Unveiling the Truth Behind Blast Furnace Pollution

Air Quality and Health Impact Assessment of South Korean Steel Plants

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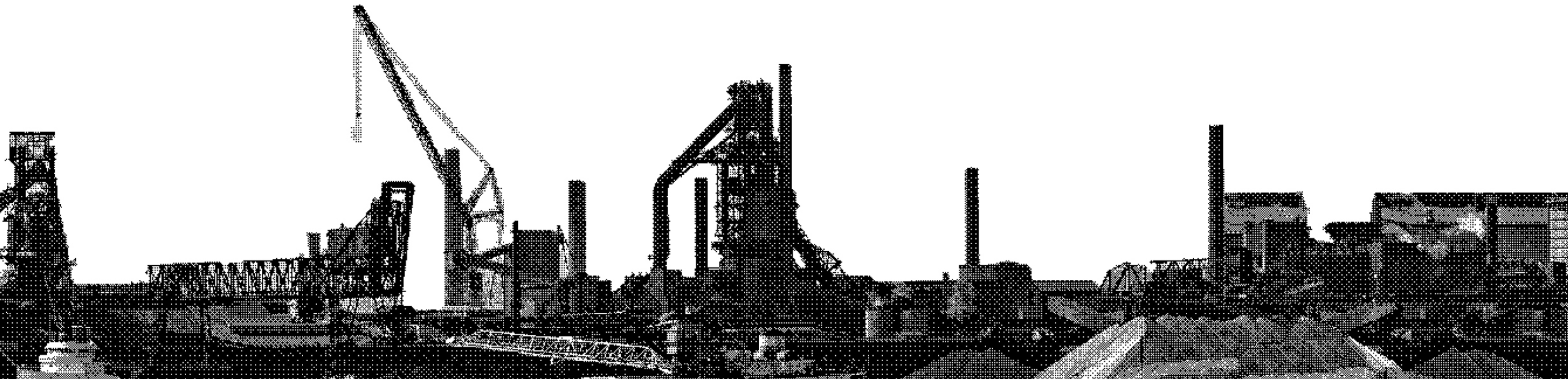

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Key Findings

Globally, the complex and energy-intensive process of steelmaking is a major contributor to air pollution and carbon dioxide (CO_2) emissions. Being based in the 6th largest steel-producing country, Korean steel plants are responsible for the emission of many pollutants and greenhouse gases (GHG), with about 70% of steel production being dependent on coal-based Blast Furnace-Basic Oxygen Furnace (BF-BOF) routes.

CREA and SFOC analyzed air pollution from integrated steel plants in Korea and assess the associated health and economic impacts under the current policy while exploring the health and economic benefits earned from 2050 Carbon Neutral policy. The key findings are as follows:

- When all three integrated BF-BOF steel plants are simultaneously operating, their emissions can cause the annual average near-surface concentration of nitrogen dioxide (NO_2) to increase by up to 1.5 $\mu g/m^3$, sulfur dioxide (SO_2) by 1.22 $\mu g/m^3$, and particulate matter (PM2.5) by 0.4 $\mu g/m^3$. Considering the annual mean air quality guideline values recommended by the World Health Organization (WHO), this means that the emissions from domestic integrated BF-BOF steel plants (hereinafter BF-BOF plants) alone can account for 8-12% of the recommended values.

- Air pollution from the three BF-BOF plants was related to approximately 506 premature deaths in 2021. Of the modelled plants, contribution to health impacts was found to be the highest in the POSCO Gwangyang plant, followed by POSCO Pohang and Hyundai Steel Dangjin plant, respectively.

- The economic cost of increased health spending and loss of productive work hours due to exposure to air pollution from the steel plants is estimated at KRW 3.4 trillion (USD 2.95 billion) in 2021.

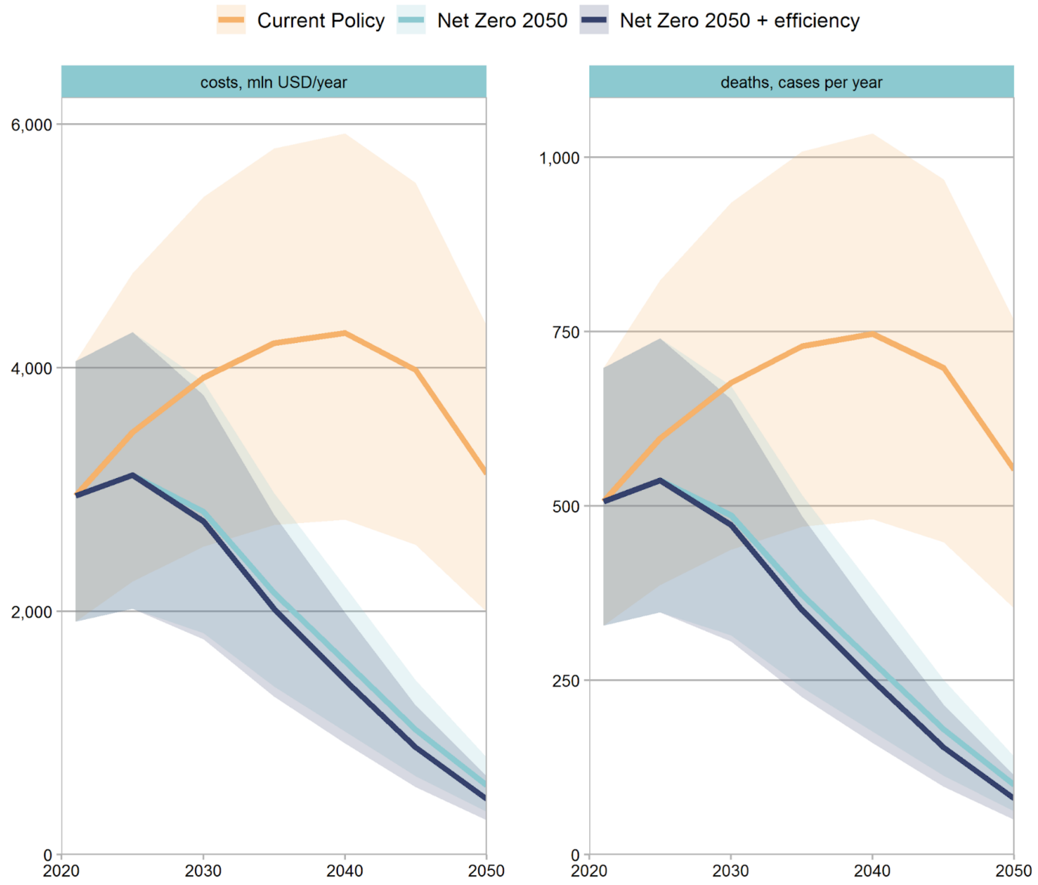
- Under South Korea's Current Policy scenario and without additional emission control interventions, pollution from BF-BOF route steel production will result in 19,400 cumulative premature deaths from 2022 to 2050. The associated cumulative economic burden is estimated at KRW 127 trillion (USD 111 billion).

- While approximately 75% of the health impacts of BF-BOF pollution are borne within South Korea, air pollution transmission from the steel plants could impact the air quality and health in neighboring countries as well.

- Analysis shows that the implementation of South Korea's 2050 carbon neutrality roadmap (NZ2050) would lead to avoiding 9,300 cumulative premature deaths from integrated BF-BOF steel plants. Improving steel consumption and production efficiency and utilizing hydrogen in addition to the proposed NZ2050 efforts (NZ2050_Eff) would avoid an additional 500 premature deaths. Overall, implementing NZ2050 would halve premature deaths in comparison to the current policy scenario.

- Implementing the most ambitious 2050 net zero scenario in the steel sector with efficiency improvements (NZ2050_Eff) would yield the highest savings, decreasing the economic cost of air pollution from BF-BOF steel plants to approximately KRW 63 trillion (USD 55 billion) from 2022 to 2050.

[Figure 1] Annual premature deaths and economic cost from steel plant emissions by scenario (2020-2050)



Shading indicates 95% confidence intervals

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I. Introduction

South Korea's steel industry is a major domestic industrial and economic sector, and a dominant player on the world stage. In 2021, South Korea ranked as the world's 6th largest steel-producing country, with 71.4 million tons of crude steel accounting for a 3.8% share of global production. In addition, the steel industry is an important material supplier for major related industries such as automotive, construction and shipbuilding, with a huge inter-industrial linkage.

Meanwhile, the industry is a major emitter of air pollutants and greenhouse gases (GHGs) from its sizable steel production. Approximately 45% of sulfur oxides (SOx), and about 25% of nitrogen oxides (NOx) and particulate matter (PM2.5) pollution, each is globally estimated to come from industrial activities (IEA, 2019). The steel industry is a significant contributor, as the complex and energy-intensive process of steelmaking involves combustion and heating at various stages and at numerous release points. In addition to primary steelmaking, the refining and production of byproducts release air pollutants as well.

Currently, South Korea's largest integrated steel plants are all mostly powered by coal and utilize highly polluting Blast Furnace-Basic Oxygen Furnace (BF-BOF) technology[1]. The three largest steel plants in the country— the POSCO-operated Gwangyang and Pohang plants, and the Hyundai Steel-operated Dangjin plant — are operating with BF-BOF facilities, with around 70% of South Korea's crude steel being produced from integrated BF-BOFs. According to the International Energy Agency (IEA), the BF-BOF route emits approximately 2.2 tons of CO_2 per ton of crude steel (2.2 t CO_2/t steel) — 86% higher in comparison to scrap-based EAF (0.3 t CO_2/t steel)[2] (IEA, 2020). Since BF-BOF steel plants are dependent on fossil fuels (coal), both air pollutants[3] and GHG emissions are significantly larger than other industries (Kim, J., & Kim, G., 2021).

The South Korean government have announced several efforts to reduce emissions from the steel industry. The country's enhanced 2030 Nationally Determined Contribution (NDC) included a target for 2.3% emission reduction below 2018 levels by 2030. Additionally, the carbon neutrality roadmap for the steel sector outlined within the Carbon Neutral Scenario that was announced in October 2021 includes the replacement of current coal based reducing agent (coke) with hydrogen, as well as the expansion of scrap based EAFs. Additionally, South Korea is also considering the improvement of facility efficiency in overall steelmaking processes, the increase of by-product recycling, and the use of carbon capture, utilization, and storage (CCU/S) for emission reduction in the steel sector.

Likewise, as the largest contributor to GHG and pollutants emission, the steel industry has been seeking significant technological innovations to control emissions from steelmaking, but many of these have not

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[1] Integrated steel plant includes all processes and facilities involved in steelmaking—from ironmaking(BF), steelmaking (BOF) to rolling and shaping.

[2] Electric Arc Furnace (EAF) melts iron sources such as scrap and direct-reduced iron (DRI) using heat generated from an electric arc between electrodes.

[3] CleanSys – Annual Emissions

been fully implemented yet. Even though the process of greening the steel industry will not be achieved at once, when considering the impact of air pollutants that affect the health and well-being of people, prompt efforts to address this issue are essential.

To highlight the importance of addressing this issue, this report analyzes the air pollution, health, and economic impacts from South Korea's three integrated BF-BOF steel plants following three scenarios outlined in the “Exploration of 2050 Net Zero Pathways for the Korean Steel Industry” study: the current policy scenario (CurPol), net zero by 2050 (NZ2050), and a net zero scenario with less steel production with efficiency improvement (NZ2050_Eff) (Eom et al., 2022).

Integrated Steel Plants Overview

» **POSCO Pohang plant** was the first integrated steel mill in South Korea, dating back to 1973. It had been initially owned and commissioned by the government, until its complete privatization in 2000. It currently operates three blast furnaces (BF) and seven basic oxygen furnaces (BOF) with the shutdown of its oldest blast furnace in 2021. The annual crude steel capacity of POSCO Pohang is estimated to be more than 16 million tons[4], taking around 35% of South Korea’s domestic production.

» **POSCO Gwangyang plant** is the largest integrated steel plant in South Korea. Its annual crude steel production capacity is estimated to be around 20 million tons[5], across five BFs. The Gwangyang steel plant started its operations in 1987 and has been constantly increasing its capacity by enlarging its inner volume with relining, as well as increasing the number of BFs.

» **Hyundai Steel Dangjin plant** has 24 million tons of annual crude steel capacity. It started its construction in 2006 and commissioned the operation of two BFs in 2010. Hyundai is operating three BFs with its third blast furnace commissioned in September 2013. The annual capacity of Hyundai Steel was approximately 18.437 million tons in 2021[6].

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4 Bank of Korea Pohang Division, (2021.03.16). “2021 January Press Release on Real Economic Status in Gyeongbuk East Coast”, p.2.

5 Ibid.

6 Park Jin-cheol, (2022.01.27). “(Hyundai Steel IR) Hyundai Steel Witnessed Revenue Increase Despite Production/Sales Drop Compared to Last Year”, Steel& Metal News.

1. Air Pollution from the Steel Industry

Unlike the power sector where emissions are released from a single stack, steelmaking has multiple processes that emit pollution. The raw material, by-products, and the way facilities are organized are highly varied in steelmaking and these factors may influence the amount of emissions along with plant's age, technology and feeds utilized. Moreover, since these factors differ from each steel facility, it is crucial to ensure thorough emission monitoring on individual facilities.

Coking and Sintering - Coke Oven and Sintering Plant

Steelmaking starts from preparing raw materials such as iron ore, limestone, and coking coal (metallurgical coal). These raw materials are heated and melted in ovens and blast furnaces at different stages of ironmaking. During the coking process, the feeds are heated to around 1000°C to 1100°C in the absence of oxygen to expel volatile compounds. This produces a hard, porous material called coke. Coke is used to produce carbon monoxide, which reacts with iron ore to produce iron and CO_2. During this process, particulate matter can be released into the atmosphere if not properly managed.

In the sintering process, fine iron ore and supplementary materials such as limestones are put into sintering furnace. Sinter is processed to maintain the consistency of the chemical properties, quality, and granule size in the blast furnace.

Ironmaking – Blast Furnace

Coke, sinter, and limestone are fed into the blast furnace at high temperatures from the top and gradually move downwards. The indirect reduction occurs in the bottom part of the furnace and molten iron (or pig iron) is created. The limestone reacts with the iron ore and coke to remove impurities in the steel.

Once a blast furnace is in operation, it is difficult to halt and restart its operation as the temperatures need to be kept at the required level for steelmaking. Hence, blast furnaces usually run 24/7 for 15 to 20 years on average, in periods referred to 'campaign'. The blast furnace is only shut down for relining at the end of a campaign, except for exceptional emergencies. Relining usually includes additional remodeling of the plant (i.e., the replacement of the refractory bricks in a furnace, inner volume expansion etc.).

Overall, the ironmaking process emits a significant amount of SOx and particulates. While the former is usually controlled through desulphurization and activated carbon, the latter is controlled primarily through wet and dry dedusting.

Steelmaking – Basic Oxygen Furnace

Molten iron (or pig iron) from the blast furnace is refined and made into steel in the Basic Oxygen Furnace (BOF). When steel scrap and/or molten iron is put into the furnace, high-purity oxygen is inserted to remove impurities from the molten iron. Alloys can be added for the desired steel composition. Pollutants from this process include particulate matter, NOx, SO_2, metals such as lead and manganese, and other volatiles. The produced steel can then be cut and processed to the varied final forms and outputs such as sheets, plates, and wire goods.

II. Air Pollution Regulation in the Steel Industry

One of the primary challenges in decarbonizing the steel sector is addressing how to transition from the current highly emitting and energy-intensive BF-BOF based steelmaking process. As hydrogen-reduced steel, the most innovative technology, is still in the stage of commercialization verification in Korea, the three largest steel plants are running on a BF-BOF process with relining.

While a clear transition roadmap to replace those remaining 11 blast furnaces is yet to be implemented, some pollutant emissions have been managed through existing emission regulations and control technologies. Clean Air Conservation Act regulates emission standards for several key pollutants, and emissions control in the steel sector has been mainly focused on particulate matter, SOx, and NOx.

1. Emission Controls and Standards

Regulations on emissions control in the steel sector are stipulated in the South Korea's Clean Air Conservation Act. The act has been revised 77 times since its first enforcement in 1991.

The Korean Ministry of Environment regulates emissions from facilities under Article 15 of the Enforced Decree of the Clean Air Conservation Act, Attachment Table 8. The emissions limitation of air pollution from facilities are determined based on their installation year (Table 1). However, some facilities are have obtained an exceptional limitation permit, which effectively takes precedence over main limitation standards (Table 2).

[Table 1] Emission standards of air pollutants from steel plants (Applicable after January 1, 2020)

Facilities	SO_2 (ppm)	NO_2 (ppm)	PM (mg/Sm^3)	Others
Roasting furnaces	140	60		Before Jan 31, 2007
	90	60		After Feb 1, 2007
	45	60		After Jan1, 2015
Cupola Combustion Gas Facilities	140	60	25	Before Jan 31, 2007
	90	60	15	After Feb 1, 2007
	45	60	10	After Jan 1, 2015
Sintering furnaces (combustion facilities)	140(15)	170(15)	-	Before Jan 31, 2007
	90(15)	100(15)	20(15)	After Feb 1, 2007 (SO_2, NO_2) Before Dec 31, 2014 (PM)
	45(15)	60(15)	10(15)	After Jan 1, 2015
Heating furnace, Heat treatment furnace, Annealing furnace, Drying furnace, Hot air furnace	-	150(11)	-	Before Jan 31, 2007
		115(11)	20(11)	After Feb 1, 2007 (SO_2, NO_2) Before Dec 31, 2014 (PM)
		80(11)	10(11)	After Jan 1, 2015
Combustion facilities in coking facilities	85(7)	190(7)	15(7)[7]	Before Dec 31, 2006 (NOx)
		115(7)		After Jan 1, 2007(NOx)

(Source: Article 15 of the Enforced Decree of the Clean Air Conservation Act, Attachment Table 8)

[Table 2] Steel plants with exceptional emissions standards

	Unit	SO_2 (ppm)	NO_2 (ppm)	Date of Application
POSCO Pohang	1, 2, 3, 4, 5, 6	-	60(4)	By Dec 31, 2021
	9		60(4)/30(4)	60(4) by June 30, 2021 30(4) from July 1, 2021
	10, 11		60(4)/30(4)	60(4) by Dec 31, 2020 30(4) from Jan 1, 2021
	Unit 2,3,4 in Sintering Furnace		190(15)/ 145(15)	190(15) by June 30, 2020 145(15) from July 1, 2020
POSCO Gwangyang	2, 6		60(4)/30(4)	60(4) by June 30, 2021 30(4) from July 1, 2021
	1, 4		60(4)/30(4)	60(4) by Dec 31, 2020 30(4) from Jan 1, 2021
	3, 8		60(4)/30(4)	60(4) by June 30, 2020 30(4) from July 1, 2020
Hyundai Steel Dangjin	Sintering Furnace		200(15)/ 120(15)	200(15) before Jan 31, 2007 120(15) from Feb 1, 2007
	Combustion facilities in sintering furnace	200(15)		Before Jan 31, 2007

(Source: Article 15 of the Enforced Decree of the Clean Air Conservation Act, Attachment Table 8)

2. Emissions Monitoring

The Korea Environment Corporation (K-eco) was established to prevent environmental pollution, improve the environment, and promote resource circulation in accordance with the Korea Environment Corporation Act. The Korea Environment Corporation collects and manages emission data from the Tele-Monitoring System (TMS) installed at emission points of facilities in varied industrial and power generation sectors including steel plants. The collected data is disclosed on the public website named CleanSys and emission information of 7 pollutants is available on the website.[8]

Emission information is reported on CleanSys in real time, every 30 minutes. However, since the emission information is only disclosed for 24 hours, there is an absence of readily-available accumulated data. Unreported cases are also frequently found due to facility repair, maintenance, and inspection, or data non-receipt. Additionally although the highest emitting, thus polluting facilities at steel plants are blast furnaces, structural constraints of the BF stacks prevented TMS installation during the first half of the year, affecting emission tracking.

Furthermore, sometimes additional emissions can occur that fall outside regular reporting and monitoring procedures. For instance, in 2019 the local governments where the integrated steel plants are located ordered a 10-day operation suspension for POSCO and Hyundai Steel, judging that they violated the Clean Air Conservation Act by releasing air pollutants through bleeder valves from blast furnaces without emission reduction and prior notice. After the kick-off of a public-private consultative body, POSCO and Hyundai Steel received conditional approval[9] for bleeder valve use.

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[7] Coke manufacturing facilities -Coke oven

[8] TSP(Total Suspended Particles), SOx, CO, NOx, HCl, HF, and NH3

[9] 1) Reporting the opening date, time, and the reduction measures etc. in advance to local governments, regional environmental agencies and other regulatory authorities for permission;
2) Minimize dust emissions through improved procedure, including wind pressure control and early cessation of coal injection before opening.

III. Methodology

This report quantified and assessed the concentration and spread of air pollution from POSCO Gwangyang, POSCO Pohang, and Hyundai Steel Dangjin plants in South Korea. The air quality, health, and economic impact from direct exposure to air pollution from the steel plants were estimated based on the air pollution assessments.[10]

Using the CALPUFF meteorological and atmospheric dispersion modeling system, the analysis first estimated the contribution to the concentrations of near-surface air pollution of steel plants, focusing on the concentration and release of pollutant emissions from key stacks within the plant. For emission concentration and dispersion analysis, data was collected from satellite image data and materials steel corporates provided to the National Assembly of the Republic of Korea.

Health impact was estimated based on this data by applying demographic statistics and health impact assessment methods. Input data on air pollutant emissions and other general information including annual production capacity of each steel plant were retrieved from public open data source (CleanSys) and materials steel companies disclosed to the National Assembly of the Republic of Korea.

As mentioned above, considering that the current company emissions reports do not represent the actual total emissions from plants, the year of 2021 when pollutants emission peaked the highest was used as the sample year for annual impacts.[11] Emissions in future scenarios were calculated based on steel production by production route from "Exploration of 2050 Net Zero Pathways for the Korean Steel Industry" study (Eom et al., 2022).

- **Current Policy (CurPol)** reflects South Korea's current position in steelmaking technologies, drawing upon the energy and climate policy instruments proposed by the Korea Institute for Industrial Economics and Trade (KIET) that are already in place or soon to be implemented as of March 2022.

- **Net Zero 2050 (NZ2050)** assumes the same parameters for the country's position in steelmaking technologies today, drawing upon the KIET's steel production forecasts and considering the energy and climate policy instruments that are currently in place like CurPol. It assumes that annual GHG emissions decline at a uniform rate from 2025 until net zero is achieved by 2050.

- **Net Zero 2050 with improvements in steel efficiency scenario (NZ2050_Eff)** This scenario adopts the same assumptions as NZ2050, except that it presumes steel production linearly decreases by 22% from 2025 to 2050. The reduction in production is enabled by increased efficiency - such as the

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[10] Increased health care costs, economic productivity loss and health impact in South Korea due to diseases and deaths caused by air pollution from steel plants.

[11] However, it should also be noted that pollutant emissions from the plants may vary by year depending on the changes in production amount and other relevant conditions, and the distribution of the impact may also be different. In addition, emissions in 2022 are expected to increase further when considering the addition of tele monitoring system to domestic steel plants in the first half year of 2022.

efficiency increase in steel consumption and production.

The cumulative impact of pollutant emissions from steel plants (2022-2050) was calculated according to three scenarios, taking into account domestic demographic changes. The cumulative impacts highlight the implementation of 2050 national carbon neutrality roadmap and evaluate the health and economic benefits that conversion in steel making facilities, fuels and processes are forecast to bring. Further details of the methodology and the dataset can be found in the appendix.

IV. Results and Findings

Air pollution from South Korea's integrated steel plants are a significant contributer to air quality across the country—the nearby cities and communities , in particular, are exposed to the highest impacts.

If all integrated steel plants operate simultaneously, their emissions are estimated to increase the annual mean near-surface concentration of NO_2 by a maximum of 1.5 μg/m^3, SO_2 by 1.22 μg/m^3, and PM2.5 by 0.4 μg/m^3.

The World Health Organization (WHO) recommends that the annual mean ambient air pollution stay below 10 μg/m^3 for NO_2 and 5 μg/m^3 for PM2.5[12] to prevent health impacts. This implies that the BF-BOF steel plants in the country alone could contribute up to 8-12% of the minimum level of pollution allowance. In 2021, South Korea recorded an annual mean of 18.9μg/m^3 for PM2.5, which far exceeds the WHO air quality guidelines.

Among the three steel plants, the POSCO-operated Gwangyang plant accounted for the largest share of pollutants emission in 2021 with 1.2 μg/m^3 of NO_2, 1.16 μg/m^3 of SO_2, and 0.37 μg/m^3 of PM2.5.

In addition, the BF-BOF steel plants emit a large volume of toxic gases toxic gases. From the three steel plants, the maximum hourly increase in the concentration of SO_2 and NO_2 at ground level can reach up to 95μg/m^3. Also, SO_2 and NOx formulate secondary particulate matter. The maximum 24-hour concentration of particulate matter from steel plants is 6.5 μg/m^3, which is more than one-third of the 24-hour mean PM2.5 limit recommended by the WHO.

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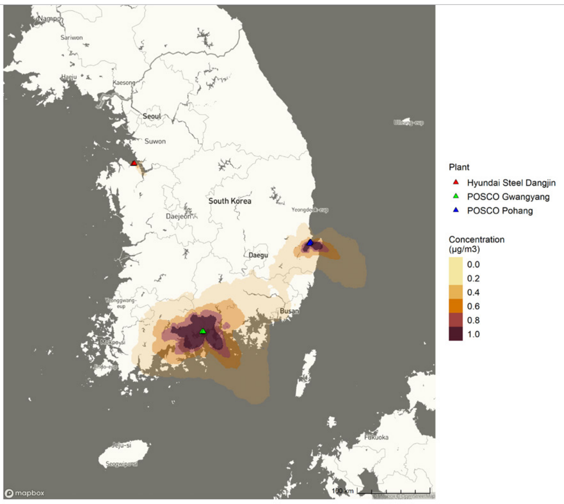
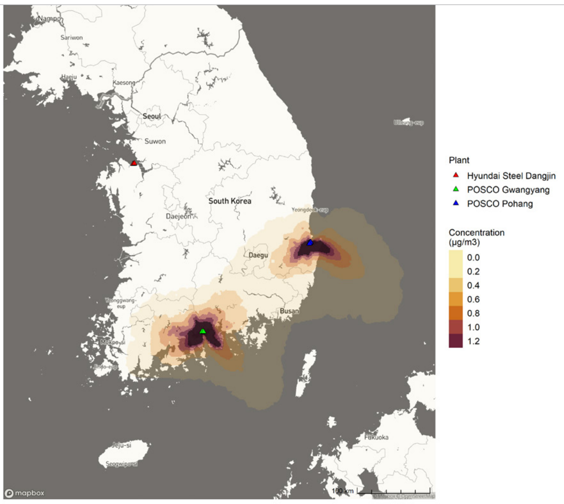
[12] WHO, (2021). Ambient (Outdoor) Air Pollution.

[Figure 2] Annual mean air pollutant concentration from all Integrated steel plants

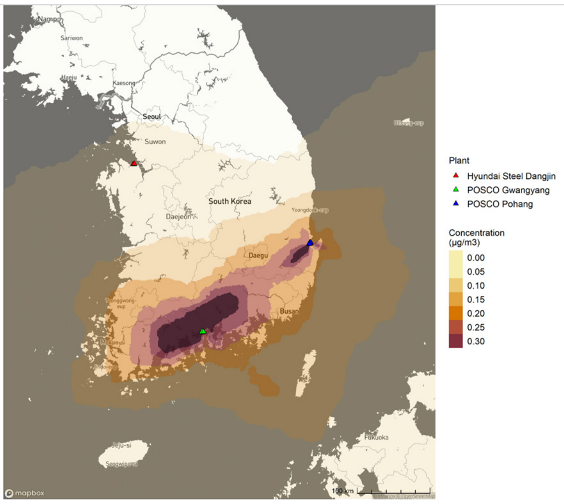
Annual Mean SO2 Concentration From All Integrated Steel Plants



Annual Mean NO2 Concentration From All Integrated Steel Plants



Annual Mean PM2.5 Concentration From All Integrated Steel Plants



V. Health & Economic Impacts

1. Annual Health Cost

The analysis shows that the total number of premature deaths caused by air pollution from BF-BOF steel plants in South Korea was 506 in 2021 (Table 3). Generally, these deaths occur within South Korea, but the pollution from the steel plants could reach some neighboring countries like North Korea, China, and Japan (Table 4). Of the modeled pollutants, the combined effects of primary and secondary PM2.5 were found to have the strongest effects on the number of premature deaths, NO_2 from the BF-BOF steel plants is another significant contributor.

[Table 3] Estimated premature deaths due to air pollution from the BF-BOF steel plants (2021)[13]

Pollutant	Cause of Death	Central Estimate	95% Confidence Interval
Total premature deaths		506[14]	329 – 698
Premature deaths caused by NO_2		204	100 – 314
NO_2	Cardiovascular diseases	165	97 – 261
	Respiratory diseases	8	4 – 93
Premature deaths caused by PM2.5		302	229 – 384
PM2.5	Chronic obstructive pulmonary disease (COPD)	24	8 – 46
	Diabetes	2	1-5
	Ischemic heart disease	54	40 – 70
	Lower respiratory infections	84	28 – 150
	Lower respiratory infections in children	0.2	0.1 – 0.2
	Lung cancer	42	20 – 69
	Stroke	52	20 – 95

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

[14] As there is a lack of evidence in confirming the individual impact of SO_2 compared to other pollutants, the total premature deaths were calculated as the sum of premature deaths caused by NO_2 and PM2.5 to avoid double accounting.

[Table 4] Estimated premature deaths as a result of emissions from the BF-BOF steel plants by country (2021)[15]

Causes of Death	South Korea	China	Japan	North Korea
Total premature deaths	292 (180 – 411)	38 (26 – 53)	150 (106 – 197)	26 (17 – 37)
Premature deaths caused by NO_2	153 (74 – 235)	5 (2 – 8)	42 (21 – 63)	5 (2 – 8)
Cardiovascular diseases	117 (70 – 187)	6 (4 – 10)	35 (19 – 53)	7 (4 – 11)
Respiratory diseases	6 (3 – 7)	0 (0 – 0)	1 (1 – 1)	1 (0 – 1)
Premature deaths caused by PM2.5	139 (106 – 176)	33 (24 – 45)	108 (85 – 134)	21 (15 – 29)
Chronic obstructive pulmonary disease (COPD)	9 (3 – 16)	5 (2 – 10)	5 (2 – 11)	5 (2 – 9)
Diabetes	2 (1-4)	0.1 (0.0 – 0.1)	1 (0 – 1)	0 (0 – 0)
Ischemic heart disease	21 (15 – 27)	10 (8 – 13)	17 (12 – 21)	6 (4 – 9)
Lower respiratory infections	33 (9 – 61)	1 (1 – 2)	47 (18 – 82)	3 (1 – 5)
Lung cancer	22 (11 – 37)	5 (2 – 8)	13 (7 – 21)	2 (1 – 3)
Stroke	22 (9 – 42)	10 (4 – 18)	12 (4 – 21)	8 (3 – 15)

(95% Confidence interval)

In addition to premature deaths, 150 new cases of asthma and 60 preterm births were estimated to occur due to the pollution exposure. Healthy life expectancy[16] is also likely to be shortened due to the impact of air pollution from the BF-BOF steel plants, with over 550 years lived with the after-effects of diabetes, stroke, and COPD (Table 5).

[Table 5] Annual health impacts due to air pollution from the BF-BOF steel plants (2021)

Pollutant	Causes / Impacts	Central Estimate	95% Confidence Interval
PM2.5	Asthma emergency room visits	126	78 – 173
PM2.5	Low birth weight	44	14 – 76
NO_2	New cases of asthma in children	154	33 – 349
PM2.5	Preterm births	63	31 – 67
PM2.5	Work absence (sick leave days)	183,877	156,429 – 211,140
PM2.5	Years lived with disability because of COPD	188	68 – 352
	Years lived with disability because of diabetes	95	19 – 234
	Years lived with disability because of stroke	276	91 – 555
PM2.5 and NO_2	Years of life lost	8,655	5,579 – 12,028

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[15] This table shows the aggregate number of premature deaths from the listed diseases, thus the total number of premature deaths does not match the actual total number of deaths.

[16] The healthy life expectancy defined in the national index system is the period excluding the period of living with disease or disability, thus refers to the period of living without any special physical or mental abnormalities.

By the number of the affected population, Gyeongsangnam-do, Gyeongsangbuk-do, Gyeonggi-do, Jeollanam-do, and Busan were most affected by air pollution from steel plants at the metropolitan and provincial level, while Pohang, Gwangju, Yeosu, and Gimhae were most affected at the city level. In general, because the population of nearby metropolitan cities or big cities is relatively larger than that of the steel plant areas, the number of people affected by pollution is higher in these more populated areas.

[Table 6] Estimated health impacts and premature deaths by steel plant (2021)

Pollutant	Causes / Impacts	POSCO Gwangyang	POSCO Pohang	Hyundai Steel Dangjin
PM2.5	Asthma emergency room visits	87 (54 – 120)	26 (16 – 36)	13 (8 – 18)
PM2.5	Low birth weight	31 (9 – 53)	9 (3 – 16)	4 (1 – 7)
NO_2	New cases of asthma in children	85 (18 – 192)	63 (14 – 143)	7 (1 – 15)
PM2.5	Preterm births	44 (22 – 47)	13 (6 – 14)	6 (3 – 7)
PM2.5	Work absence (sick leave days)	127,118 (108,142 – 145,967)	38,866 (33,064 – 44,630)	18,786 (15,981 – 21,572)
PM2.5	Years lived with disability because of COPD	130 (47 – 244)	41 (15 – 77)	18 (6 -33)
	Years lived with disability because of diabetes	65 (13 – 162)	23 (4 – 60)	6 (1 – 15)
	Years lived with disability because of stroke	192 (63 – 385)	60 (20 – 121)	26 (9 – 52)
All	Years of life lost	5,519 (3,632 - 7,603)	2,535 (1,539 - 3,609)	624 (426 – 846)
Total premature deaths		323 (205 – 341)	150 (92 – 213)	34 (23 – 46)
Premature death caused by NO_2		112 (54 – 172)	84 (41 – 129)	8 (4 – 13)
Premature death caused by PM2.5		210 (159 – 268)	67 (51 – 85)	26 (19 – 33)
PM2.5	Chronic obstructive pulmonary disease	17 (6 – 32)	5 (2 – 9)	2 (2 – 4)
	Diabetes	2 (0.4 – 3.4)	0.6 (0.2 – 1)	0.2 (0.1 – 0.4)
	Ischemic heart disease	39 (28 – 49)	11 (8 – 15)	5 (3 – 6)
	Lower respiratory infections	58 (19 – 104)	21 (7 – 37)	6 (2 – 10)
	Lower respiratory infections in children	0.12 (0.1 – 0.2)	0.03 (0.02 – 0.04)	0.02 (0.01 – 0.03)
	Lung cancer	29 (14 – 48)	9 (4 – 15)	4 (2 – 6)
	Stroke	37 (14 – 67)	11 (4 – 19)	5 (2 – 9)

(95% Confidence interval)

2. Future Health Impact

This study projected the health impacts of blast furnace production under three future pathways – a current policy scenario and two pathways consistent with a net zero emissions target by 2050 (Figure 1).

Under South Korea's Current Policy (CurPol) scenario and without additional emission control, cumulative premature deaths as a result of exposure to air pollution from the three BF-BOF steel facilities is estimated to be 19,400 from 2022 to 2050 (Table 7). Such premature deaths can be avoided and reduced by minimizing pollutant emissions and reducing BF-based steel production.

Achieving net zero (NZ2050) target would reduce these cumulative premature deaths to approximately 10,000 over the next 28 years. The added steel plants efficiency (NZ2050_Eff) is projected to bring the number down to 9,560. The expected number of premature deaths in both carbon neutrality scenarios (NZ2050 and NZ2050_Eff) will be more than halved compared to the current policy (CurPol) scenario.

[Table 7] Cumulative premature deaths due to BF-BOF pollution under scenarios (2022-2050)

Pollutant	Causes of Death	Current Policy (CurPol)	Net Zero 2050 (NZ2050)	Net Zero 2050 + Efficiency (NZ2050_Eff)
Total cumulative premature deaths		19,355 (12,478 - 26,774)	10,052 (6,471 - 13,915)	9,556 (6,157 – 13,223)
Premature death caused by NO_2		11,280 (8,540 - 14,344)	5,814 (4,404 - 7,392)	5,545 (4,200 - 7,049)
NO_2	Cardiovascular diseases	6,493 (3,828 - 10,273)	3,413 (2,011 - 5,397)	3,231 (1,904 - 5,109)
	Respiratory diseases	310 (168 - 357)	163 (88 - 187)	154 (83 - 177)
Premature death caused by PM2.5		8,075 (3,938 - 12,430)	4,238 (2,067 - 6,523)	4,011 (1,957 - 6,174)
PM2.5	Chronic obstructive pulmonary disease	880 (316 - 1,695)	453 (162 - 873)	432 (155 - 833)
	Diabetes	96 (27 - 196)	49 (13 - 99)	46 (13 - 95)
	Ischemic heart disease	2,021 (1,473 - 2,593)	1,042 (760 - 1,337)	994 (725 - 1,275)
	Lower respiratory infections	3,011 (976 - 5,418)	1,572 (512 - 2,823)	1,501 (489 - 2,695)
	Lower respiratory infections in children	3 (2 - 4)	2 (1 - 3)	2 (1 - 3)
	Lung cancer	1,590 (772 - 2,612)	816 (396 - 1,339)	777 (378 - 1,276)
	Stroke	1,967 (754 - 3,605)	1,010 (387 - 1,849)	963 (369 - 1,763)

(95% Confidence interval)

The overall health and associated cost benefits are significant under the net zero scenario (NZ2050) (Table 8). Work absence caused by sickness or caregiving from air pollution can be reduced from 5.3 million to 2.9 million days under the NZ2050 scenario. Years lived with disability due to COPD, diabetes, or stroke totals 21,130 under the current policy (CurPol), but could be cut to 10,800 under NZ2050, or even to 10,300 with the additional facility efficiency improvements (NZ2050_Eff).

[Table 8] Cumulative health impacts due to BF-BOF steel pollution under scenarios (2022-2050)

Pollutant	Causes	Current Policy (CurPol)	Net Zero 2050 (NZ2050)	Net Zero 2050 + Efficiency (NZ2050_Eff)
PM2.5	Asthma emergency room visits	3,638 (2,251 - 5,012)	2,009 (1,243 - 2,768)	1,928 (1,193 - 2,656)
PM2.5	Low birth weight	1,120 (347 - 1,944)	633 (196 - 1,098)	608 (189 - 1,056)
NO_2	New cases of asthma in children	4,458 (964 - 10,082)	2,534 (548 - 5,731)	2,420 (523 - 5,474)
NO_2	New cases of asthmain children(prevalence rate)	20,931 (5,233 - 45,015)	11,897 (2,974 - 25,584)	11,363 (2,841 - 24,438)
PM2.5	Preterm births	1,617 (783 - 1,717)	914 (443 - 971)	879 (426 - 933)
PM2.5	Work absence (sick leave days)	5,304,182 (4,512,407 - 6,090,624)	2,932,248 (2,494,540 - 3,367,007)	2,813,959 (2,393,908 - 3,231,179)
PM2.5	Years lived with disability because of COPD	7,168 (2,585 - 13,442)	3,670 (1,324 - 6,884)	3,498 (1,262 - 6,561)
	Years lived with disability because of diabetes	3,470 (708 - 8,553)	1,801 (364 - 4,439)	1,719 (347 - 4,236)
	Years lived with disability because of stroke	10,495 (3,471 - 21,110)	5,382 (1,780 - 10,824)	5,130 (1,697 - 10,317)
All	Years of life lost	335,033 (214,616 - 466,934)	173,391 (110,878 - 241,842)	164,779 (105,452 - 229,748)

(95% Confidence interval)

3. Economic Cost

Exposure to air pollution from South Korea's steel plants had an estimated economic cost of KRW 3.4 trillion (USD 2.95 billion) in 2021. Without additional policy interventions and with continued aging demography, the annual economic cost of health impacts due to steel plant pollution is projected to increase year-on-year.

[Table 9] Annual economic cost of BF-BOF steel plants pollution and plant contribution (2021)

	Total	POSCO Gwangyang	POSCO Pohang	Hyundai Steel Dangjin
Total annual cost (in 10 billion KRW)	3,375 (2,189 - 4,640)	2,121 (1,409 - 2,885)	1,055 (646 - 1,488)	208 (143 - 279)
Total annual cost (in billion USD)	2.95 (1.91 - 4.05)	1.85 (1.23 - 2.52)	0.92 (0.56 - 1.30)	0.18 (0.13 - 244)

(95% Confidence interval)

In the current policy scenario (CurPol), the cumulative economic burden of air pollution from the BF-BOF process is estimated to reach KRW 127 trillion (USD 111 billion) from 2022 to 2050. Approximately 75% of the estimated cost is expected to be incurred at domestic cost.

The implementation of net zero needs to increase the efficiency of steel production, as well as decrease the consumption and use of coal in the sector. The deployment of the appropriate emission and pollution reduction policies under NZ2050 could save about KRW 61 trillion (USD 53 billion), compared to the CurPol scenario. When implementing the most ambitious NZ2050_Eff pathway, which would include the use of hydrogen, the estimated economic cost from the BF-BOF steel pollution is further reduced to KRW 63 trillion (USD 55 billion) by 2050.

Table 10. Cumulative economic cost of BF-BOF steel plants pollution by scenarios (2022 – 2050)

	Current Policy	Net Zero 2050	Net Zero 2050 + Efficiency
Total annual cost (in 10 billion KRW)	127,428 (176,022 - 819,926)	66,450 (42,710 - 91,813)	63,192 (40,649 - 87,277)
Total annual cost (in billion USD)	114.4 (71.7 - 153.9)	58.1 (37.3 - 80.4)	55.2 (35.5 - 76.3)

(95% Confidence interval)

VI. Conclusions and Recommendations

The growth of South Korea's economy has been inseparable from its industrial sector. As the health and economic impacts arising from energy-intensive manufacturing processes such as steel production are rising to the surface, finding ways to align prosperity for both the nation's economy and its people is critical. The analysis estimates that air pollution from integrated BF-BOF steel plants in operation would have caused approximately 506 premature deaths in 2021. If the steel sector fails to achieve its carbon neutrality by 2050, the cumulative premature deaths arising from continued BF-BOF steel production from 2022 to 2050 are estimated to reach 19,400.

Meanwhile, if transition in technology and energy sources is realized in conjunction with the carbon neutrality roadmap (NZ2050 scenario), around 9,300 premature deaths could be prevented. Improving steel consumption efficiency alongside this net zero trajectory (NZ2050_Eff) would avoid an additional 500 deaths, essentially avoiding more or less than half of the premature deaths estimated under the current policy (CurPol).

As carbon neutrality emerges globally, POSCO and Hyundai Steel also announced plans to replace conventional fossil fuel-based steelmaking with varied low carbon alternatives, including hydrogen-based processes.[17] Although zero-emission steel technologies at a commercial scale are yet to be fully realized in Korea, efforts to minimize various environmental, health and social impacts in the process of transition must be accelerated. Following recommendations and measures can be considered.

First, technological transition from BF-BOF routes to EAF and Hydrogen-based steelmaking is also linked to the procurement of larger amount of electricity. In order to reduce air pollutants and GHG emissions in the entire primary steelmaking process, improvement in indirect emissions as well as direct emissions will be required. Securing sufficient renewable energy is therefore an essential first step. Regulatory support and investment aimed at increasing renewables and green hydrogen must therefore be expanded.

Second, as the steel industry's effort to reduce GHG emissions are closely related to the reduction of pollutant emissions, efforts from steelmakers running integrated mills are also required to readjust and establish detailed plans for carbon neutrality that are more specific and ambitious than the current policies. Additionally, as the steel industry has a serious impact on forward and backward linkages, the ripple effect of the transition of the steel industry is also expected to be wide. It is therefore necessary for the public and private sectors to consider a more comprehensive transition plan by expanding the scope of transition discussions that are currently limited at the technology and facility considerations to include the transition in jobs and other factors.

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[17] POSCO is planning to develop and commercialize hydrogen reduction steelmaking by 2040, replacing existing facilities with new ones by 2050. In the process, POSCO plans to reduce coal and energy consumption at plant level with electric arc furnaces, low-carbon raw materials and CCUS (POSCO, 2022). Hyundai Steel also announced that they would introduce a hydrogen based fusion steel production system named Hy-Cube by 2030.

Lastly, efforts to strengthen monitoring systems and enhance emission management should be continued. Reflecting the ongoing persistence of reporting gaps, emissions manipulation in the industrial complex have been caught a few years ago. The government has been trying to strengthen existing regulations by increasing the number of TMS (Tele-Monitoring System),[18] strengthening penalties, and expanding the scope of mandatory emission reporting, but there remains room for further improvement, including the following:

- Disclosing cumulative data on pollutants emissions by emission points instead of the current 24-hour information disclosure on CleanSys.

- Adopting measures and strengthening reporting systems on fugitive emissions from the facilities or processes with no reduction or measurement equipment, such as slag yard, materials yard, or coke oven materials inlet.

Lastly, notwithstanding the positive potential of improved regulatory and reporting frameworks, the current measured and reported emissions may fail to adequately represent all plant emissions. Therefore, improved transparency and communication between the steel makers, local government, and residents is an important supplementary policy for protecting the health rights of steel mill workers and nearby residents in the affected communities.

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[18] Expanding up to 2,000 in phase from 2020.

[Appendix 1] Methodology

The study follows the "impact pathway" approach, the most common approach for studying the health impacts of air pollutant emissions. This approach tracks air pollution emissions from the studied sources — from the release to dispersion. The analysis covers the dispersion and chemical transformation of emissions, the resulting pollution levels in different locations and the population exposure, the increase in health risks, and the total health impacts on the population level. Based on these findings, the study estimates the economic costs of air pollution exposure and resulting health impacts.

1. Emissions

First, the study of the health impacts of integrated steel plants requires detailed information on the location, operation and emissions of the plants. For annual emissions of SOx, NOx, and PM2.5, the emission data of 2019, 2020 and 2021 was secured from CleanSys. In some cases, total emission mass release (kg per year) was only available for certain pollutants. For the remaining pollutants, average flue gas concentration (FGC, ppm or mg/Nm^3) was available instead, which is the case when there are missing data in some parts of the year. To deal with the missing data, we estimated the emission mass release for pollutant B using the following equation:

$$E_B = E_A \times FGC_B / FGC_A$$

where E_A is the emission mass release for pollutant A.

[Table A-1] Emission release points/stacks at POSCO Gwangyang plant

Facility	Number of Stacks	Plant/Section
Sinter Machine	5	Sintering
Rotary Kiln	1	Incinerator
Electric Arc Furnace	2	Electric Arc Furnace
Steam Turbine Power Generation Facility	9	Power Generation
Off-gas Combined Cycle Power Plant	2	
LNG Combined Cycle Power Plants	2	
COKE pushing emission control system (P-ECS)	2	Cokes Extractor and Cold Roll(ing)
COKE emission control system (ECS)	8	
COKE Coke Dry Quenching (CDQ)	4	
SNNC FerroNickel Plant	4	FerroNickel Manufacturing Electric Arc Furnace
FerroManganese (FeMn) Facility Electric Arc Furnace	2	

[Table A-2] Emission release points/stacks at POSCO Pohang plant

Facility	Number of Stacks	Plant/Section
Blast Furnace and Sinter Machine	4	Sintering
Incinerator - Rotary Kiln	1	
Electric Arc Furnace	2	STS
Rust Removal Facility	1	
IC Engine Power Generation	4	Power Generation
Generation Facility (Steam Turbine Power Plant)	12	
Off-gas Combined Cycle Power Plants	2	
PCM Hydrochloric Acid Facility	2	Cold Roll(ing)
3NO APL Pickling - Acidification Facility (Hydrochloric Acid)	1	Electric Steel Plate
Coating CGL(PGL) Rust Removal Facility	1	Cold Roll(ing)
COKE Extractor	5	Cokes Extractor and Cold Roll(ing)
COKE ECS	8	
COKE Coke Dry Quenching (CDQ)	4	
COKE CDQ WGT	1	

[Table A-3] Emission release points/stacks at Hyundai Steel Dangjin plant

Facility	Number of Stacks	Plant/Section
Sinter Machine	3	Sintering
Blast Furnace	3	
Hyundai Green Power Plants	8	Power Generation
Incinerator - Rotary Kiln	1	Lime Shaft Kiln
Shaft Kiln	5	
PCM Hydrochloric Acid Facility	2	Electric Arc Furnace
COKE Extractor	3	Coke Extractor and Cold Roll(ing)

[Table A-4] Details of blast furnaces in Korea

Blast Furnace	Starting Year (Years in Operation)	Latest Relining
Pohang BF#1	1973 (48 years/retired)	1993 Feb
Pohang BF#2	1976 (46 years)	2015 May
Pohang BF#3	1978 (44 years)	2017
Pohang BF#4	1994 (28 years)	2010 Oct
Gwangyang BF#1	1987 (35 years)	2013 June
Gwangyang BF#2	1988 (34 years)	2005 May
Gwangyang BF#3	1990 (32 years)	2020 July
Gwangyang BF#4	1992 (30 years)	2022 June
Gwangyang BF#5	1999 (23 years)	2016 June
Dangjin BF#1	2010 (12 years)	*by 3Q of 2024 (TBD)
Dangjin BF#2	2010 (12 years)	2027 (TBD)
Dangjin BF#3	2013 (9 years)	2030 (TBD)

This study uses the CALPUFF atmospheric dispersion model, which includes a detailed model for plume rise from power plant stacks by using the information on stack height, inner diameter, flue gas temperature, and release velocity. This data is sourced from materials steel companies provided to the National Assembly of the Republic of Korea.

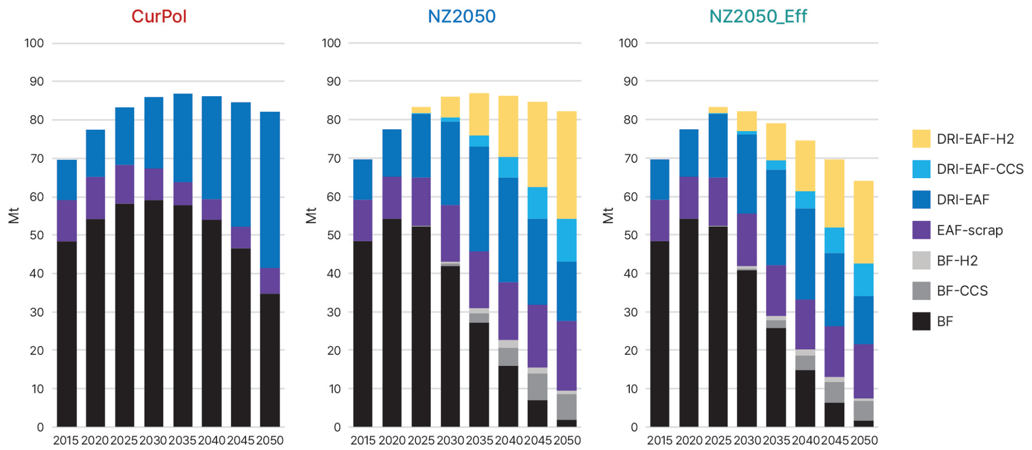
2. Future Scenarios

The study also projects future impacts of air pollution under three scenarios—CurPol, NZ2050, and NZ2050_Eff, which are derived from KAIST & SFOC's joint study on "Steel Sector Pathways for Korea's 2050 Carbon Neutrality" (Eom et al., 2022).

Pollution emissions were scaled under the three pathways assuming constant emission rates per unit of output from the blast furnace production in 2021. The analysis assumed the application of Carbon Capture and Storage (CCS) reduces SO_2, NOx, and PM emissions by 85%, 29%, and 6%, respectively in the NZ2050 scenario (European Environment Agency, 2011).

Under the NZ2050_Eff scenario, hydrogen and efficiency enhancements are assumed to incur a further 30% reduction on all pollutants based on the study conducted by the University of Oulu (2022). The CO_2 reductions indicate an equivalent reduction in fuel combustion and therefore combustion-related pollutants. However, since the ratio of hydrogen is not high overall on the path of the carbon neutral efficiency improvement scenario (NZ2050_Eff), the additional impact of efficiency improvement was not significant compared to the carbon neutral scenario (NZ2050).

[Figure A-1] Steel output by steel production technology



(Source: Eom et al., 2022)

3. Atmospheric and air quality modeling

This study has conducted detailed atmospheric modeling to estimate the contribution of BF-BOF steel plants to air pollutant concentrations and air pollution health impacts across South Korea.

Atmospheric dispersion modeling was done using the latest version 7 (June 2015) of the CALPUFF modeling system (Scire et al., 2000; Exponent, 2015). CALPUFF is the most widely used industry-standard model for long-range air quality impacts of point sources among the air quality regulators around. The model has been extensively validated by the U.S. EPA and other regulatory authorities; it is open source and fully documented.

CALPUFF has several important capabilities for this project. It is able to model the formation of secondary nitrate and sulfate particles and secondary PM2.5 from industrial NOx and SO_2 emissions and model the long-range transport of these pollutants. These two mechanisms are responsible for more than 90% of the population's exposure to PM2.5 and for the health impacts of coal-burning emissions from high-stack sources equipped with air pollutant controls (Zhou Y et al., 2006). This implies that their exclusion would neglect the majority of the PM2.5 health impacts. CALPUFF can also model near-field pollution at a very high resolution and manageable computational costs.

Meteorological and geophysical data for the simulations were generated with the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008). WRF (version 4.2.2.) was set up with 33 vertical levels and two nested grids of 15 km and 3 km resolution, centered on the three integrated steel plants covering 1500 x 1500 km and 450 x 450 km, respectively. Mother and inner domains use a two-way nesting technique which ensures dynamic interaction between them. WRF simulations use initial and lateral boundary conditions from the NCEP (National Centers for Environmental Prediction) CFRS (Climate Forecast System Reanalysis) dataset of NOAA (National Oceanic and Atmospheric Administration) producing three-dimensional, hourly meteorological data covering the full calendar year 2020.

WRF outputs were converted into formats accepted by CALPUFF's meteorological preprocessor, CALMET, using the CALWRF 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, 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 the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

The CALPUFF model uses the meteorological dataset to predict the atmospheric transport, dispersion, chemical transformation, and deposition of the pollutants and resulting incremental ground-level concentrations attributed to the studied emissions sources. The model performs a detailed simulation of the rise of the plume from the power plant stack, where the emissions are discharged.

For CALPUFF dispersion modeling, concentric receptor grids were defined, with a resolution of 1000x1000 m used for the finest grid within 10km of the modeled sources. A spin-up period of 6 days was used before the beginning of the calendar year to ensure that model start-up effects do not affect the meteorology and that the concentration fields are populated in the model before the start of the study period. The chemical transformation of sulfur and nitrogen was modeled using the ISORROPIA chemistry module within CALPUFF, which requires data on atmospheric chemistry parameters (ozone, ammonia, and H2O2 levels). Monthly average concentrations of these compounds were input into the model from baseline simulations using the Geos-Chem global atmospheric model with a nested grid for Southeast Asia (Koplitz et al., 2017).

The CALPUFF results were reprocessed using the POSTUTIL utility to repartition different nitrogen compounds (NO, NO_2, NO_3, and HNO_3) based on background ammonia concentrations. We carried out a separate simulation for each steel plant located in the study to project the impacts of future scenarios.

4. Health impact assessment

The Centre for Research on Energy and Clean Air (CREA) has developed a detailed globally implementable health impact assessment framework, based on the latest scientific research , 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 A-5).

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:

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

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), $Frac_{age}$ 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 ΔCsteel is the concentration attributed to BF-BOF steel plants, with the current contribution to pollutant concentrations from the plants having a negative sign (subtracted from the baseline concentration) and projected future incremental concentration 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 steel was eliminated.

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

$$RR\ (c) = RR_0 \frac{c - c0}{\Delta c} \quad when\ c > c_0, 1\ (otherwise),$$

where RR_0 is the risk ratio found in epidemiological research, Δc_0 is the concentration change that RR_0 refers to, and c_0 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 PM2.5 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 PM2.5 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 PM2.5 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 PM2.5. As Faustini et al. did not 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 PM2.5 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 A-6. 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 PM2.5 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 BF-BOF steel 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.

Future health impacts projects account for projected population growth on the national level, and for mortality impacts, using projected changes in age-specific death rates based on the United Nations (2019) medium variant. Use of age-specific death rates captures the impact of expected improvements in population health status and health services, which results in lower mortality for children, while increasing the susceptibility of the adult population to non-communicable diseases associated with air pollution.

5. Economic cost of air pollution

Economic losses as a result of air pollution from operating BF-BOF steel plants were calculated using the methods outlined in "Quantifying the Economic Costs of Air Pollution from Fossil Fuels" (Myllyvirta, 2020).

Air pollution both increases the risk of developing respiratory and cardiovascular diseases, and increases complications from them, significantly lowering the quality of life and economic productivity of people affected and increasing healthcare costs. The Global Burden of Disease project has quantified the degree of disability caused by each disease into a "disability weight" that can be used to compare the costs of different illnesses. The economic cost of disability and reduced quality of life caused by these diseases and disabilities are assessed based on disability weights, combined with the economic valuation of disability used by the UK environmental regulator DEFRA (Birchby et al., 2019), and adjusted by GNI and PPP for South Korea and the other countries included in the modeling domain.

The economic losses from air pollution-related deaths were assessed based on the results of a comprehensive survey of Viscusi & Masterman (2017) for valuation of mortality.

The estimates for economic costs per case of each health outcome for South Korea were calculated using 2019 GDP per capita, GNI per capita, purchasing power and exchange rate data from the World Bank (undated), assuming that the costs are proportional to either GNI or GDP as indicated:

$$[\text{cost per case}] = \frac{[\text{cost at reference income level}] \times [\text{ income level}]}{[\text{reference income level}]}$$

The economic cost of each health outcome was converted using the purchasing power parity (PPP) international dollars at 2011 prices adjusted to the unit cost calculated based on country-specific GDP or GNI as indicated (Table A-5). Results were then converted to US dollars and to Korea Won 2019 prices and exchange rates (Table A-7). Impacts related to productivity were adjusted by GDP, whereas those related to income or welfare loss were adjusted by GNI.

Future costs were projected based on OECD long-term GDP forecasts (OECD, 2018) and discounted at 3% per year, following U.S. EPA (2010) recommendations.

[Table A-5] Economic cost of different health outcomes

Effect	Valuation	Currency	Unit	Year	Source	Adjustment	Reference Income Level	Elasticity
New asthma cases	496,000	GBP	case	2018	Birchby (2019)	GNI PPP	UK	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	U.S.	1
Disability	62,800	GBP	year(s) lived with disability	2018	Birchby (2019)	GNI PPP	UK	1
Premature deaths	9,631,000	USD	death	2015	Viscusi & Masterman (2017)	GNI	U.S.	1
Work absence	130	EUR	work day	2005	EEA (2014)	GDP PPP	EU	1

[Table A-6] Input parameters

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	PM2.5	1.025 (1.013, 1.037)	10 ug/m^3	6 ug/m^3	Zheng (2015)	Achakulwisut et al. (2019)
18-99	Asthma emergency room visits	PM2.5	1.023 (1.015, 1.031)	10 ug/m^3	6 ug/m^3	Zheng (2015)	Anenberg et al. (2018)
Newborn	Preterm birth	PM2.5	1.15 (1.07, 1.16)	10 ug/m^3	8.8 ug/m^3	Sapkota et al. (2012)	Chawanpaiboo et al. (2019)
20-65	Work absence	PM2.5	1.046 (1.039-1.053)	10 ug/m^3	N/A	WHO (2013)	EEA (2014)
0-4	Deaths from lower respiratory infections	PM2.5	IHME (2020)		5.8 ug/m^3	IHME (2020)	IHME (2020)
25-99	Deaths from noncommunicable diseases, disaggregated by cause, and from lower respiratory infections	PM2.5	Burnett et al. (2018)		2.4 ug/m^3	Burnett et al. (2018)	IHME (2020)
25-99	Disability caused by diabetes, stroke and chronic respiratory disease	PM2.5	IHME (2020)		2.4 ug/m^3	Burnett et al. (2018)	IHME (2020)
25-99	Premature deaths	NO_2	1.04 (1.02-1.06)	10 ug/m^3	4.5 ug/m^3	Faustini et al. (2014); Stieb et al. (2021)	IHME (2020)

Numeric values in the column "Concentration-response function" refer to relative risk corresponding to the increase in concentrations given in the column "concentration change". No-harm threshold refers to a concentration below which the health impact is not quantified, generally due to lack of evidence in the studies on which the function is based.

[Table A-7] Valuation applied for different health outcomes in South Korea

Outcome	Valuation, USD (2019)	Valuation,M KRW (2019)
Years lived with disability	65,700	76.6
Deaths	5,807,000	6,768
Number of children suffering from asthma due to pollution exposure (Increased prevalence)	2,480	2.89
Asthma emergency room visits	535	0.62
Preterm births	224,300	261.3
Work absence (Sick leave days)	180	0.21

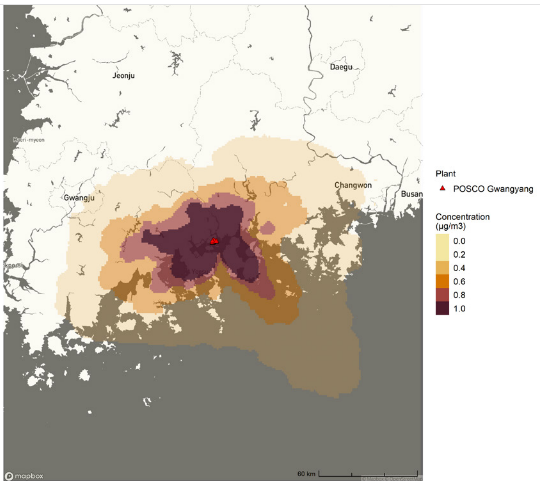
[Table A-8] Cumulative premature deaths by region under the three scenarios

Province	CurPol	NZ2050	NZ2050_Eff
Busan	1,267 (778 - 1,785)	644 (395 - 910)	611 (374 - 862)
Chungcheongbuk-do	248 (163 - 340)	126 (82 - 172)	119 (78 - 163)
Chungcheongnam-do	287 (187 - 393)	145 (94 - 199)	138 (90 - 189)
Daegu	868 (522 - 1,235)	442 (265 - 631)	419 (251 - 597)
Daejeon	231 (151 - 316)	117 (76 - 160)	111 (72 - 152)
Gangwon-do	94 (65 - 126)	48 (33 - 64)	45 (31 - 61)
Gwangju	596 (370 - 836)	303 (187 - 426)	287 (178 - 404)
Gyeonggi-do	1,413 (942 - 1,916)	714 (475 - 970)	677 (451 - 920)
Gyeongsangbuk-do	1,834 (1,054 - 2,659)	938 (537 - 1,362)	888 (509 - 1,289)
Gyeongsangnam-do	2,003 (1,216 - 2,837)	1,020 (617 - 1,448)	966 (585 - 1,371)
Incheon	243 (162 - 330)	123 (82 - 167)	117 (78 - 158)
Jeju	63 (45 - 83)	32 (22 - 42)	30 (21 - 40)
Jeollabuk-do	395 (255 - 545)	200 (129 - 277)	190 (122 - 262)
Jeollanam-do	1,380 (813 - 1,980)	704 (414 - 1,012)	667 (392 - 958)
Sejong	13 (8 - 18)	7 (4 - 9)	6 (4 - 9)
Seoul	638 (427 - 863)	322 (215 - 437)	306 (204 - 414)
Ulsan	517 (308 - 740)	264 (156 - 378)	250 (148 - 358)

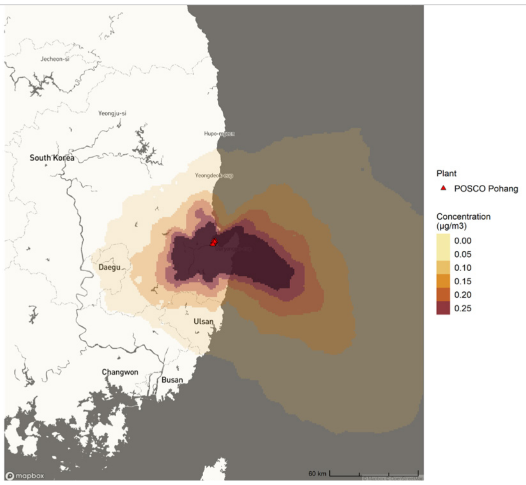
[Appendix 2] Emissions Concentrations

Sulfur Dioxide (SO_2)

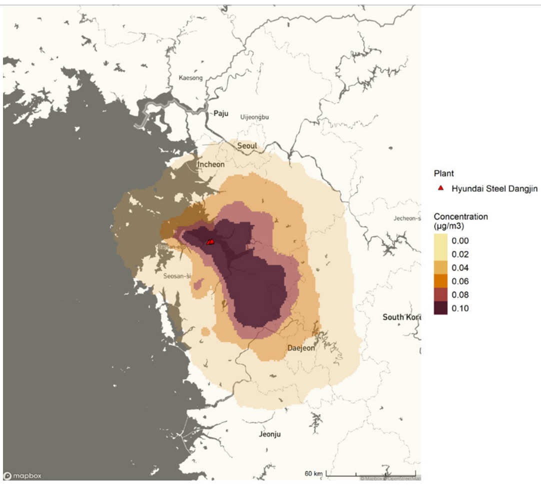
Annual mean SO_2 concentration from POSCO Gwangyang steel plant



Annual mean SO_2 concentraation from POSCO Pohang steel plant

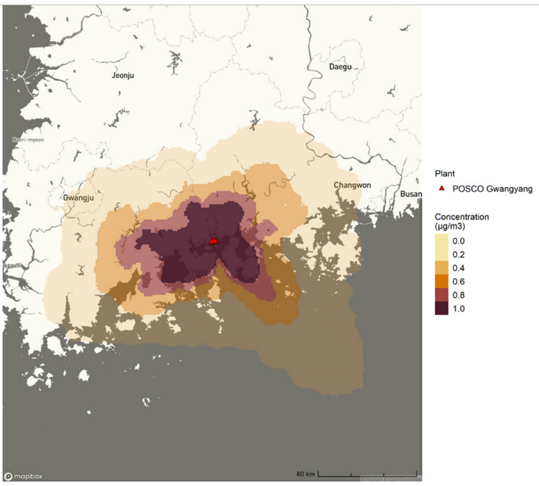


Annual mean SO_2 concentration from Hyundai

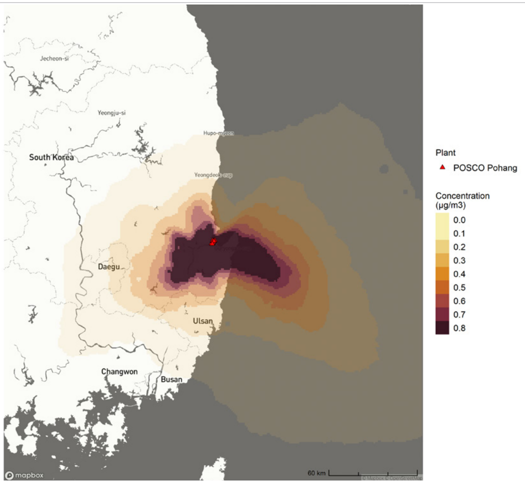


Nitrogen Dioxide (NO_2)

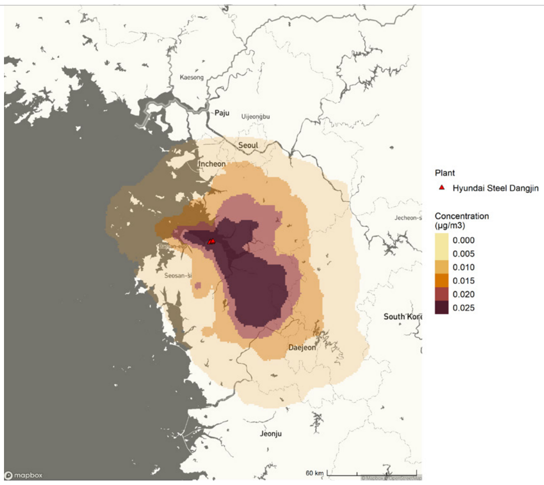
Annual mean NO_2 concentration from POSCO Gwangyang steel plant



Annual mean NO_2 concentraation from POSCO Pohang steel plant

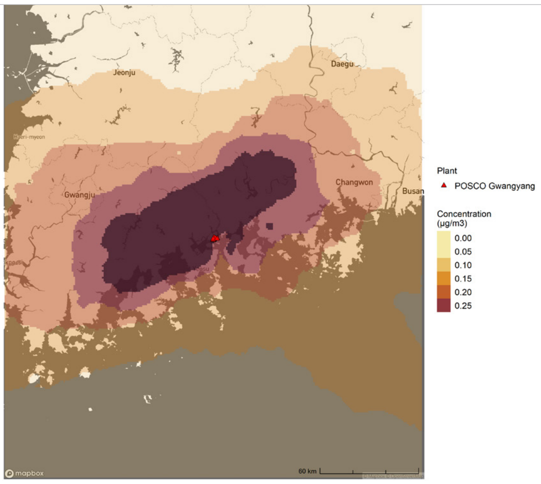


Annual mean NO_2 concentration from Hyundai

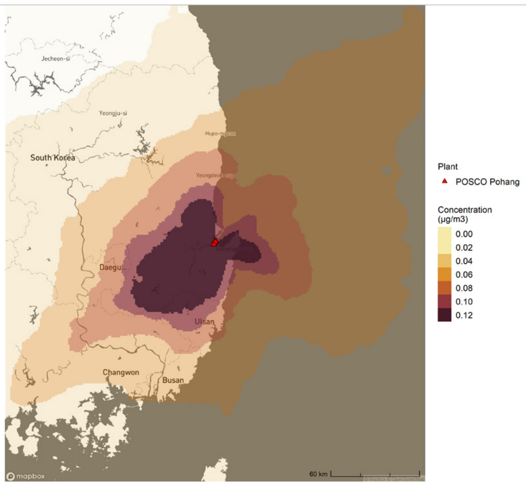


Particulate Matter 2.5 (PM2.5)

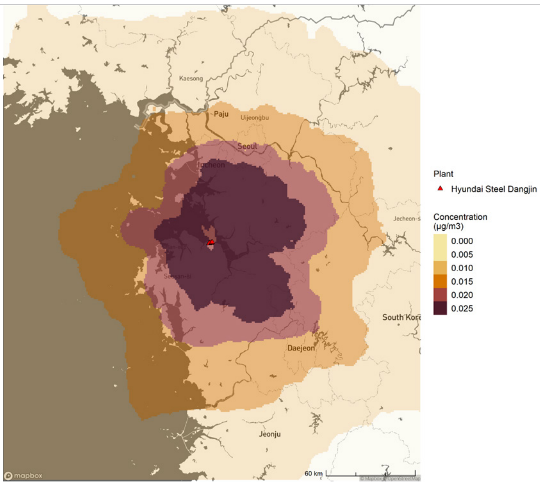
Annual mean PM2.5 concentration from POSCO Gwangyang steel plant



Annual mean PM2.5 concentration from POSCO Pohang steel plant



Annual mean PM2.5 concentration from Hyundai



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Authors
Geunha Kim | Solutions for Our Climate(SFOC) | geunha.kim@forourclimate.org
Isabella Suarez | Centre for Research on Energy and Clean Air | isabella@energyandcleanair.org
David Ecal | Centre for Research on Energy and Clean Air | david@energyandcleanair.org

Modeling
Lauri Myllyvirta | Centre for Research on Energy and Clean Air (CREA)

Advisory
Jongjun Yu | Dangjin Civic Environmental Monitoring Center

Design
Nature Rhythm

Contact
solutions@forourclimate.org (Policy and Regional Data)
getintouch@energyandcleanair.org (Methodology)