The Inconsistent "Coal-Free Pledge" of Korea's National Pension Service

An analysis on the air pollution and health damage caused by the NPS' coal investment

CREA
Centre for Research on Energy and Clean Air

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Centre for Research on Energy and Clean Air

About CREA

The Centre for Research on Energy and Clean Air is an independent research organisation focused on revealing the trends, causes, and health impacts, as well as the solutions to air pollution.

CREA uses scientific data, research and evidence to support the efforts of governments, companies and campaigning organizations worldwide in their efforts to move towards clean energy and clean air. We believe that effective research and communication are the key to successful policies, investment decisions and advocacy efforts. CREA was founded in December 2019 in Helsinki, Finland and has staff in several Asian and European countries.

Solutions for Our Climate

About SFOC

Solutions for Our Climate (SFOC) is a nonprofit organization established in 2016 for more effective climate action and energy transition based in Seoul, South Korea. SFOC is led by legal, economic, financial and environmental experts with experience in energy and climate policy and works closely with domestic and international players.

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Key findings

- The National Pension Service (NPS) has yet to establish a specific policy to limit its coal investments, more than two years after coal divestment declaration in May 2021. Meanwhile, the NPS continues to invest large amounts of capital directly and indirectly in South Korean coal-fired power plants (CFPPs).

- This study analyzes the air pollution and health impacts caused by the NPS' investment in domestic CFPPs based on the CALPUFF modeling system, an industry-standard emission diffusion model. It also estimated the resulting economic losses.

- Between 2021 and 2022, exposure to air pollution from CFPPs in South Korea is estimated to have caused approximately 1,970 deaths[1]. Approximately 11.2%, 220[2], can be linked to the NPS through its investment in domestic coal power plants.

- Health and economic impacts as a result of air pollution from coal in the country also include approximately 580 new cases of asthma in children, 280 preterm births, over 800,000 days of work absence (sick leave days), and 560 asthma-related emergency room visits in South Korea for 2021 and 2022 combined. Of these, the NPS-linked number of cases is 67 new cases of asthma in children, 32 preterm births, 90,690 days of work absence, and approximately 63 asthma emergency room visits.

- The total costs of exposure to air pollution from CFPPs in South Korea between 2021 and 2022 amounted to approximately USD 10 billion[3] (KRW 12.9 trillion[4]) in healthcare and welfare expenditures. Of these, around USD 1.1 billion[5] (KRW 1.4 trillion[6]) can be attributed to the NPS' investment in domestic coal.

1 95% CI: 1,340 to 2,860
2 95% CI: 150–321
3 95% CI: USD 6.6 – 13.8 billion
4 95% CI: KRW 8.5 – 17.9 trillion; Currency conversions are done using 2022 average exchange rate of 1 USD = 1292 KRW.
5 95% CI: USD 0.7 – 1.5 billion
6 95% CI: KRW 0.9 – 2.0 trillion

- In terms of regions, the largest health and economic impacts were found to be in Chungcheongnam-do, where the Taean and Dangjin coal power plants are located, and Incheon Metropolitan City, where the Yeongheung power plant operates. The annual deaths linked to the NPS for these plants were estimated at 26, 23 and 18 annual deaths in 2022. Furthermore, the total NPS-linked costs caused by these plants are USD 120 million[7] (KRW 155 billion[8]), USD 110 million (KRW 142 billion[10]), and USD 87 million[11] (KRW 113 billion[12]), respectively.

7 95% CI: USD 81 – 177 million
8 95% CI: KRW 105 – 228 billion
9 95% CI: USD 75 – 160 million
10 95% CI: KRW 97 – 206 billion
11 95% CI: USD 59 – 127 million
12 95% CI: KRW 76 – 164 billion

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I. Introduction

In the age of the Climate Crisis, the movement of capital towards the sustainability of the world's environment and human society has become an irrefutable paradigm. Financial markets are indeed striving to pave the path for restoring sustainability, and the first step towards this sustainable path is "coal-free" finance. Among fossil fuels, coal is one of the main culprits of the climate crisis due to its high concentrations of greenhouse gasses (GHG). Moreover, coal-fired generation is one of the main causes of air pollution that consequently has adverse effects on health, such as cardiovascular and respiratory diseases.

In South Korea, the National Pension Service (NPS) recognizes the issues related to coal power generation and the necessity of reducing carbon emissions. Indeed, in May 2021, the NPS made its "coal-free declaration"(Ministry of Health and Welfare, 2021). As a "big player" in the capital markets in the domestic and global arenas, this declaration is more than just some ESG policy from one institution. In fact, the NPS holds shares in more than a thousand companies in South Korea and is a universal owner with its share of market capitalization of more than 6%. It also accounts for around 10% of the bond market. Furthermore, at the end of February 2023 the Korean pension fund's reserves totaled approximately USD 726 billion, thus ensuring its place among the top three public pension funds. Consequently, the ESG policies of the NPS have significant influence in the financial markets and on ESG investment and governance policies of companies.

As of today, the NPS continues to invest in coal power generation without developing concrete exclusion policies despite being two years since the fund's coal-free declaration. Hence, the declaration is a mere statement lacking practical planning and implementation. First of its kind, this study analyzes the air pollution and health impacts of the Korean National Pension Service's national coal investment, and the consequent economic losses over these past two years (from 2021 to 2022).

II. NPS's investment attribution to the impact of domestic coal power plants

There are a total of 15 domestic coal-fired power plants in South Korea, including those under construction. Of these, except for four power plants with private operators, 11 power plants are operated by five power generating companies totally owned (100% shareholding) by Korea Electric Power Corporation (KEPCO). This study calculated the degree of responsibility, the attribution factor, of the NPS's investment in coal in the air pollution and health damage impacts generated by domestic coal-fired power plants.

The calculation methodology was developed based on the carbon accounting reporting standards for the financial industry proposed by the Partnership Carbon Accounting Financials (PCAF) in consultation with Jun-hee Jung, a professor of accounting at Daegu University, and the amount of coal investment was based on data submitted by the National Pension Service from the office of Choi Young-hee, a member of the National Assembly's Health and Welfare Committee.

PCAF is a global coalition led by financial institutions that aims to drive capital into low-carbon economic activities through standardized carbon accounting. PCAF's carbon accounting reporting standard is widely used as a method for calculating GHG emissions (financial emissions) from financial institutions' investment activities, and the basic unit of calculation is the investee company. However, since this study analyzed air pollution and health damage impacts at the level of 'coal power plants', it was inappropriate to apply the PCAF methodology directly. Therefore, the PCAF methodology was used as the basic framework, but the annual air pollution emissions of each power plant unit were multiplied by an attribution factor attributable to the investment activities of the National Pension Service to calculate the final contribution.

The attribution factors were calculated and summed for stocks and corporate bonds for which specific investments can be identified among the seven asset classes presented in the PCAF Carbon Accounting Reporting Standard: listed stocks and corporate bonds, corporate loans and unlisted stocks, project finance, commercial real estate, mortgages, auto loans, and government bonds (PCAF, 2022). The detailed calculation methodology can be found in Appendix 1.

Table 1. The final attribution factor for stocks and bonds combined is as follows.

Power company	Power plant	NPS final attribution factor (%)
KOEN	Yeongheung Power Plant	11.673
	Yeosu Power Plant	11.485
	Samcheonpo Power Plant	11.576
Gangneung Eco Power	Gangneung Anin Coal Power Plant	0.194
Goseong Green Power	Goseong Hai Power Plant	3.349
KOSPO	Hadong Coal Power Plant	11.595
	Samcheok Green Power Plant	11.679
KOMIPO	Boryeong Power Plant	11.607
	Shin Boryeong Power Plant	11.557
	Shin Seocheon Power Plant	11.531
EWP	Dangjin Coal Power Plant	11.774
	Donghae Power Plant	11.470
GS Donghae Power	Bukpyeong Power Plant	4.100
KOWEPO	Taean Power Plant	11.865
Samcheok Blue Power	Samcheok Power Plant	3.036

III. Emissions load and air quality impact analysis

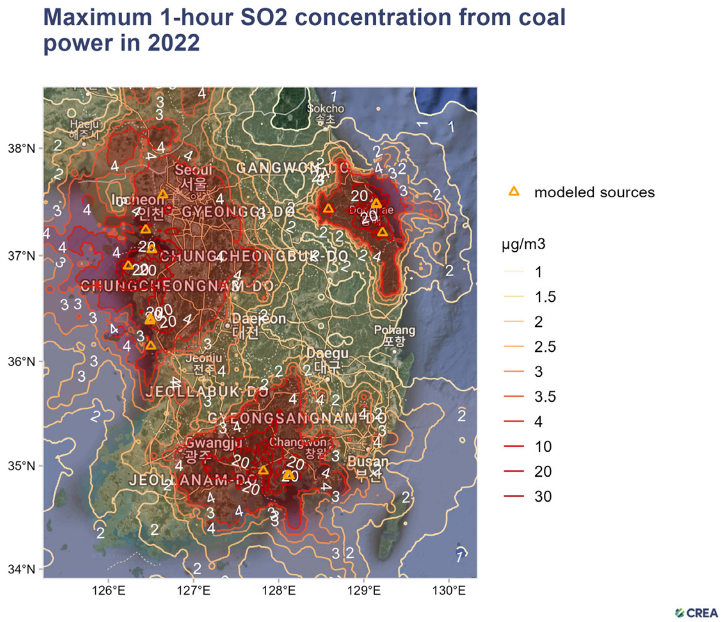
Coal-fired power plants emit pollutants such as sulfur dioxide (SO_2), nitrogen oxide (NO_x), and fine particulate matter ($PM_{2.5}$). Sulfur dioxide is a major air pollutant that at high concentrations is highly absorbed through the respiratory system, where it reacts with mucous membrane fluids and causes inflammation. Prolonged exposure to sulfur dioxide can lead to diseases such as pneumonia and asthma (Seoul Metropolitan Government, n.d). Similarly, long-term exposure to nitrogen oxide[13], however low the concentrations, can lead to chronic poisoning, emphysema, and other health problems (Seoul Metropolitan Government, n.d). Ultrafine particulate matter is dust with a diameter of 2.5 micrometers (μm) or less, which cannot be filtered from the airways during the inhalation process and penetrate even the alveoli. Ultrafine particulates can cause heart and respiratory diseases increasing premature mortality (Seoul Metropolitan Government, n.d).

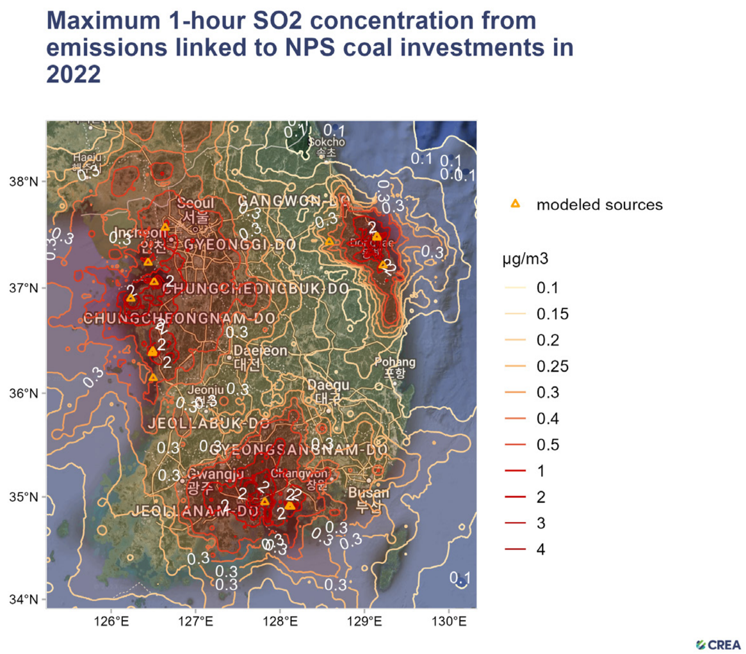
Based on data on air pollutants and emission facilities of domestic coal-fired power plants submitted by the Ministry of Environment to the office of Representative Jin Sung-joon of the National Assembly (Environment and Labour Committee), the operating coal-based power plants listed are estimated to have emitted 21.5 kilotons (kt) of SO_2, 19.2 kt of NO_x, and 1.6 kt of particulate matter (PM) pollution in 2022. The amount of pollution that can be attributed to NPS's share of coal investments is 2.5 kt of SO_2 , 2.2 kt of NO_x, and 0.2 kt of PM.

Figure 1 visualizes the impacts of maximum hourly (1-hr and 24-hr) concentrations of SO_2, NO_2 and $PM_{2.5}$ from the modeled power plant units in 2022 compared with the concentrations of the pollutant emissions linked to NPS' investments. Figure 2 presents the annual mean concentrations of the same pollutants. As can be seen from the figures, the emissions that can be linked to NPS are noticeable, therefore its impact on air quality, the environment and human health are also observable.

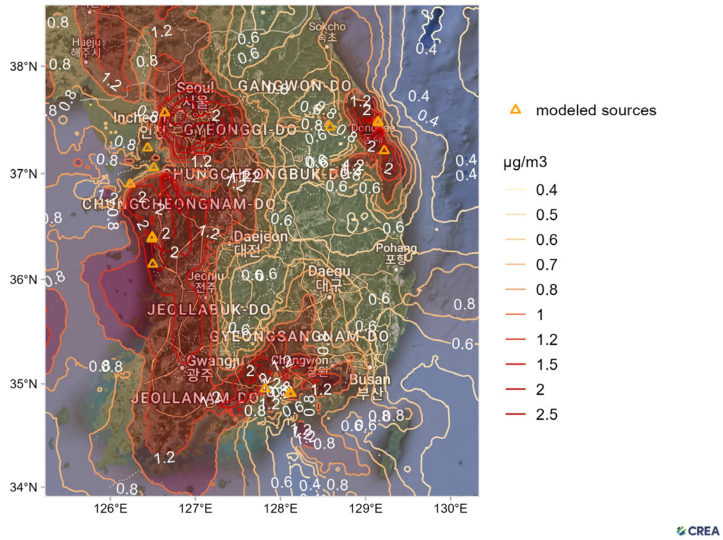
13 However, NOx gets quickly converted to NO2 which is the pollutant associated with health impacts.

Figure 1. Maximum 1-hour and 24-hour concentrations of SO_2, NO_2 and $PM_{2.5}$ from all coal power in 2022 compared to NPS-attributed investments in coal in 2022

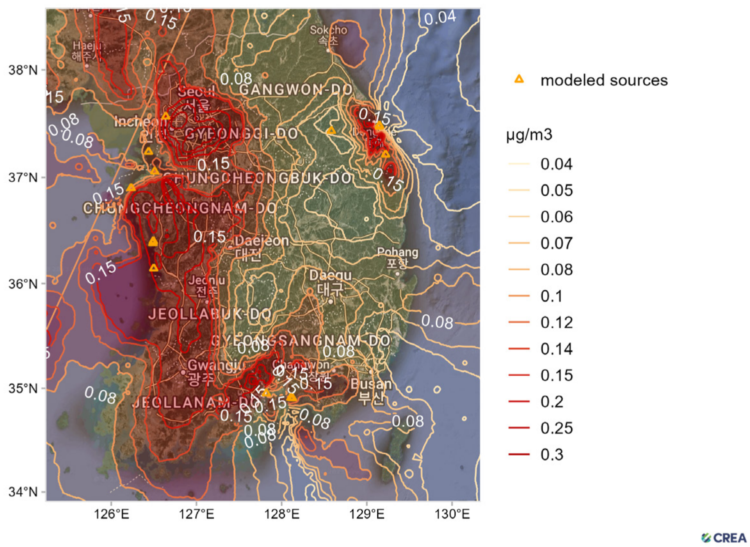




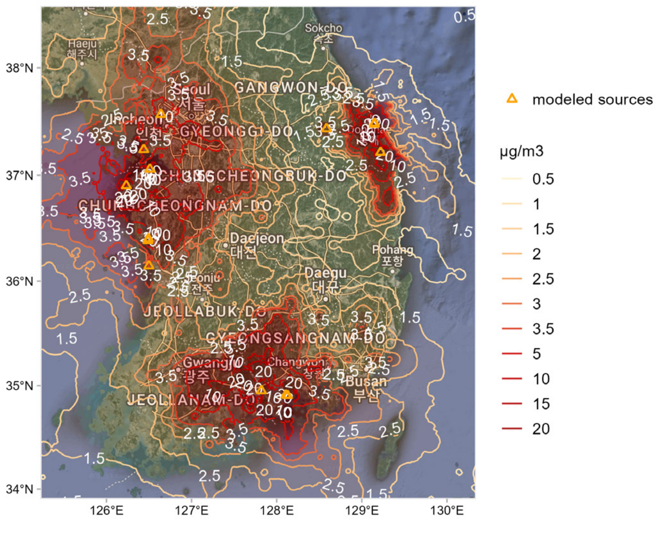
Maximum 24-hour PM2.5 concentration from coal power in 2022



Maximum 24-hour PM2.5 concentration from emissions linked to NPS coal investments in 2022



Maximum 1-hour NO2 concentration from coal power in 2022



Maximum 1-hour NO2 concentration from emissions linked to NPS coal investments in 2022

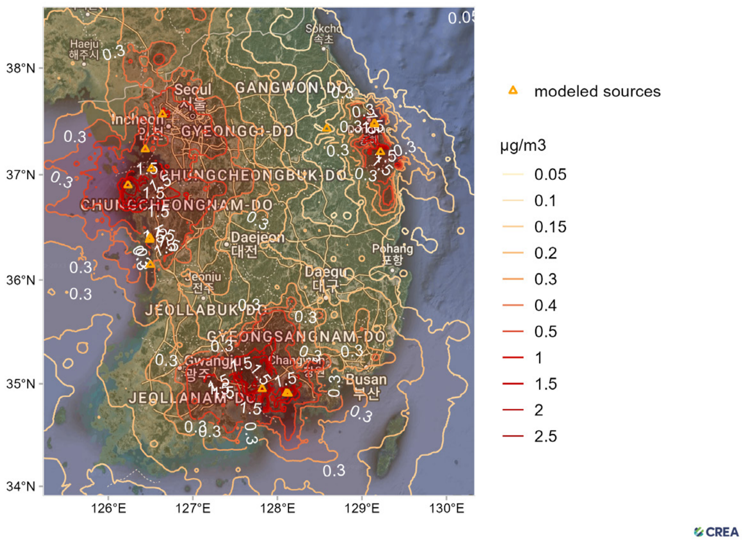
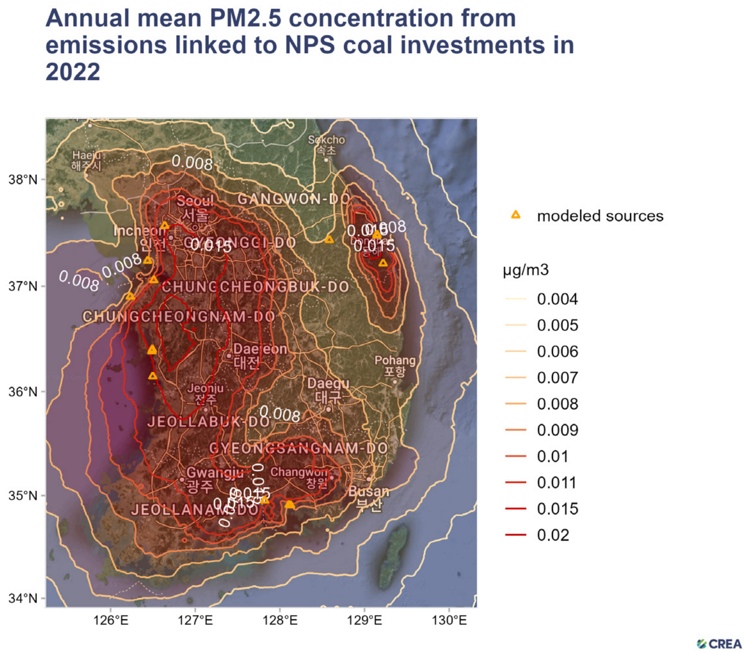
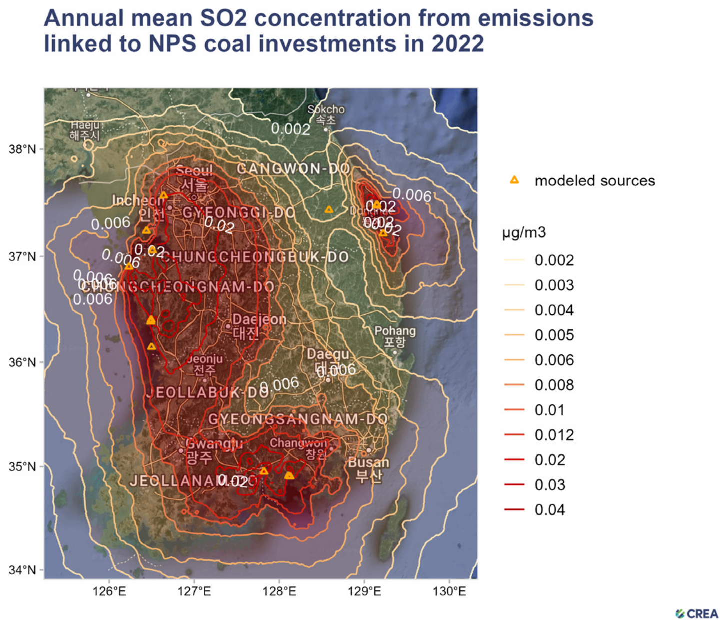
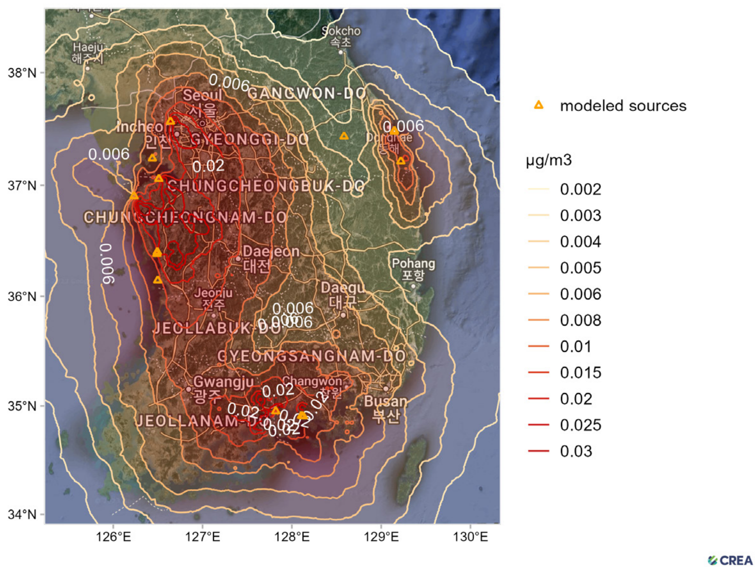


Figure 2. Annual Mean Concentrations from the modeled power plants





Annual mean NO2 concentration from emissions linked to NPS coal investments in 2022



IV. Health impacts and economic costs

The operational coal fleet in South Korea caused an estimated 1,968 deaths in the country between 2021 and 2022. Of this, approximately 220 deaths could be attributed to NPS' share of the power plants, that being 11.2% of all deaths across the country for two years. The total cost of all health impacts on the economy for the two years is estimated at USD 9.6 billion (KRW 12,400 billion). Again, over 11% — or USD 1.1 billion (KRW 1,400 billion) — of the total health costs to society can be linked to NPS' share of the power plants.

Table 2. South Korea total and NPS attributed deaths from coal power air pollution between 2021 and 2022, by cause (95% confidence interval in parentheses)

Pollutant	Causes	South Korea total	NPS
NO_2	all causes	401 (194–831)	46 (22–94)
$PM_{2.5}$	chronic obstructive pulmonary disease	110 (39–212)	12 (4–24)
	diabetes	10 (3–20)	1.1 (0.3–2.2)
	ischaemic heart disease	230 (167–300)	26 (19–33)
	lower respiratory infections	283 (89–517)	31 (10–56)
	lung cancer	173 (83–288)	19 (9–32)
	stroke	239 (92–442)	27 (10–49)
SO_2	all causes	336 (226–454)	38 (26–52)
total cases of deaths		**1,968 (1,345–2,861)**	**220 (150–321)**
total economic costs (USD billion)		**9.6 (6.6–13.8)**	**1.1 (0.7–1.5)**

Other health impacts occur as a result of coal-fired pollution in South Korea. An estimated 2,760 children suffered from asthma due to pollution exposure in 2021 and 2022 combined, of which 315 can be attributed to NPS' linkage with the power plants. 589 new cases of asthma in children arose in the two years with 67 linked to NPS, and a further 285 preterm births occurred, 32 of which linked to NPS. Over 2,000 years lived with disability due to chronic obstructive pulmonary disease, diabetes or stroke of which an estimated 260 were linked to NPS. Additionally, there were approximately 809,000 work absences as a result of people having to take sick leave days due to numerous pollution-related health issues, of which over 90,000 cases can be ascribed to NPS.

Table 3. Total health impacts in South Korea and NPS attributed health impacts between 2021 and 2022 from coal power air pollution

Cause	Total number of cases			NPS-linked number of cases		
	Best estimate	Low estimate	High estimate	Best estimate	Low estimate	High estimate
new cases of asthma in children	589	127	1,332	67	14	152
number of children suffering from asthma due to pollution exposure (increased prevalence)	2,767	692	5,961	315	79	679
asthma emergency room visits	563	348	775	63	39	87
preterm births	285	138	302	32	15	34
work absence (sick leave days)	809,800	688,900	929,900	90,690	77,150	104,100
years lived with disability	2,333	761	4,705	259	84	522

Isolating the health impacts per plant and by the share attributed to NPS, the highest impacts come from power plants with the highest capacities, namely the 6,400 MW Taean power plant with 26 annual deaths and costs of USD 120 million (KRW 155 billion), the 6,040 MW Dangjin plant with 23 deaths and total economic costs of USD 110 million (KRW 142 billion), and the 5,080 MW Yeongheung plant with 18 deaths in 2022 and all its impacts costing the economy USD 113 million (KRW 84 billion).

Table 4. Annual NPS attributed health impacts and total costs in 2022, per power plant

Plant name	Asthma emergency room visits	Deaths	New cases of asthma in children	Work absences	Cost, USD million	Cost, KRW billion
Boryeong	2 (1 – 3)	6 (4 – 9)	1 (0 – 3)	2,990 (2,540 – 3,440)	30 (21 – 42)	39 (27 – 54)
Bukpyeong	0 (0 – 0)	0 (0 – 1)	0 (0 – 0)	169 (143 - 194)	2 (1 – 3)	3 (1 – 4)
Dangjin	7 (4 – 9)	23 (16 – 33)	7 (1 – 15)	9,500 (8,080 – 10,900)	110 (75 – 160)	142 (97 – 206)
Donghae	1 (1 – 1)	3 (2 – 4)	0 (0 – 0)	1,440 (1,220 – 1,650)	15 (11 – 19)	19 (14 – 25)
Gangneung Anin	0(0 – 0)	0 (0 – 0)	0 (0 – 0)	18 (15 – 21)	0 (0 - 0)	0 (0 - 0)
Goseong Hi	0 (0 - 0)	1 (1 – 1)	0 (0 – 0)	375 (319 – 431)	5 (3 – 6)	6 (4 – 8)
Hadong	3 (2 – 4)	10 (7 – 15)	3 (1 – 6)	4,250 (3,620 – 4,880)	56 (39 – 78)	72 (50 – 101)
Samcheok Green Power	1 (1 – 2)	4 (3 – 6)	1 (0 – 1)	2,030 (1,720 – 2,330)	22 (16 – 30)	28 (21 – 39)
Samcheonpo	1 (1 – 2)	5 (3 – 7)	1 (0 – 3)	1,930 (1,640 – 2,220)	26 (18 – 38)	34 (23 – 49)
ShinBoryeong	1 (1 – 1)	3 (2 – 4)	1 (0 – 1)	1,500 (1,270 – 1,720)	15 (10 – 21)	19 (13 – 27)
Shin Seocheon	0 (0 – 0)	1 (0 – 1)	0 (0 – 1)	251 (214 – 289)	3 (2 – 4)	4 (3 – 5)
Taean	8 (5 – 11)	26 (18 – 39)	9 (2 – 20)	10,900 (9,310 – 12,600)	120 (81 – 177)	155 (105 – 228)
Yeongheung	5 (3 – 7)	18 (12 – 27)	5 (1 – 12)	7,210 (6,140 – 8,280)	87 (59 – 127)	113 (76 – 164)
Yeosu	0 (0 – 1)	4 (2 – 7)	4 (1 – 9)	664 (565 – 763)	20 (11 – 37)	26 (14 – 48)

As the Ministry of Health and Welfare of South Korea (MOHW) oversees the NPS and is also responsible for public health, it seems imperative to identify the current situation regarding public health related to coal-linked emissions and prepare countermeasures at the national health level. However, related research and policies seem to be lacking.

Recommendations

This study shows alarming results in terms of air pollution and health damage caused by the National Pension Service's domestic coal investments. The cumulative losses are expected to increase if the NPS continues to delay establishing science-based and effective policies restricting coal investments. This study proposes the following coal divestment policies to prevent further health and economic losses.

1. As a public pension fund, the NPS should actively engage in climate action to remain within the 1.5°C degree limit set out in the Paris Climate Agreement.
2. Expand the definition of the coal industry to include the entire coal value chain.
3. The quantitative criteria for classifying coal companies should be set at a minimum of 30% by revenue (or, in the case of power generation companies, by electricity generation). The criteria must be progressively strengthened.
4. Establish standards for active stewardship activities and enhance transparency for coal companies.

Appendix A: Calculation methodology for NPS financed emissions from domestic coal power plants

A. Shareholding Attribution Factor

The attribution factor for stocks is calculated through the following two steps.

[Step 1] Calculate the proportion of the total assets of the power plant in the total assets for the power company.

$$\frac{\textit{Power plant's consolidated total assets}}{\textit{Power company's consolidated total assets}} = a$$

In the case of unlisted companies, the "consolidated total assets' is used in the consolidated financial statements. The total assets of power plants under construction are replaced by the project costs in the business plan.

[Step 2] In order to have the final attribution factor linked to shareholding, calculate the proportion of the NPS's investment in the power generation company multiplied by the result in Step 1.

$$a * \frac{\textit{Market Cap of the parent company} * \textit{equity share of NPS}}{\textit{Market Cap of the parent company} + \textit{Consolidated debt}}$$

The five power generation companies - KOEN, KOMIPO, KOWEPO, KOSPO, and EWP - are all subsidiaries of the publicly traded KEPCO. The PCAF methodology uses Enterprise Value Including Cash (EVIC) for the calculation, which can be derived as the sum of the parent company's market capitalization and its consolidated debt.

However, the four power plants involving private operators - Bukpyeong Power Plant, Samcheok Coal Power Plant, Gangneung Anin Coal Power Plant, and Goseong Hai Thermal Power Plant – receive the investment of the Pension Service through affiliated companies connected to the power plants between Step 1 and Step 2. Hence, the following step is calculated between Step 1 and Step 2 and the resulting value (b) is multiplied in Step 2 instead of the value (a) derived in Step 1.

$$a * \textit{arent company investment (equity share) in the power generation company}$$

B. Bondholding Attribution Factor

The attribution factor related to bonds is the sum of the direct investment made by the NPS by acquiring bonds issued by the power generation company and the indirect investment made through the acquisition of bonds issued by the parent company.

The only actors involved in the operation of coal-fired power plants in South Korea are KEPCO and its 5 subsidiaries, and Samcheok Blue Power, operator of Samcheok Coal Power Plant, and POSCO Holdings, which established Samcheok Blue Power. Consequently, the following will focus on these specific actors.

[Direct Bond Investment]

$$\frac{\textit{Total bonds acquired by the NPS from KEPCO and Subsidiaries OR Samcheok Blue Power}}{\begin{array}{c}\textit{KEPCO Market cap of the power company} + \\ \textit{Consolidated debt OR Samcheok Blue Power total assets} + \textit{debt}\end{array}}$$

[Indirect Bond Investment]

$$\frac{\begin{array}{c}\textit{Total bonds acquired by NPS from POSCO Holdings consolidated entity} * \\ \textit{POSCO Holdings equity share in the power generation company}\end{array}}{\textit{POSCO Holdings Market cap} + \textit{Consolidated debt}}$$

C. NPS related financial data sources

The data on direct and indirect equity investments of the NPS in coal power plants is based on business reports published in the Financial Supervisory Service's Electronic Disclosure System (DART).

NPS bond investment data

Table A-C-1. NPS bond investment data

Investor	Investee	Investment amount (USD)	Data source
National Pension Service	POSCO Holdings	239,808,153	National Pension - Courtesy of the Office of Choi Younghee, National Assembly Member (2023.02.13)
National Pension Service	Korea Electric Power Corp (KEPCO)	15,166,608,500,000	National Pension - Courtesy of the Office of Choi Younghee, National Assembly Member (2023.02.13)
National Pension Service	Samcheok Blue Power	23,207,240	National Pension - Courtesy of the Office of Choi Younghee, National Assembly Member (2023.02.13)

Power plant and power generator consolidated financial data

Table A-C-2. Power plant and power generator consolidated financial data

Company name	Type of data	Source
All Power Company	Total Assets	Request to the National Assembly (2023.04.06)
All Power Plants	Asset Value	Request to the National Assembly (2023.04.06)
Korea Electric Power Corp (KEPCO)	Market Capitalisation	Top Market Cap/Korea Exchange/Information & Data Systems (krx.co.kr) (KOSPI on 2022.12.29)
Korea Electric Power Corp (KEPCO)	Current and Non-current Financial Liabilities	KEPCO/Business Report/Consolidated Financial Statement (2023.04.10) (fss.or.kr)
POSCO Holdings	Market Capitalisation	Top Market Cap/Korea Exchange/Information & Data Systems (krx.co.kr) (KOSPI on 2022.12.29)
POSCO Holdings	Long Term Borrowings Borrowings	POSCO/Business Report/Consolidated Financial Statement (2023.03.09) (fss.or.kr)
POSCO International	Market Capitalisation	Top Market Cap/Korea Exchange/Information & Data Systems (krx.co.kr) (KOSPI on 2022.12.29)
POSCO International	Number of Shares	POSCO International/Business Report/Consolidated Financial Statement (2023.03.10) (fss.or.kr)
POSCO International	Share Price	Google Finance (on 2022.12.29)
Samcheok Blue Power	Total Assets	Samcheok Blue Power/Business Report/Financial Statement (2023.03.30) (fss.or.kr)
Samcheok Blue Power	Liquidity Debt + Debenture + Long Term Borrowings	Samcheok Blue Power/Business Report/Financial Statement (2023.03.30) (fss.or.kr)

Appendix B: Air pollution and health impact analysis methodology and data

This study follows CREA's impact pathway approach (IPA) to quantify the health impacts of coal power generation. It is carried out by (1) developing a plant-by-plant inventory of emissions; (2) estimating pollution dispersion from CFPPs through atmospheric modeling; (3) quantifying air pollution health impacts resulting from changes in ambient concentration; and (4) valuing impacts in monetary terms using a cost of illness method. The analysis was carried out in the R data analysis software, in a global spatial grid with 1x1 km resolution, with health impacts calculated for each grid cell. All datasets were aggregated or interpolated to this resolution as required.

A. Emissions

A plant-by-plant emissions inventory was used as input data to the CALPUFF model, accounting for plant-specific technology, location, and capacity for every operating coal plant in the country (see Appendix C). Information on combustion and emission control technology, coal type used, stack height and diameter, as well as flue gas release velocity and temperature were used to calculate emissions load and account for plume release height and thermal rise of pollutants.

If a plant's emissions values were lacking or unavailable, it was generalized using average values for projects with similar capacity and combustion technology. We assumed that such plants were in compliance with the country's emissions standards and operating emission controls technology at full capacity. Information on installed emission controls was also collected from these primary documents, as well as the S&P (2020) World Electric Power Plants database.

Stack height as well as flue gas exit velocity and temperature were imputed from available data following the same approach. When missing, the stack diameter was calculated based on the estimated total flue gas volume flow and velocity. If unavailable, thermal efficiencies of 37%, 41% and 43% were assumed for subcritical, supercritical and ultra-supercritical plants, respectively, in line with industry standards.

Separately, mercury emissions were projected using the formula: EHg = CC x MC x (1 - CE), where CC is the coal consumption mass rate of the plant, MC is the mercury content of the coal, and CE is the capture efficiency. For toxic deposition from main boilers of the power plants, 30% of emitted fly ash was assumed to be $PM_{2.5}$, and 37.5% PM10, in line with the U.S. EPA (1998) AP-42 default value for electrostatic precipitators (ESP). Mercury deposition was modeled for three different types of mercury: elemental, reactive gaseous and particle-bound mercury, with the speciation between the three types calculated based on Lee et al. (2006).

For other heavy metals, emissions data was not available.

NPS responsibility for emissions and impacts estimates are calculated using the 10th and 90th percentiles of values in USGS coal samples (USGS, 2011), and assuming an enrichment factor of 1 from ash in unburned coal to fly ash emitted from the stack, in line e.g. with the empirical results of Linak et al. (2000).

B.Atmospheric modeling

The CALPUFF modeling system was used to predict the contribution of CFPPs to ambient air pollutant concentrations at every modeled “receptor” location. These results were processed to extract the annual mean, 24-hour maximum and 1-hour maximum pollutant concentrations for 2019. CALPUFF is the most widely used, industry-standard emission dispersion model for long-range air quality impacts of point sources. It is able to model the formation of secondary sulfate and nitrate particles from coal power SO_2 and NO_x emissions and long-range transport. These two mechanisms are responsible for more than 90% of the population's exposure to $PM_{2.5}$ and for the health impacts of CFPP emissions; their exclusion would mean omitting the majority of the health impacts. By accounting for transport, chemical transformation and deposition of pollutants, it provides short and long-range impacts caused by coal plant emissions.

Meteorological data used for the simulations were generated with the WRF model, on a 9x9 km grid. Land-use data were obtained from the European Space Agency (2018) and terrain elevation data were obtained from NASA Shuttle Radar Topography Mission (SRTM) high-resolution datasets (Farr et al., 2007).

Deposition results were differentiated by land-use type using the European Space Agency global land-use map for the year 2015 at a 300 m resolution (ESA, 2018). Land-use codes 10-30 were mapped as cropland; codes 50-100 were mapped as forest and code 170 as mangrove. Monthly average backgrounds for NH_3, O3 and H2O2 concentrations were also obtained from the Geos-Chem model results (Koplitz et al., 2017) and were inputted into the CALPUFF chemistry module (ISORROPIA/RIVAD).

C. Health impact assessment & economic valuation

Major air pollutants

The health impact assessment methodology and the economic valuation are adapted from CREA's "Quantifying the Economic Costs of Air Pollution from Fossil Fuels" (Myllyvirta, 2020). Data on the total population and population age structure, as well as all mortality results, baseline death rates and years of life lost in South Korea were taken from the GBD project 2019 (IHME, 2020). The baseline concentrations of PM2.5 and NO2 were taken from van Donkelaar et al. (2016) and Larkin et al. (2017), respectively.

The health impacts are adjusted by age group-specific changes in population and all-cause mortality, based on historical data and projections in UNPD World Population Prospects 2019 (medium variant). Additionally, economic costs are adjusted by changes in per capita GDP (PPP). Up to 2019, the data are taken from the World Bank Databank, and future projections from OECD GDP long-term forecasts. The forecasts and historical data until 1989 include GDP in constant prices but without PPP adjustment, so growth rates in PPP adjusted GDP are assumed equal to the growth rates of real GDP. Past and future costs are discounted to 2019 value at 4%/year, as recommended by e.g. Hurley et al. (2005).

Table B-C-1. Power plant and power generator consolidated financial data

Effect	Valuation	Currency	Unit	Year	Source	Adjustment	Reference Income level	Elasticity
New asthma cases	3,914	USD	case	2010	Brandt et al.(2012)	GDP PPP	California	1
Asthma emergency room visits	844	USD	visit	2010	Brandt et al. (2012)	GDP PPP	California	1
Preterm birth	321,989	USD	birth	2010	Trasande et al. (2016)	GDP PPP	US	1
Disability	62,800	GBP	years lived with disability	2018	Birchby (2019)	GNI PPP	UK	1
Premature deaths	56,000	EUR	lost life year	2005	EEA (2014)	GNI PPP	EU	0.9
Work absence	130	EUR	work day	2005	EEA (2014)	GDP PPP	EU	1

Table B-C-2. Input parameters and data used to estimate economic costs of health impacts converted to South Korean Won (KRW)

Outcome	World Avg. GDP, 2011 USD	Valuation in South Korea, 2011 USD	Valuation in South Korea, 2019 USD	Valuation in South Korea, 2019 KRW
preterm births	105,725	283,419.47	211,010.67	245,902,871.97
work absence (sick leave days)	85	227.86	169.65	197,699.16
years of life lost	39,324	95,517.83	71,114.67	82,874,018.24
years lived with disability	31,047	83,228.41	61,964.99	72,211,364.07
number of children suffering from asthma due to pollution exposure (increased prevalence)	1,168	3,131.08	2,331.15	2,716,619.10
asthma emergency room visits	252	675.54	502.95	586,119.87

Appendix C: Stack properties and emissions data

The following table includes data for each of the individual coal-fired power plants and units in South Korea that were used for the modeling. The emissions inputs were used as input data in the CALPUFF Modeling.

Table C-1. Coordinates, stack properties and air pollutant emissions (2021 and 2022) of South Korean coal-fired power plants

	Coordinates		Stack Properties				Emissions inputs (t/pa), 2021			Emissions inputs (t/pa), 2022		
Power Plant	Lat	Long	Stack height, meter	Dia-meter, meter	Exit Temp, Celsius	Flue Gas Velocity	SOx	NOx	PM	SOx	NOx	PM
Yeosu Unit 1	37.569	126.640	150	5.1	85.96	24.593	29.75	283.50	12.37	17.77	254.13	7.75
Yeosu Unit 2	37.569	126.640	150	4.8	79.3	27.092	33.66	272.9	10.48	37.68	256.39	9.15
Yeongheung Unit 1	37.237	126.438	200	6.6	77.5	22.05	583.60	536.51	38.11	0	0	0
Yeongheung Unit 2	37.237	126.438	200	6.6	79.7	25.7	871.84	733.53	47.17	113.24	84.79	6.44
Yeongheung Unit 3	37.235	126.438	198	6.3	90.5	28.7	561.78	355.71	19.37	829.81	531.86	30.41
Yeongheung Unit 4	37.235	126.438	198	6.3	87.6	29.7	706.79	441.93	22.62	642.67	408.04	27.20
Yeongheung Unit 5	37.249	126.438	200	6.8	99.5	27.6	463.08	373.79	21.82	497.83	437.88	31.35
Yeongheung Unit 6	37.249	126.438	200	6.8	92.5	28.4	528.19	362.50	22.10	501.42	401.13	32.83
Taean Unit 1	36.904	126.238	150.3	8.83	111	17.5	305.19	327.49	34.65	305.38	336.14	47.58
Taean Unit 2	36.905	126.237	150.3	8.83	111	17.5	247.86	324.58	45.27	246.17	227.72	32.73
Taean Unit 3	36.904	126.236	150.3	8.83	111	17.5	290.61	337.61	33.45	251.45	358.97	39.23
Taean Unit 4	36.904	126.236	150.3	8.83	111	17.5	271.86	385.47	36.01	596.46	371.36	34.93
Taean Unit 5	36.902	126.2296	150	5.4	137	14.2	341.15	359.66	12.10	602.87	469.16	26.44
Taean Unit 6	36.902	126.2259	150	5.4	137	14.2	706.61	532.23	40.25	588.86	471.36	31.85
Taean Unit 7	36.903	126.232	150	5.4	139	16.5	317.02	494.08	21.27	227.30	337.53	19.43
Taean Unit 8	36.902	126.232	150	5.4	139	16.5	241.57	340.60	18.90	304.09	424.65	18.32
Taean Unit 9	36.9022	126.229	150	7.7	135	14	375.71	541.88	19.40	249.34	429.01	16.05
Taean Unit 10	36.902	126.229	150	7.7	135	14	399.42	440.23	23.52	511.68	586.40	23.04
Shin Boryeo-ng Unit 1	36.385	126.488	150	7.5	90	27.62	439.44	222.39	17.21	523.63	271.05	21.29
Shin Boryeo-ng Unit 2	36.385	126.488	150	7.5	90	27.62	645.18	382.25	33.17	267.31	208.34	18.03
Samcheonpo Unit 3	34.911	128.108	200	5.16	97.22	17.4725	558.41	806.72	27.80	624.92	855.06	45.69
Samcheonpo Unit 4	34.910	128.189	200	5.16	99.21	18.3925	754.72	1091.44	53.36	410.33	654.81	49.53
Samcheonpo Unit 5	34.911	128.108	200	5.16	84.97	16.805	90.97	101.97	8.56	256.23	166.56	8.18
Samcheonpo Unit 6	34.911	128.108	200	5.16	80.02	16.792	2.60	21.68	2.24	180.36	180.65	11.26

	Coordinates		Stack Properties				Emissions inputs (t/pa), 2021			Emissions inputs (t/pa), 2022		
Power Plant	Lat	Long	Stack height, meter	Dia-meter, meter	Exit Temp, Celsius	Flue Gas Velocity	SO_x	NO_x	PM	SO_x	NO_x	PM
Samcheok Green Power Unit 1	37.186	129.338	90	7.97	155.3	25.2785	447.11	375.40	48.31	234.63	450.08	50.67
Samcheok Green Power Unit 2	37.187	129.338	90	7.97	155.3	25.2785	296.56	241.39	48.18	254.24	407.04	60.02
Samcheok Blue Power Unit 1*	37.243	129.102	320	7.4	90	30	691.96	332.53	65.35	691.96	332.53	65.35
Samcheok Blue Power Unit 2*	37.243	129.102	320	7.4	90	30	691.96	332.53	65.35	691.96	332.53	65.35
Hadong Unit 1	34.9497	127.82	150	9.3	85	15.12	597.14	337.89	38.22	481.30	271.46	31.28
Hadong Unit 2	34.951	127.82	150	9.3	85	15.12	467.82	403.77	29.90	422.45	444.64	32.84
Hadong Unit 3	34.9504	127.819	150	9.3	85	15.12	390.71	399.45	27.76	392.84	507.60	31.47
Hadong Unit 4	34.952	127.29	150	9.3	85	15.12	432.07	426.51	25.88	323.30	362.10	19.35
Hadong Unit 5	34.952	127.819	150	9.3	85	15.12	319.61	355.37	28.28	562.75	518.34	41.02
Hadong Unit 6	34.953	127.819	150	9.3	85	15.12	511.84	548.06	31.07	500.85	447.72	23.91
Hadong Unit 7	34.955	127.819	150	5.4	91	22.66	471.30	432.11	29.97	430.08	369.24	26.56
Hadong Unit 8	34.954	127.818	150	5.4	91	22.66	539.11	410.83	40.83	455.06	398.58	41.36
Donghae Unit 1	37.2907	129.085	150	4	140	19.43	656.93	221.64	8.17	712.04	219.77	8.50
Donghae Unit 2	37.2909	129.085	150	4	140	19.43	611.72	205.97	9.64	551.30	178.72	7.26
Dangjin Unit 1	37.0568	126.515	150	6.5	85	1.03	295.42	168.05	35.66	0	0	0
Dangjin Unit 2	37.057	126.515	150	6.5	85	19.03	280.36	156.71	28.84	455.20	298.07	46.45
Dangjin Unit 3	37.057	126.513	150	6.5	85	19.03	312.22	164.40	37.33	357.51	251.39	32.62
Dangjin Unit 4	37.057	126.512	150	6.5	85	19.03	310.25	131.49	25.50	32.51	11.07	2.48
Dangjin Unit 5	37.058	126.511	150	5.4	91	24.03	244.37	182.23	38.34	352.04	289.48	57.04
Dangjin Unit 6	37.058	126.5085	150	5.4	91	24.03	382.21	183.76	35.75	199.59	212.82	34.60
Dangjin Unit 7	37.059	126.508	150	5.4	90	23.32	256.76	163.46	31.77	258.51	195.26	31.53
Dangjin Unit 8	37.059	126.5069	150	5.4	91	23.32	371.36	212.97	44.62	299.05	239.85	47.68
Dangjin Unit 9	37.0536	126.506	208	7.3	90	26.17	900.30	426.99	0.40	615.67	469.24	18.84
Dangjin Unit 10	37.0547	126.503	208	7.3	90	26.17	692.32	360.47	0.36	702.45	591.20	54.31
Bukpyeong Unit 1	37.477	129.146	150	5.4	93	26.817	95.22	306.81	16.15	163.79	309.25	18.23
Bukpyeong Unit 2	37.477	129.146	150	5.4	93	26.817	102.64	304.15	12.14	167.51	271.75	16.91
Boryeong Unit 3	36.402	126.491	150	8.79	90	22.25	100.24	65.49	21.33	117.42	58.70	39.26

*Samcheok Blue Power emissions inputs are future estimates

	Coordinates		Stack Properties				Emissions inputs (t/pa), 2021			Emissions inputs (t/pa), 2022		
Power Plant	Lat	Long	Stack height, meter	Dia-meter, meter	Exit Temp, Celsius	Flue Gas Velocity	SOx	NOx	PM	SOx	NOx	PM
Boryeong Unit 4	36.402	126.491	150	8.76	90	19.96	384.77	275.98	32.43	0.57	1.57	0.24
Boryeong Unit 5	36.402	126.493	150	8.79	90	19.96	654.25	378.80	47.44	439.52	312.78	24.89
Boryeong Unit 6	36.402	126.493	150	8.79	90	19.96	554.91	303.74	28.76	541.84	316.77	33.27
Boryeong Unit 7	36.402	126.495	150	5.4	90	32.7	158.46	170.09	30.70	184.17	154.50	31.38
Boryeong Unit 8	36.402	126.495	150	5.4	90	32.7	274.17	197.61	29.63	248.18	215.47	26.88
Shin Seocheon	36.145	126.498	150	7.5	91	24.8	90.25	133.81	12.10	119.92	206.57	12.64
Goseong Hi Unit 1	34.906	128.127	190	7.5	90	24.78	429.15	407.61	10.02	618.73	378.23	13.07
Goseong Hi Unit 2	34.906	128.127	190	7.5	90	24.78	84.20	75.41	2.17	623.17	378.43	13.46
Gangneung Anin Unit 1	37.435	128.584	107	7.6	93.8	20	442.09	269.10	38.44	442.09	269.10	38.44
Gangneung Anin Unit 2	37.435	128.584	107	7.6	93.8	20	442.09	269.10	38.44	442.09	269.10	38.44

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