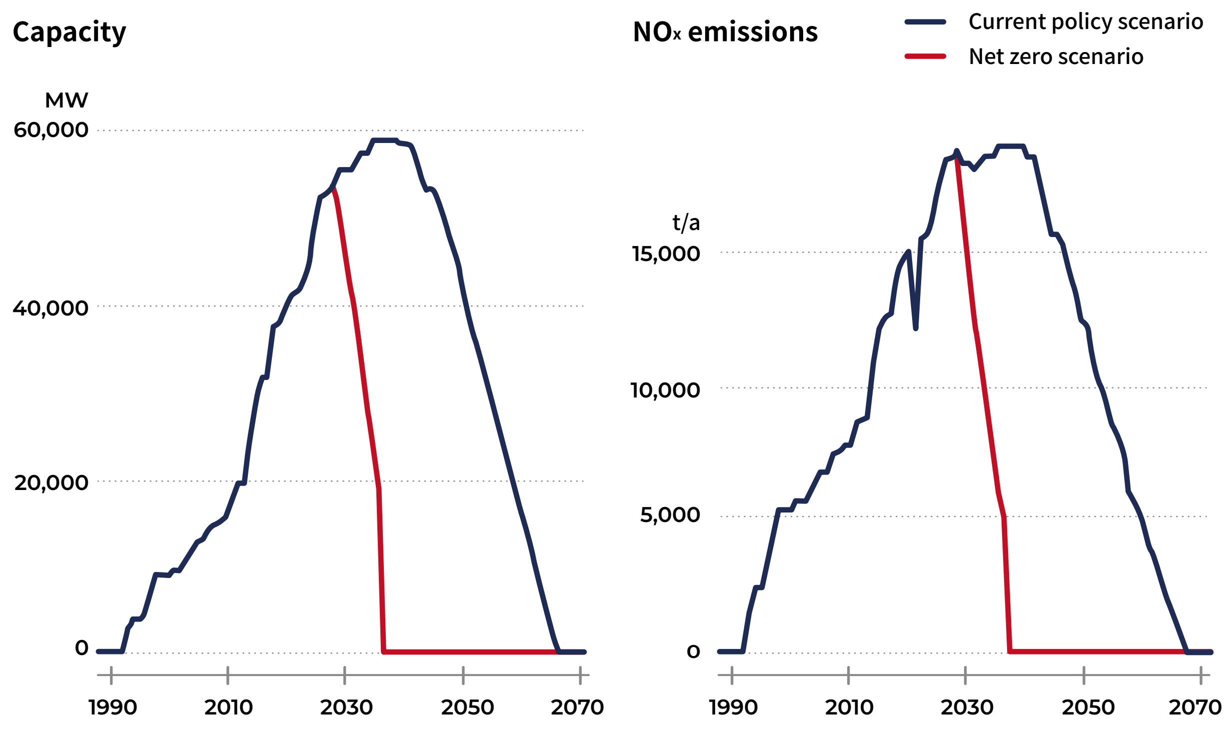


Figure 10. Operating gas-fired capacity and emissions by year

C. Atmospheric and air quality modeling

We carried out detailed atmospheric modeling to estimate the contribution of gas-fired power plants to air pollutant concentrations and air pollution health impacts across South Korea.

Emissions dispersion modeling was done using the latest version of the CALPUFF modeling system.[38] CALPUFF is the most widely used, industry standard model for long-range air quality impacts of point sources, and a model with which air quality regulators around the world are familiar. The model has been extensively validated by the U.S. EPA and other regulatory authorities; it is open source and fully documented.

38. Exponent, "CALPUFF Modeling System"

CALPUFF has several important capabilities for this project: it is able to model the formation of secondary nitrate and sulfate particles from power plant NO_x and SO_2 emissions, and able to model long-range transport. These two mechanisms are responsible for more than 90% of the population exposure to $PM_{2.5}$ and of the health impacts of power plant emissions (see e.g. Zhou et al 2006), so their exclusion would mean omitting the majority of the $PM_{2.5}$ health impact. CALPUFF can also model near-field pollution at a very high resolution and manageable computational costs.

Three-dimensional meteorological data for the simulations was generated using the TAPM modeling system (The Air Pollution Model), developed by Australia's national science agency CSIRO. TAPM uses as its inputs global weather data from the GASP model of the Australian Bureau of Meteorology, combined with higher-resolution terrain data.

The modeling domain covered an area of 1500x1500km centered on South Korea, with the outermost grid having a horizontal resolution of 20km and 35 vertical levels. We used two concentric nested grids with resolutions of 10km and 5km to increase the level of detail near the sources (Figure 11). All grids comprised 75x75 horizontal cells.

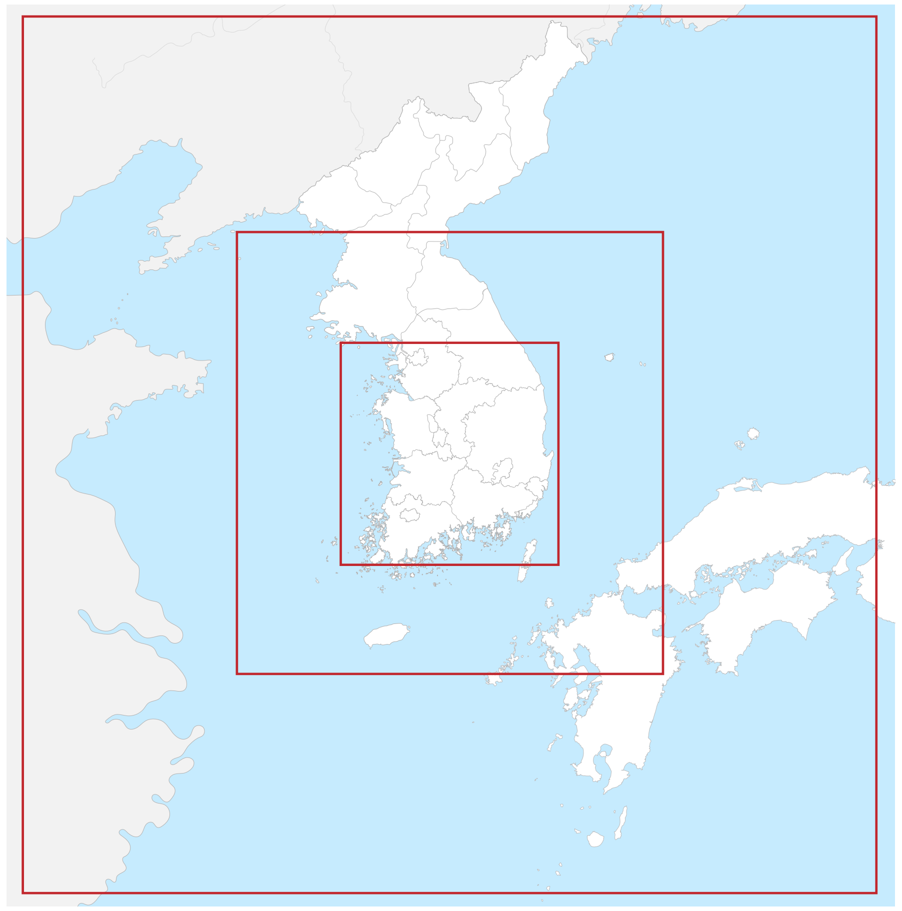


Figure 11. Modeling Domains

TAPM outputs were converted into formats accepted by CALPUFF's meteorological preprocessor, CALMET, using the CALTAPM utility, and the meteorological data were then prepared for CALPUFF execution using CALMET. CALMET generates a set of time-varying micrometeorological parameters (hourly 3-dimensional temperature fields, and hourly gridded stability class, surface friction velocity, mixing height, Monin-Obukhov length, convective velocity scale, air density, short-wave solar radiation, surface relative humidity and temperature, precipitation code, and precipitation rate) for input to CALPUFF.

Terrain height and land-use data were also prepared using the TAPM system and global datasets made available by CSIRO.

For CALPUFF dispersion modeling, concentric receptor grids were defined, with a resolution of 1000x1000 m used for the finest grid near the modeled sources. A spin-up period of three days was used before the beginning of the calendar year to ensure that model start-up effects don't affect the meteorology and that the concentration fields are populated in the model before the start of the study period.

Chemical transformation of sulphur and nitrogen species was modeled using the RIVAD chemistry module within CALPUFF, which requires data on atmospheric chemistry parameters (ozone, ammonia and H2O2 levels). Hourly ozone data from official monitoring stations within the modeling domain was imported into the model, when available. For the other chemical species which are generally not covered by regular air quality monitoring, as well as for ozone when measurement data was not available, monthly average concentrations were input into the model from baseline simulations using the Geos-Chem global atmospheric model with nested grid for Southeast Asia (Koplitz et al 2017). The CALPUFF results were reprocessed using the POSTUTIL utility to repartition different nitrogen species (NO, NO_2, NO3 and HNO3) based on background ammonia concentrations.

We carried out a separate simulation for each power plant location in the study, in order to be able to project the impacts of future scenarios in which each power plant unit comes online and retires at a different time.

D. Health impact assessment

CREA has developed a detailed globally implementable health impact assessment framework, based on latest science, that includes as complete a set of health outcomes as possible without obvious overlaps. The emphasis is on outcomes for which incidence data is available on the national level from global datasets and that have a high relevance for health care costs and labor productivity (see Table 12).

For each evaluated health outcome, we have selected a concentration-response relationship that has already been used to quantify the health burden of air pollution at the global level, in peer-reviewed literature. This indicates the evidence is mature enough to be applied across geographies and exposure levels.

The calculation of health impacts follows a standard epidemiological equation:

$$\Delta cases = POP \times \sum_{age}\left[Frac_{age} \times Incidence_{age} \times \left(1 - \frac{RR(c_{base} + \Delta c_{gas}, age)}{RR(c_{base}, age)}\right)\right],$$

where POP is the total population in the grid location, age is the analysed age group (in the case of age-dependent concentration-response functions, a 5-year age segment; in other cases, the total age range to which the function is applicable), Fracage is the fraction of the population belonging to the analysed age group, Incidence is the baseline incidence of the analysed health condition, c is pollutant concentration, with cbase referring to the baseline concentration (current ambient concentration) and Δcgas is the concentration attributed to gas-fired power plants, with the contribution from existing plants having a negative sign (subtracted from the baseline concentration) and projected future incremental concentration from new plants a positive sign (added on top of the baseline concentration). RR(c, age) is the function giving the risk ratio of the analysed health outcome at the given concentration, for the given age group, compared with clean air. The result of the equation is negative for existing plants, representing cases that would be avoided if pollution from gas was eliminated, and positive for new plants, representing additional cases resulting from the increase in pollution.

In the case of a log-linear, non-age specific concentration-response function, the RR function becomes:

$$RR(c) = RR_0^{\frac{c-c_0}{\Delta c_0}} \text{ when } c > c, 1 \text{ otherwise},$$

where RR0 is the risk ratio found in epidemiological research, Δc0 is the concentration change that RR0 refers to, and c0 is the assumed no-harm concentration (generally, the lowest concentration found in the study data).

Data on country-specific total population and population age structure was taken from Global Burden of Disease results for 2019 (IHME 2020). The spatial distribution of population within each country, as projected for 2020, was based on Gridded Population of the World v4 (CIESIN 2018).

Adult deaths and years of life lost from $PM_{2.5}$ exposure were estimated using the risk functions developed by Burnett et al (2018), as applied by Lelieveld et al (2019). For deaths, the GEMM (Burnett et al 2018) risk model is chosen rather than the Global Burden of Disease model which includes indoor air pollution and smoking in addition to outdoor air pollution.

Although the GBD model is more widely used, it incorporates excessively conservative assumptions about health risks at low and high ends of the concentration range. At the extreme, the model indicates no reduction in risk when air pollutant concentrations are reduced by a small amount at low and high concentrations, as it would be applied here for reduction from the energy sector only.

GEMM is based on latest evidence, including from studies in East Asia, and focuses on outdoor air pollution which is the subject of this study.

The $PM_{2.5}$ mortality results from the GEMM model include deaths from "all causes", which specifically refers to all non-communicable diseases and lower respiratory infections, as well as cause-specific results for the most important causes. The all-cause results exceed the sum of the cause-specific results, due to other non-communicable diseases being included, and likely also due to higher confidence afforded by aggregating the different causes.

Deaths from long-term NO_2 exposure were quantified applying the findings of Faustini et al (2014) meta-analysis which paid particular attention to the combined impacts of $PM_{2.5}$ and NO_2 in multi-pollutant risk models. The concentration-response relationship (odds ratio of 1.04) also aligns closely with the recommendations from the WHO HRAPIE project (WHO 2013). The WHO recommended an odds ratio of 1.057 but indicated that up to one third of the deaths attributed to NO_2 exposure could overlap with deaths attributed to $PM_{2.5}$. As Faustini et al didn't document the lowest concentrations found in the included studies, the assumed no-harm concentration was adopted from Stieb et al (2021).

Deaths of small children (under five years old) from lower respiratory infections linked to $PM_{2.5}$ pollution were assessed using the Global Burden of Disease risk function for lower respiratory diseases (IHME 2020).

For all mortality results, the required cause-specific data was taken from the Global Burden of Disease project results for 2019 (IHME 2020). For other health outcomes, national-level incidence data was used, with the sources given in Table 12.

Health impact modelling projects the effects of pollutant exposure during the study year. Some health impacts are immediate, such as exacerbation of asthma symptoms and lost working days, while other, chronic impacts may have a latency of several years.
Concentration-response relationships for emergency room visits for asthma and work absences are based on studies that evaluated daily variations in pollutant concentrations and health outcomes; these relationships are applied to changes in annual average concentrations.

The annual average baseline concentrations of $PM_{2.5}$ and NO_2 were taken from van Donkelaar et al (2016) and Larkin et al (2017) respectively. These baseline (current ambient) concentrations are needed, in addition to the modeled contributions from gas power plants, to apply non-linear concentration-response relationships and concentration thresholds. The resolution of the Larkin et al dataset is 100 meters and that of the van Donkelaar et al dataset is 0.01 degrees; both datasets were aggregated and interpolated to the 1km resolution used for the health impact assessment.

All analysis was carried out in the R data analysis software, in spatial grids with 1x1km resolution, with health impacts calculated for each grid cell. All datasets were aggregated or interpolated to this resolution as required.

Age group	Effect	Pollutant	Concentration-response function	Concentration change	No-risk threshold	Reference	Incidence data
1-18	New asthma cases	NO_2	1.26 (1.10 – 1.37)	10 ppb	2 ppb	Khreis et al 2017	Achakulwisut et al 2019
0-17	Asthma emergency room visits	$PM_{2.5}$	1.025 (1.013, 1.037)	10 ug/m³	6 ug/m³	Zheng 2015	Achakulwisut et al 2018
18-99	Asthma emergency room visits	$PM_{2.5}$	1.023 (1.015, 1.031)	10 ug/m³	6 ug/m³	Zheng 2015	Anenberg et al 2018
Newborn	Preterm birth	$PM_{2.5}$	1.15 (1.07, 1.16)	10 ug/m³	8.8 ug/m³	Sapkota et al 2012	Chawanpaiboon et al 2019
20-65	Work absence	$PM_{2.5}$	1.046 (1.039-1.053)	10 ug/m³	N/A	WHO 2013	EEA 2014
0-4	Deaths from lower respiratory infections	$PM_{2.5}$	IHME 2020		5.8 ug/m³	IHME 2020	IHME 2020
25-99	Deaths from non-communicable diseases, disaggregated by cause, and from lower respiratory infections	$PM_{2.5}$	Burnett et al 2018		2.4 ug/m³	Burnett et al 2018	IHME 2020
25-99	Disability caused by diabetes, stroke and chronic respiratory disease	$PM_{2.5}$	IHME 2020		2.4 ug/m³	Burnett et al 2018	IHME 2020
25-99	Premature deaths	NO_2	1.04 (1.02-1.06)	10 ug/m³	4.5 ug/m³	Faustini et al 2014; NRT from Stieb et al 2021	IHME 2020

Table 12. Input parameters and data used in estimating physical health impacts.
Numeric values in the column "Concentration-response function" refer to odds ratio corresponding to the increase in concentrations given in the column "concentration change". Literature references indicate the use of a non-linear concentration-response function. No-harm threshold refers to a concentration below which the health impact is not quantified, generally because the studies on which the function is based did not include people with lower exposure levels.

E. Projections of future health impacts

The health impacts of air pollution will increase over time in most impact categories, unless air quality improves, due to population growth, population aging and the epidemiological transition that increases the prevalence of chronic diseases, the risk of which is affected by air pollution.

To capture these effects, we used country-specific projections of total population and population age distribution, as well as death rates, from UNPD World Population Prospects. The distribution of age group-specific mortality by cause was assumed to stay constant.

We projected the air pollutant attributed to gas-fired power in each grid cell over time by scaling the contributions from each plant location to account for new units coming online or units retiring.

Appendix B. Comparison of pollutant concentrations under the Current Policy scenario and the Net-Zero scenario

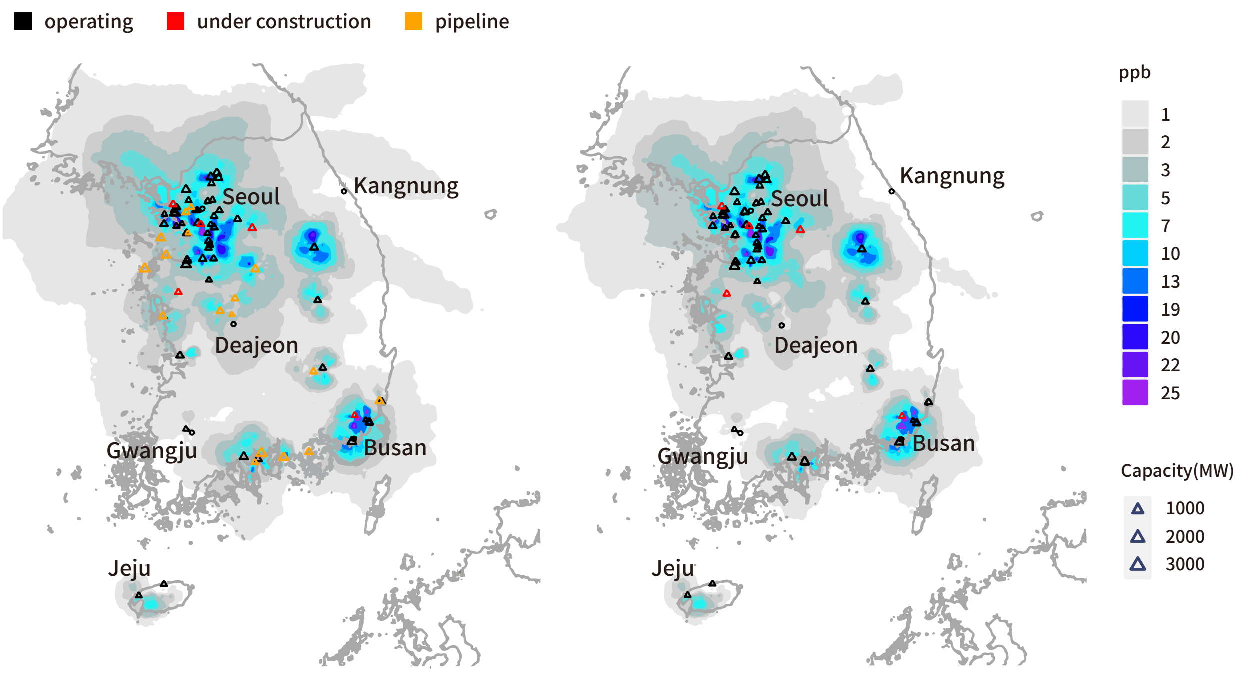


Figure 12. Comparison of the hourly mean NO_2 concentration under the Current Policy scenario and the Net-Zero scenario

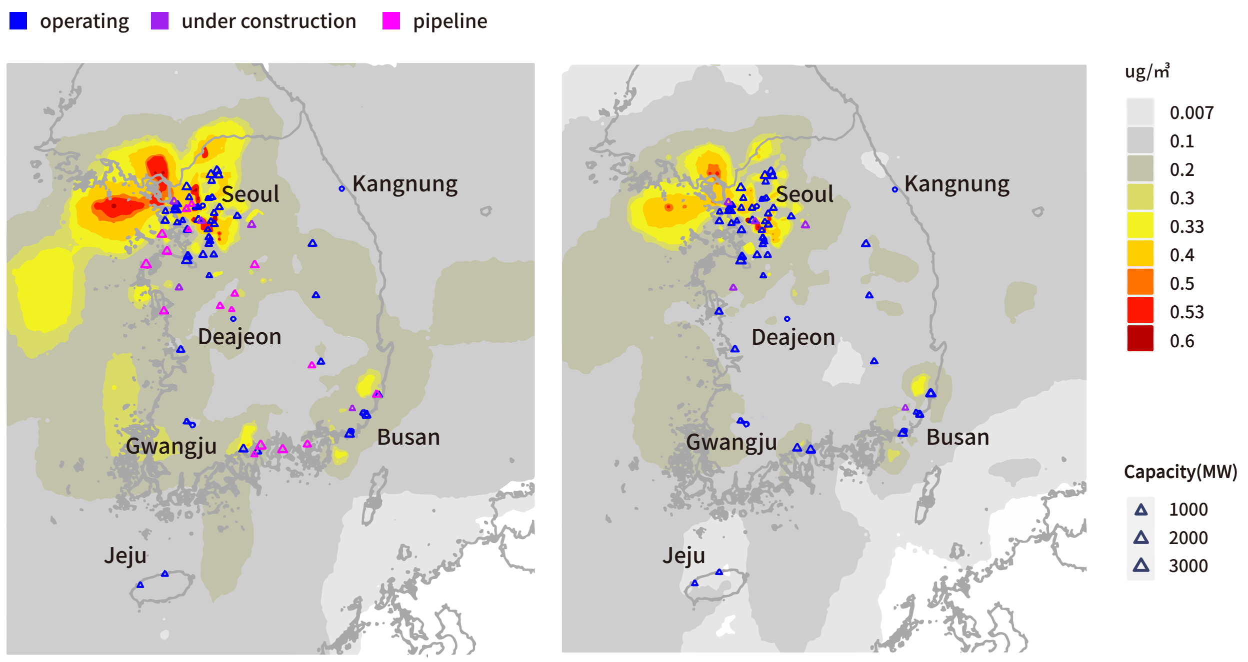


Figure 13. Comparison of the daily mean particulate matter ($PM_{2.5}$) concentration under the Current Policy scenario and the Net-Zero scenario

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