Aerosol and Air Quality Research

ORIGINAL RESEARCH
https://doi.org/10.4209/aaqr.230066

Estimation of Air Pollutant Emissions from Heavy Industry Sector in North Korea

Young Won Lee[1], Yong Pyo Kim[1], Min Ju Yeo[2*‡]

[1] Department of Chemical Engineering & Materials Science, Ewha Womans University, Seoul 03760, Korea
[2] Department of Environmental Science and Engineering, Ewha Womans University, Seoul 003760, Korea

ABSTRACT

This study aims to estimate the amount of air pollutants emitted from heavy industrial facilities in North Korea. The heavy industry sector in North Korea was classified according to the South Korean definition, and the air pollutant emissions that it generated were estimated for 2017. Emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur oxides (SO_x) by the heavy industry sector in North Korea were 22, 73, and 31%, respectively, of those in South Korea' air pollutant emissions. Moreover, the CO, NO_x, and SO_x emissions comprised 0.6, 124, and 24%, respectively, of the total air pollutant emission in North Korea estimated from the Emissions Database for Global Atmospheric Research version 5.0 (EDGAR v5.0). Geographically, the NO_x emissions were concentrated in the western part of North Korea, while CO and SO_x were concentrated in North Hamgyong Province.

Keywords: North Korea, Heavy industry, Air pollutant emissions

OPEN ACCESS

Received: March 23, 2023
Revised: March 23, 2023
Accepted: April 24, 2023

* **Corresponding Author:**
mjyeo@yonsei.ac.kr

‡ **Present address:** Department of Atmospheric Sciences, Yonsei University, Seoul 03722, Korea

This article is an English version of "Estimation of air pollutant emissions from heavy industry sector in North Korea [Korean]" published in the *Particle and Aerosol Research* in December 2021.

Publisher:
Taiwan Association for Aerosol Research
ISSN: 1680-8584 print
ISSN: 2071-1409 online

1 INTRODUCTION

In South Korea, the interest in the air quality of North Korea has increased in recent years. As fine particles became problematic in South Korea, the quantification of external influences became important. Air pollutants in North Korea can affect the air quality of South Korea, and its impact is expected to be greater than that of other countries due to its proximity (Bae *et al.*, 2018; Kim *et al.*, 2013).

The total primary energy supply of North Korea in 2016 was 8.8 Mtoe, which was equivalent to approximately 3% of that of South Korea (284 Mtoe; IEA, 2018). In comparison, data produced by North Korea show that the total primary energy supply in North Korea was about 8% of that of South Korea in 2000, but emissions of carbon monoxide (CO) and sulfur oxides (SO_x) were approximately 2.7 times greater (Yeo and Kim, 2019), from which it can be inferred that management of air pollutant emission facilities are underdeveloped (Yeo and Kim, 2018). The particulate matter with an aerodynamic diameter less than or equal to a nominal 2.5 μm ($PM_{2.5}$) concentration during the last 20 years in North Korea is hypothesized to be similar to that in South Korea (Yeo and Kim, 2019), but the mortality rate due to air pollution was 238 per 10,000 people in 2012 (WHO, 2017) and ranked first among 172 countries. In 2016, it ranked 15th among 183 countries at approximately 207 per 10,000 people, which was about 10 times the mortality rate in South Korea (WHO, 2019).

North Korea is located in an area affected by the regional transport of air pollutants; thus, elucidating sources of air pollutant emissions in North Korea contributes to the wider understanding of the causes and behavior of air pollution in Northeast Asia. The air quality in North Korea is becoming better understood, albeit indirectly, as results of recent research on the impact of air pollutants in North Korea on the air quality of South Korea (Bae *et al.*, 2018; Kim *et al.*, 2013),

satellite data (Richter *et al.*, 2005; Shaddick *et al.*, 2018), and visibility data measured in North Korea (Yeo *et al.*, 2019) are integrated. However, the understanding of emission sources within North Korea that are expected to primarily impact air quality in North Korea are inadequately understood, and a more specific and comprehensive analysis of relevant data is required. Moreover, as it is difficult to estimate air pollutant emissions solely from data provided by North Korea due to their limitations, this study indirectly estimated air pollutant emissions from heavy industrial sectors in North Korea using air pollutant emission data from the equivalent sectors in South Korea as a proxy.

North Korea started pursuing socialist industrialization in earnest in the 1960s, with heavy industry being one of the primary pillars of its economic policy (MOU, 2021). North Korea's industrial crisis began due to the shortage of materials and foreign currency caused by the decline in crude oil imports in the early 1990s, after which the country revised its development path of prioritizing heavy industry to focus on agriculture, light industry, and trade. However, heavy industry remains critical in North Korea, as demonstrated by the second target of a substantial development in the coal, metal, and railroad transport sectors, in addition to the third target of development in the machinery, chemical, construction, and building industries, as detailed in the 'Five-Year Economic Development Strategy' (MOU, 2021).

This study estimated the nitrogen oxides (NO_x), SO_x, and CO emitted by heavy industry in North Korea. For that, (1) the current state of North Korea's heavy industry was evaluated, (2) South Korea's official air pollutant emissions data (Clean Air Policy Support System (CAPSS); NIER, 2020) was used to identify the air pollutants in South Korea's heavy industries. In addition, (3) the production performance of the heavy industries of both nations was compared to estimate the air pollutant emissions in North Korea's heavy industry sector and identify the regional distribution of emissions. Subsequently, (4) the total air pollutant emissions in North Korea provided by the Regional Emission Inventory in Asia version 3 (REAS v3; Kurokawa and Ohara, 2020) and the Emissions Database for Global Atmospheric Research version 5.0 (EDGAR v5.0; EDGAR, 2020a) were compared with the air pollutant emissions of the heavy industry sector estimated in this study. According to Kim and Kim (2019), the majority of NO_x and SO_x emitted due to fuel combustion in North Korea derives from the industrial sector. Although the transportation sector accounts for a significant portion of NO_x emissions in advanced nations, in North Korea, the majority was produced by the industrial sector and was responsible for half of the entire emissions (Kim *et al.*, 2014). Additionally, North Korea emits approximately 6.3 times the amount of CO than South Korea.

2 MATERIALS AND METHODS

2.1 Current State of Heavy Industry North Korea

This research compares the production capacity and production output of the heavy industry sector in North Korea and South Korea in 2017 (KOSIS, 2020; KDB, 2020b). Data for 2017 were synthesized from the latest CAPSS data (NIER, 2020) in South Korea. In cases where data were unavailable, older data closest to 2017 were used. The industrial classification presented by the KDB (2020b) was applied to North Korea; whereas for South Korea, the KSIC (2017) was referenced. The North Korean heavy industry classification is presented in Table S1. This detailed classification enabled a quantitative comparison of North and South Korea's heavy industrial sectors. Through this detailed classification, the industry that allowed a quantitative comparison of the heavy industries of South and North Korea was named 'equivalent heavy industries'.

2.2 Method of Estimating Air Pollutant Emissions in North Korean Heavy Industries

The air pollutant emissions from heavy industry in North Korea were estimated using the rate of industrial activity and the air pollutant emissions that correspond to the equivalent heavy industries in South Korea. The method of calculating the air pollutant emissions (E) from South Korea's fuel combustion sector is shown in Eq. (1) (NIER, 2016).

$$E = Fuel \times EF \times (100 - CF) \quad (1)$$

where, *Fuel* is the quantity of fuel used (e.g., [ton yr^{-1}] for coal), *EF* is the emission factor of the fuel (e.g., [kg ton^{-1}] for coal), and *CF* is the efficiency (%) of the emission control facilities. The EFs have been defined considering the size, shape, and emission characteristics of each facility, which are industry-dependent, and the fuel type and usage (Kim *et al.*, 2021). However, because *EF*, *Fuel*, and *CF* are not provided by North Korea it is difficult to determine air pollutant emissions through conventional calculation methods. Thus, the North Korean air pollutant emissions were estimated using the emissions value of South Korea as shown in Eq. (2).

$$E_{NK} = E_{SK} \times \frac{A_{NK}}{A_{SK}} \times \frac{100 - CF_{NK}}{100 - CF_{SK}} \tag{2}$$

where, *NK* is North Korea, *SK* is South Korea, and *A* refers to the rate of activity.

In this study, *A*, which represents the production capacity and/or production output (e.g., [kt yr^{-1}] for steel industry), and *CF* for North and South Korea were varied to estimate the air pollutant emissions in North Korea. The capacity utilization rate (CUR) refers to the ratio of production output to production capacity (KOSIS, 2021b, 2021c, 2021d). When calculating *A*, the CUR was applied to the production capacity in cases when direct measures of product output were unavailable. Table 1 shows available production output and production capacity data for North and South Korea. An average CUR of 90% was determined for South Korean industries using the sum of the production outputs and the sum of the production capacities, which was applied to the equivalent heavy industry sectors of North and South Korea. In order to verify the reliability of this approach, a sensitivity analysis was performed on CUR and CF. The CUR in North Korea was assumed to be a maximum of 90% and a minimum of 10%; 10% intervals of this range were presented as CUR 0%, CUR 10%, etc. A CF of 90% was applied for South Korea. However, because North Korean air pollutant emission reduction facilities are absent or not operated (Chu, 2018), CF 0% was assumed to best reflect reality.

2.3 REAS and EDGAR North Korea Air Pollutant Emissions

REAS v3 and EDGAR v5.0 data were used to estimate the rate of heavy industrial air pollutant emissions in North Korea. REAS v3 shows the trend in air pollutant and greenhouse gas emissions in Asia from 1950 to 2015. The main sources of emission are domestic fuel combustion in power plants, industry, and transportation. Industrial activities, fugitive, and agriculture are included in non-combustion emission sources. For cases where data did not exist, the relevant trend was extrapolated (Kurokawa and Ohara, 2020). EDGAR v5.0 collates the air pollutants emitted by anthropogenic sources and profiles of greenhouse gases from 1970 to 2015 (Crippa *et al.*, 2020). Cases, where data did not exist, were represented as blank. REAS v3 and EDGAR v5.0 were compared with air pollutant emissions provided by North Korea (NCCE, 2012) to identify data with low uncertainties. In addition, the air pollutant emissions in heavy industry sector estimated in this study were compared with the published data (Crippa *et al.*, 2020; Kurokawa and Ohara, 2020; NCCE, 2012).

3 RESULTS

3.1 Current State of Heavy Industry in North Korea

The current state of the North Korean heavy industry is presented in Table 1 (KDB, 2020b; KOSIS, 2020). For example, the 2017 output of North Korea's steel industry was 1,090 kt yr^{-1} based on the smelting, steelmaking, and rolling, which was 1.5% of the production of South Korea at 71,030 kt yr^{-1}. North Korea's oil refining capacity of petroleum industry in 2020 was 70,000 barrels per stream day (BPSD), which corresponds to 2.3% of the 3,060 thousand BPSD of South Korea. The 2017 cement production capacity of North Korea was 9,090 kt yr^{-1}, which is 15% of South Korea's 61,470 kt yr^{-1}, and the production output was 6,840 kt yr^{-1}, which is 12% of South Korea's 57,400 kt yr^{-1}. North Korea's automobile industry had a production capacity of 63,000 cars yr^{-1} in 2017 yet output 3,000 cars yr^{-1}, which represents 1.4% of the 4,590,000 cars yr^{-1} capacity and 0.1% of the 4,110,000 cars yr^{-1} output of South Korea. Overall, North Korea has a

Table 1. Comparison of production capacity (PC) and output (PO) by heavy industry sector in North and South Korea (source: KDB, 2020b; KOSIS, 2020). SK: South Korea, NK: North Korea. PC data: 2017.

Sector		Unit	Production Capacity (PC)			Production Output (PO)			
			SK	NK	Ratio (%)	SK	NK	Ratio (%)	
Steel & Nonferrous Metal Processing Industry	Steel industry	kt yr^{-1}	–	13,720	–	71,030	1,090	1.5	Capacity: iron making, steel making, rolling; Output: cast steel PO data: 2017
	Pb (lead)	kt yr^{-1}	–	93	–	807	–	–	PO data: 2017
	Zn (Zinc)	kt yr^{-1}	–	305	–	962	–	–	PO data: 2017
Machinery Manufacturing Industry	Machine tool	thousands yr^{-1}	–	35	–	–	–	–	
	Precision machinery industry	thousands yr^{-1}	–	32	–	–	–	–	
Chemical Industry	Inorganic chemistry	kt yr^{-1}	6,980	3,150	45	–	–	–	Nitric acid, sulfuric acid
	Petrochemical	kt yr^{-1}	61,420	190	0.3	–	–	–	Petrochemical products
		thousand BPSD	3,060	70	2.3	–	–	–	Oil refining ability
		thousand barrels yr^{-1}	–	–	–	1,118,170	3,890	0.3	Crude oil intake PO data: 2020
	Chemical fertilizer	kt yr^{-1}	3,930	2,870	73	2,280	610	27	PO data: 2019
	Fine chemical	kt yr^{-1}	58	15	26	–	–	–	Pesticide
		thousands yr^{-1}	103,600	1,170	1.1	–	–	–	Tire
Building Materials Industry	Cement	kt yr^{-1}	61,470	9,090	15	57,400	6,840	12	PO data: 2017
	Plate glass	thousand boxes yr^{-1}	35,000	2,780	7.9	–	–	–	Calculated in terms of 2 mm flat glass
	Refractory	kt yr^{-1}	1,090	2,500	229	660	300	45	PO data: 2019 (SK), 2017 (NK)
	Bricks and construction porcelain	billion sheets yr^{-1}	–	1.8	–	2.7	–	–	PO data: 2020
Shipbuilding Industry	Tonnage	thousand GT yr^{-1} (NK) thousand CGT yr^{-1} (SK)	–	–	–	11,700	1,010	8.6	PO data: 2018
	Ship building	thousand GT yr^{-1} (NK) thousand CGT yr^{-1} (SK)	–	270	–	7,720	–	–	PO data: 2018
Automotive Industry		thousand cars yr^{-1}	4,590	63		4,110	3	0.1	PO data: 2017

Table 2. Carbon monoxide (CO), nitrogen oxides (NO_x) and sulfur oxides (SO_x) emissions from heavy industry in South Korea. Step 1 selects North Korea's heavy industry sectors that are directly comparable. Step 2 identifies the three heavy industries with the highest emissions. Step 3 determined the equivalent heavy industry sectors.

	Step 1			Step 2			Step 3		
	CO (%)	NO_x (%)	SO_x (%)	CO (%)	NO_x (%)	SO_x (%)	CO (%)	NO_x (%)	SO_x (%)
Steel & Nonferrous Metal Processing Industry	9.73 (28.1)	77.48 (42.9)	80.59 (50.0)	9.73 (29.0)	77.48 (43.7)	80.59 (50.2)	8.76 (37.5)	73.52 (46.2)	78.21 (51.6)
Chemical Industry	21.94 (63.4)	16.46 (9.1)	60.69 (37.6)	21.94 (65.5)	16.46 (9.3)	60.69 (37.8)	12.88 (55.1)	4.62 (2.9)	59.22 (39.0)
Building Materials Industry	1.83 (5.3)	83.29 (46.1)	19.41 (12.0)	1.83 (5.5)	83.29 (47.0)	19.41 (12.1)	1.73 (7.4)	81.08 (50.9)	14.23 (9.4)
Electrical and Electronic Industry	0.45 (1.3)	1.23 (0.7)	0.01 (0.0)	–	–	–	–	–	–
Shipbuilding Industry	0.23 (0.7)	1.13 (0.6)	0.60 (0.4)	–	–	–	–	–	–
Automotive Industry	0.40 (1.2)	1.13 (0.6)	0.00 (0.0)	–	–	–	–	–	–
SUM	34.58 (100)	180.72 (100)	161.30 (100)	33.50 (100)	177.23 (100)	160.69 (100)	23.37 (100)	159.22 (100)	151.66 (100)

production capacity equivalent to approximately 3% of that of South Korea in the primary materials sectors of steel, petroleum refining, and assembly industries, such as shipbuilding and automobile industries. However, North Korea's production capacity of chemical fertilizers, inorganic chemicals (nitric and sulfuric acid), and refractories is at least 45% that of South Korea. South Korea is heavily dependent on imports in these three sectors (KDB, 2020b).

3.2 Determination of Equivalent Heavy Industries

Step 1: North Korean industries for which production output and capacity data exist include the steel and non-ferrous metal, chemical, building materials, electrical and electronic, shipbuilding, and automobile industries (Table 1). The steel and non-ferrous metal industries were classified as a single category because 'primary metal manufacturing' is considered as a single subcategory of CAPSS emission sources that comprises steel manufacturing, non-ferrous metal manufacturing, and metal casting (KSIC, 2017), whereas the classification criteria are unclear for North Korea's industrial sector. The machinery manufacturing industry comprised only 13% of heavy industry, based on South Korea's data (ISTANS, 2021), and contributed 2, 1, and 0% of the CO, NO_x, and SO_x pollution, respectively. Owing to data limitations and differences between the types of machinery produced in North and South Korea, analysis of the production output and capacity was unreliable thus this industrial sector was excluded from the selection.

Step 2: The steel and non-ferrous metal, chemical, and building materials industries were identified as the three that produced the largest percentage of air pollutants. Table 2 shows the CO, NO_x, and SO_x discharged by each industry. The chemical industry accounted for the greatest emissions of CO, followed by the steel and non-ferrous metal, and building materials industries. In the case of NO_x, the building materials industry generated the highest emissions, followed by the steel and non-ferrous metal, and chemical industries. The release of SO_x, was greatest from the steel and non-ferrous metal industries, followed by chemical, and building materials industries.

Step 3: The proportion of air pollutant emissions generated by the equivalent heavy industries are shown in Fig. S1.

3.3 Estimation of Air Pollutant Emissions of Equivalent Heavy Industry

Fig. 1 shows that heavy industry was responsible for 4.3, 15.3, and 51.1% of the total CO, NO_x, and SO_x air pollution, respectively, in South Korea. The contribution to these emissions by the equivalent heavy industries was determined by scaling these percentages by the ratio of equivalent-to-total heavy industries. Thus, equivalent heavy industries were responsible for 2.9, 13.4, and 48.1% of the CAPSS CO, NO_x, and SO_x emissions, respectively.

It is reported that North Korea did not install or operate air pollutant reduction facilities (Chu, 2018), therefore a CF of 0% was expected to generate realistic results. Therefore, estimated air pollutant emissions of equivalent heavy industries with CF 0% are shown in Fig. 2. For CO, NO_x,

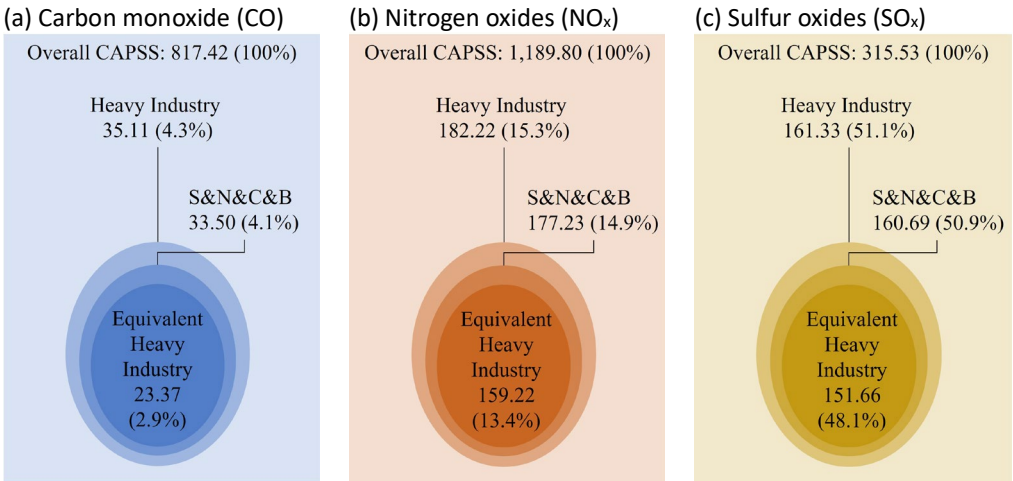

Fig. 1. The proportion of the equivalent heavy industry sector in the Clean Air Policy Support System (CAPSS) in South Korea (unit: kt yr^{-1}). Unlike Table 2, each heavy industry' sector includes machine industry. S&N&C&B: steel, nonferrous metal processing, chemical, and building materials industries.

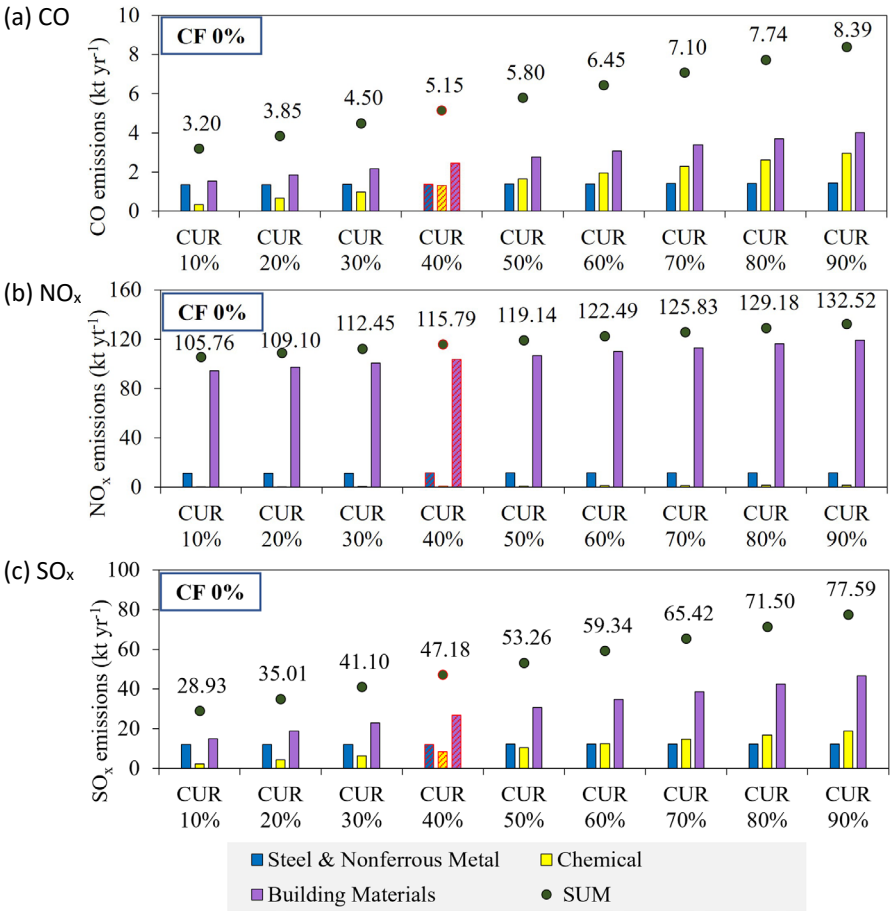

Fig. 2. Estimate of emissions of (a) carbon monoxide (CO), (b) nitrogen oxides (NO_x), and (c) sulfur oxides (SO_x) by the heavy industry sector in North Korea by CUR (Capacity Utilization Ratio) case when CF (Control Factor) is 0%.

and SO_x, the minimum and maximum annual emissions were 3.20, 105.76, and 28.93 kt yr^{-1}, and 8.39, 132.52, and 77.59 kt yr^{-1}, respectively. The change in air pollutant emissions caused by changes in CF is shown in Fig. S2.

Most thermal power plants in North Korea are operated at a rate of 50% or less due to the lack of spare parts and equipment failure (Kim *et al.*, 2017), and coal-fired power plants between 17 and 83% (Yeo and Kim, 2018). Therefore, it seems unlikely that the CUR of North Korean heavy industries exceeded 50% during the study period. Thus, the CF 0% and CUR 40% case (hereafter 'CUR 40') was considered to be the most appropriate air pollutant emission coefficients for North Korea. In CUR 40, the annual CO, NO_x, and SO_x emissions are 5.15, 115.79, and 47.18 kt, respectively, which are 61, 87, and 61% of the maximum estimated emission values (CF 0%; CUR 90%). It is important to note that the emissions assume that the removal efficiency and CUR of South Korea are 90%. Thus, if the CF of South Korea is lower than the 90% that was applied in this study, North Korea's air pollutant emissions will be lower than the current estimates and vice versa. Similarly, if South Korea's CUR is assumed to be lower, the air pollutant emissions of the equivalent heavy industries in North Korea will increase.

Fig. 3 compares the estimated air pollutant emissions of the equivalent heavy industries in North (CUR 40) and South Korea. Emissions of CO, NO_x, and SO_x by North Korea were 23.36, 159, 22, and 151.66 kt yr^{-1}, which are equivalent to 22, 3, and 31% of South Korea's emissions, respectively. The chemical industry accounted for the greatest share of South Korea's CO emissions, the building materials industry for its NO_x emissions, and the steel industry for its SO_x emissions. Moreover, the building materials industry accounted for the greatest proportion of total air pollutants because it comprised a higher percentage of the equivalent heavy industries than other sectors.

The chemical industry in South Korea emitted the greatest amount of CO, but the equivalent emissions in North Korea are negligible. North Korea's petroleum refining capacity was only 2.3% of that of South Korea (Table 1). In the case of NO_x, the contribution of South Korea's steel and non-ferrous metal industries to its emissions was large, while the building materials sector in North Korea accounted for 90% of its total NO_x emissions. This is because North Korea's steel industry production was only 1.5% of that of South Korea thus the emissions from this sector were low (Table 2). Furthermore, the production capacity and rate of the building materials sector in North Korea were greater than for other heavy industries. The steel and non-ferrous metal industries produced 52% of the SO_x emissions in South Korea, which was the greatest proportion of the total emissions (Table 2). However, the sources of North Korea's SO_x emissions were similar to those for NO_x.

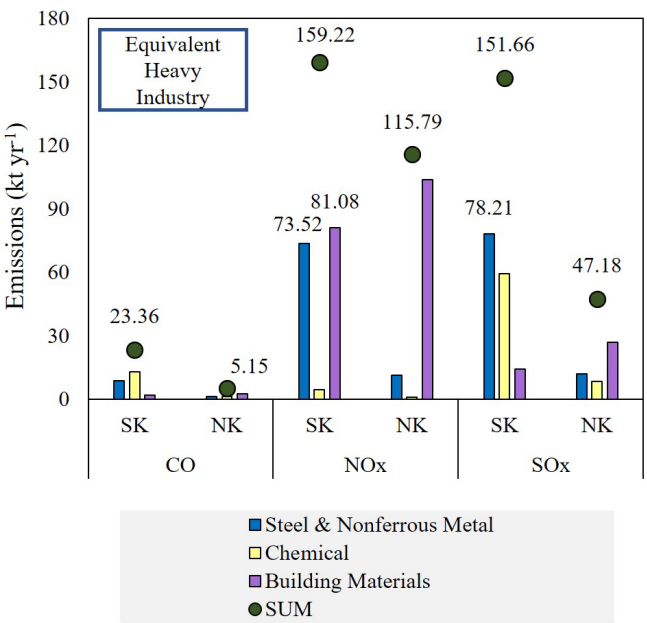

Fig. 3. Comparison of emissions of CO, NO_x, and SO_x in the North (NK) and South Korean (SK) heavy industry sectors (CUR 40%, CF 0% case).

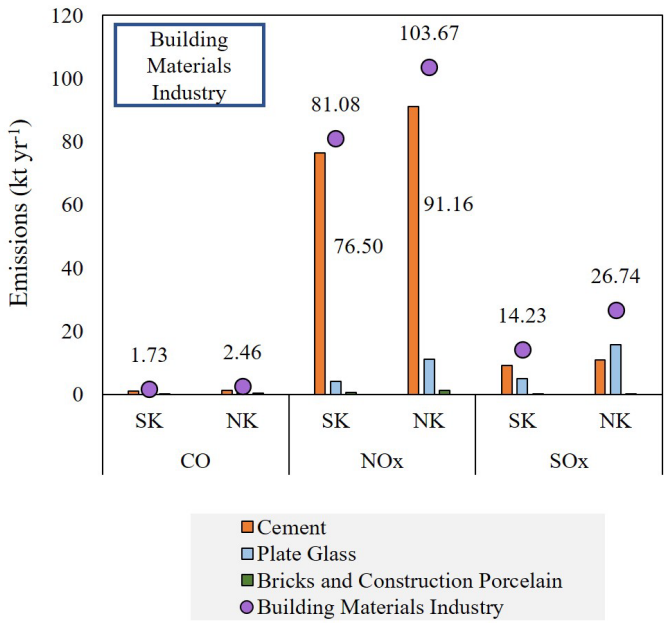

Fig. 4. Comparison of emissions of CO, NO_x, and SO_x from the building materials industry sector in North (NK) and South Korea (SK) (CUR 40%, CF 0% case).

Fig. 4 shows that emissions of CO, NO_x, and SO_x from the North Korean building materials industry were all higher than those in South Korea for CUR 40. In South Korea, the greatest contributor to all emissions was the cement sector, which also emitted the highest amounts of CO and NO_x, in North Korea, where the plate glass sector emitted the greatest quantity of SO_x.

3.4 Spatial Distribution of Air Pollutant Emissions of Equivalent Heavy Industry in North Korea

The regional distribution of equivalent heavy industry air pollutant emissions in North Korea is presented in Fig. 5. The maps show that CO was concentrated in North Hamgyong Province, NO_x were concentrated in Nampo, Pyongyang, and South Pyongan Province, and SO_x were concentrated in Nampo and North Hamgyong Province. All three pollutants are precursors to fine particles, and the $PM_{2.5}$ concentration in North Korea is elevated in the west of the country (Yeo and Kim, 2019). NO_x emissions were also concentrated in the west, whereas CO and SO_x emissions were concentrated

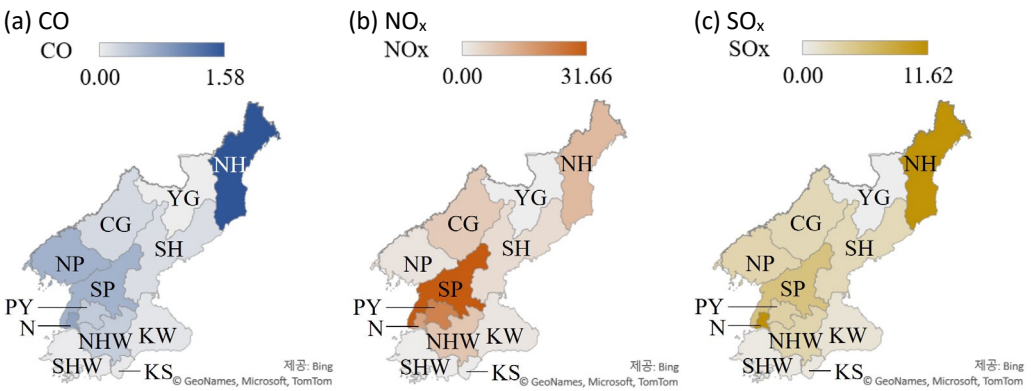

Fig. 5. Distribution of emissions (kt yr^{-1}) from the North Korean heavy industry sector by administrative district (a) CO, (b) NO_x, (c) SO_x. NH: North Hamgyong Province, SH: South Hamgyong Province, YG: Yanggang Province, CG: Chagang Province, NP: North Pyongan Province, SP: South Pyongan Province, PY: Pyongyang, N: Nampo, NHW: North Hwanghae Province, SHW: South Hwanghae Province, KS: Kaesong, KW: Kangwon Province.

in North Hamgyong Province in northeast North Korea. According to Kim (2006), the major factors affecting the concentration of fine particles in the atmosphere are the local emissions, secondary formation due to chemical reactions, external inflow, and removal from the atmosphere. Clearly, several factors impact the concentration of fine particles, but this study only considered emissions from heavy industries, which may have contributed to the difference between the distributions of concentration and emissions of fine particles.

In North Hamgyong Province, where CO and SO_x emissions were concentrated, there were equivalent heavy industries in sectors of steel & nonferrous metal processing, chemical and building materials industries. The largest steel production facility in North Korea is located in North Hamgyong Province (Kim Chaek iron and steel complex; KDB, 2020b), as is the Seungri chemical complex that conducts at least half of petroleum refining in North Korea. Furthermore, the Gomusan cement plant and Cheongjin glass plant are substantial manufacturing facilities in the building materials industry. Thus, CO was determined to have been primarily emitted by the steel industry and the petroleum refining sector of the chemical industry, whereas the steel industry and the cement sector of the building industry were responsible for SO_x.

The largest plate-glass production facility in North Korea, the Taean friendship glass plant (KDB, 2020b), is located in Nampo, and is believed to have significantly contributed to the CO and SO_x emissions. Chemical and building material plants are primarily mainly located in South Pyongan Province. In particular, the Sunchon cement complex is the largest cement factory in North Korea and appears to have significantly affected to the CO and NO_x emissions. In Pyongyang, the presence of Sangwon cement complex is expected to have had a substantial impact on NO_x emissions.

3.5 Estimation of Air Pollutant Emissions from All Heavy Industries in North Korea

Fig. 6 compares CO, NO_x, and SO_x emissions data from REAS v3, EDGAR v5.0, and North Korean (NCCE, 2012) databases. Air pollutant emission data from North Korea have been collected since 1990, enabling the analysis of trends in air pollutant emissions. REAS v3 and EDGAR v5.0 generally showed similar energy-use trends. North Korea's energy use (KOSIS, 2021a) decreased from 1990 to 1998 when it plateaued, it oscillated sharply between 2006 and 2008, and decreased again from 2008 to 2015. Comparing REAS v3 and EDGAR v5.0 with the published North Korean data, CO and NO_x were both overestimated in REAS v3, whereas EDGAR v5.0 emissions were similar to the North Korean data. SO_x tended to be underestimated by both REAS v3 and EDGAR v5.0, although the latter showed a similar trend to the North Korean data. Therefore, the EDGAR v5.0 was selected for comparison with the heavy industry air pollutant emissions estimated in this study.

The total CO emissions in 2015 in North Korea were 844.03 kt, whereas the predicted CUR 40 emissions were 5.15 kt, which is only 0.6% of the total. The total SO_x emissions in North Korea for the same period were 197.68 kt, while the predicted CUR 40 emissions were 47.18 kt, which corresponds to 24% of gross emissions. Evidently, the CO and SO_x emissions from equivalent heavy industries in North Korea did not comprise a significant proportion of the total emissions. This was also considered as the reason for the distributions of total CO and SO_x emissions in EDGAR-data (Fig. 7) differing from the regional distributions of equivalent heavy industries (Fig. 5). Unlike CO and SO_x, NO_x emissions from the equivalent heavy industries in North Korea were responsible for a significant share of the total NO_x emissions, which were 93.07 kt in 2015. The predicted NO_x emissions under CUR 40 were 115.79 kt, which corresponds to 124% of the actual mass and is deemed representative. The regional distributions of total NO_x emissions and equivalent heavy industry (Fig. 5) are both more concentrated near South Pyongan Province. Additionally, considering that the NO_x emissions from equivalent heavy industries (CUR 40) are higher than the total emissions, the actual CUR of North Korea's facilities is expected to be lower than 40%, which had previously been assumed to be most realistic value.

4 CONCLUSIONS

This study describes the determination of equivalent heavy industries to identify sources of industrial air pollutant emissions in North Korea and the CO, NO_x, and SO_x emissions for equivalent heavy industries in North Korea were estimated. The emissions estimated for CF 0% and CUR 40%

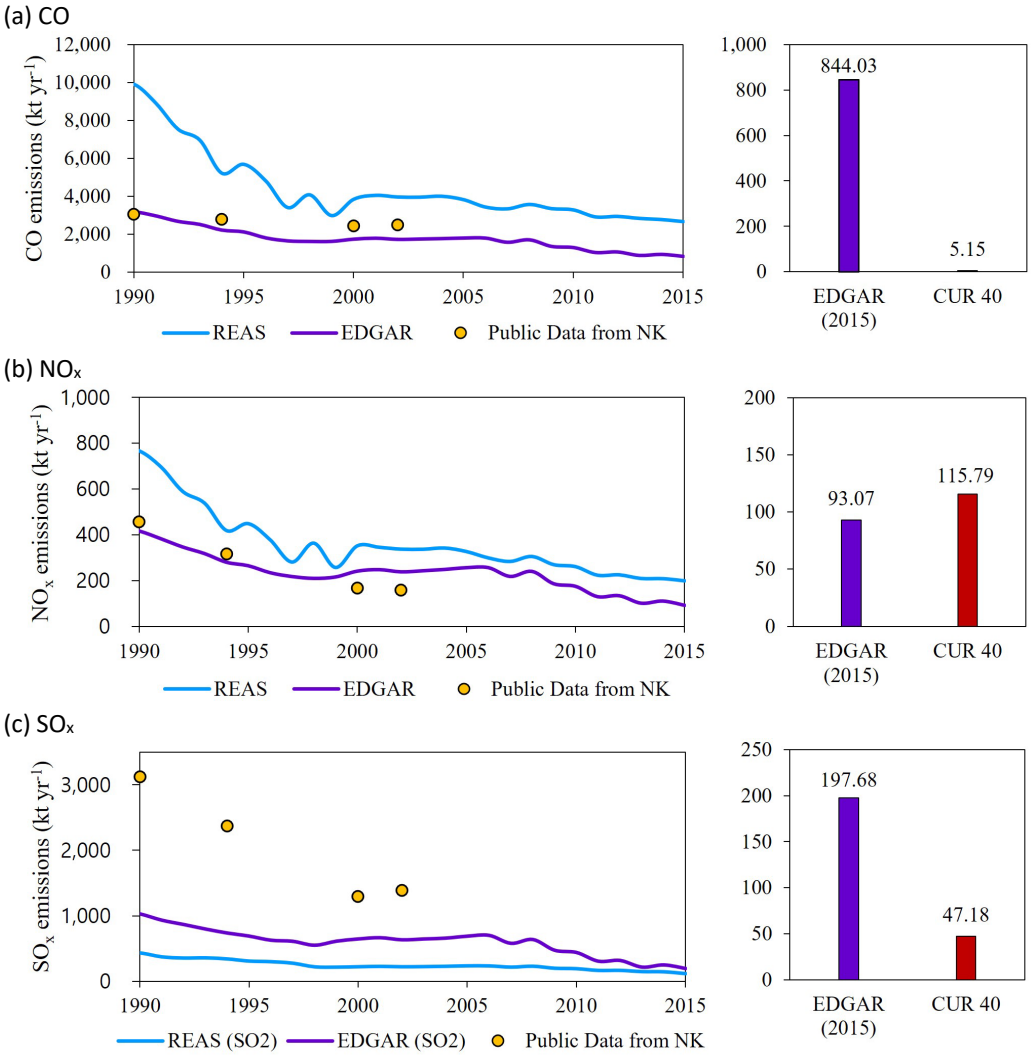

Fig. 6. Comparison of emission trends in North Korea using REAS v3 (Kurokawa and Ohara, 2020), EDGAR v5.0 (EDGAR, 2020a, 2020b), and the second National Communication on Climate Change (NCCE, 2012), and comparison of EDGAR v5.0 2015 data and CUR 40 (CUR 40%, CF 0% case). (a) CO, (b) NO_x, and (c) SO_x.

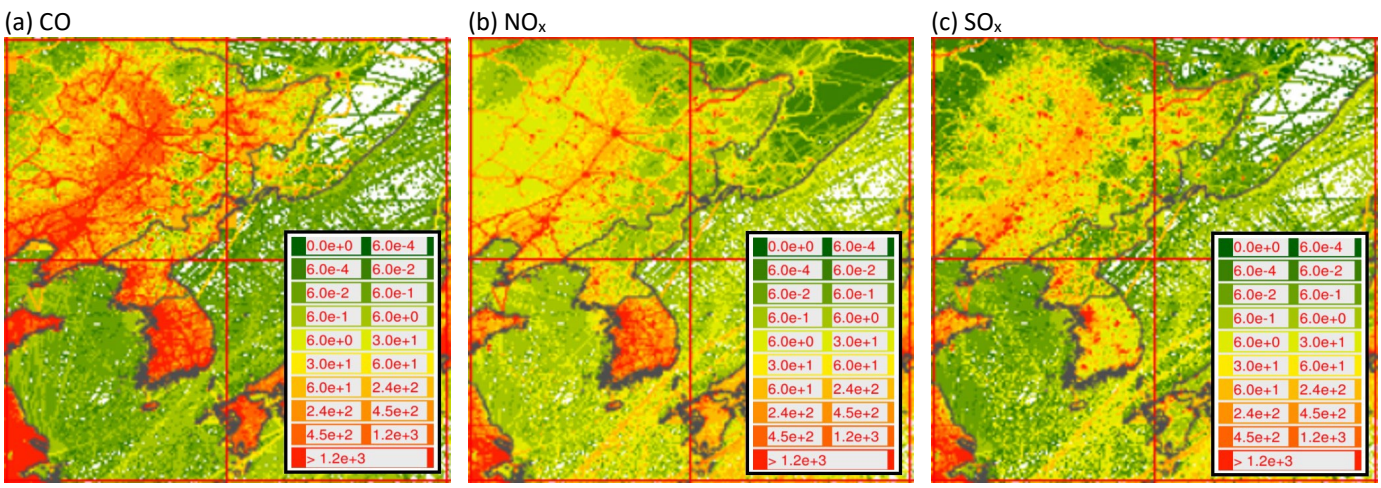

Fig. 7. EDGAR (Emissions Database for Global Atmospheric Research version 5.0) regional annual emission distribution map from 30°N/120°E to 50°N/140°E provided in 0.1° × 0.1° increments (unit: tons year^{-1} gridcell^{-1}) (EDGAR, 2020b).

were considered to best reflect the situation in North Korea: CO emissions were 5.15 kt yr^{-1}, NO_x were 115.79 kt yr^{-1}, and SO_x were 47.18 kt yr^{-1}. The CUR 40 modelled total CO, NO_x, and SO_x emissions from equivalent heavy industries in North Korea were equal to 22, 73, and 31% of South Korea's emissions. Among them, the CO, NO_x, and SO_x emissions from the building materials industry were greater than those from South Korea, so it was considered to be the primary emission sector. The total CO emissions for North Korea in 2015 were 844.03 kt (EDGAR, 2020a) and 5.15 kt estimated for CUR 40 in this study, which is 0.6% of the total emissions. The total NO_x emission in North Korea for the same period were 93.07 kt, and 115.79 kt estimated for CUR 40, which is 124% of the total emissions. This is believed to be because of the large proportion of NO_x emissions that are derived from equivalent heavy industries.

The North Korean regional distributions of air pollutant emissions from equivalent heavy industries and total air pollution EDGAR were compared. The distribution of NO_x from equivalent heavy industries was concentrated in the west, whereas CO and SO_x were concentrated in Hamgyong-bukto, in northeast North Korea. However, all three substances were concentrated in the west of the country in the total air pollutant emission distribution from EDGAR v.5. The NO_x emissions estimated in this study for equivalent heavy industry exceeded the total emissions in North Korea presented by EDGAR, therefore equivalent heavy industries were considered to be the major source of NO_x emissions within North Korea. The CO and SO_x emissions of equivalent heavy industries did not account for a significant share of the total emissions in North Korea, and they were not considered to be representative source for the total emissions in North Korea. Therefore, it was concluded that the distributions of total emissions and those related to heavy industries differ. Additional research will be required to identify the source and quantity of CO and SO_x emissions for other industries and non-industrial sectors.

This research only evaluated heavy industrial sectors that were represented in both North and South Korea due to data limitations in North Korea. It is important to note that this doesn't represent air pollutant emissions from all heavy industries in North Korea. In addition, the EF was not considered for estimating the emissions. In the future, estimating the emissions using the general calculation method as shown in Eq. (1) by applying the EF that considers factors such as the quality of the fuel in North Korea will increase the reliability of the results.

ACKNOWLEDGEMENTS

This research was supported by Ministry of Education (NRF-2020R1I1A1A01054651) through the National Research Foundation of Korea (NRF).

SUPPLEMENTARY MATERIAL

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.230066

REFERENCES

Bae, M., Kim, H.C., Kim, B.U., Kim, S. (2018). $PM_{2.5}$ simulations for the Seoul metropolitan area: (V) Estimation of North Korean emission contribution. J. Korean Soc. Atmos. Environ. 34, 294–305. https://doi.org/10.5572/KOSAE.2018.34.2.294 (in Korean with English abstract)

Chu, J.M. (2018). Cooperation for air pollution between South Korea and North Korea. Workshop on Special Committee on Air Pollution in the Korean Peninsula, Seoul, Korea. (in Korean)

Crippa, M., Solazzo, E., Huang, G., Guizzardi, D., Koffi, E., Muntean, M., Schieberle, C., Friedrich, R., Janssens-Maenhout, G. (2020). High resolution temporal profiles in the Emissions Database for Global Atmospheric Research. Sci. Data 7, 121. https://doi.org/10.1038/s41597-020-0462-2

Emission Database for Global Atmospheric Research (EDGAR) (2020a). EDGARv5.0 air pollutants. Emission Database for Global Atmospheric Research. https://edgar.jrc.ec.europa.eu/overview.php?v=50_AP (accessed 16 September 2021).

Emission Database for Global Atmospheric Research (EDGAR) (2020b). Emissions data and maps.

Emission Database for Global Atmospheric Research. https://edgar.jrc.ec.europa.eu/emissions_data_and_maps (accessed 2 October 2021).

Industrial Statistics Analysis System (ISTANS) (2021). Key indicators of major industries. Industrial Statistics Analysis System, Korea. https://www.istans.or.kr/re/reIndex_view01.do?chn=1 (accessed 2 December 2021).

International Energy Agency (IEA) (2018). CO_2 emissions from fuel combustion 2018 Highlights. International Energy Agency, Paris. https://doi.org/10.1787/co2_fuel-2018-en

Kim, B.U., Hong, Y.K., Lee, Y.S., Yang, S.P., Hyun, G.W., Yi G.H. (2021). Emission characteristics and coefficients of air pollutants in iron and steel manufacturing facilities. J. Environ. Health Sci. 47, 259–266. https://doi.org/10.5668/JEHS.2021.47.3.259

Kim, I.S., Lee, J.Y., Kim, Y.P. (2013). Impact of polycyclic aromatic hydrocarbon (PAH) emissions from North Korea to the air quality in the Seoul Metropolitan Area, South Korea. Atmos. Environ. 70, 159–165. https://doi.org/10.1016/j.atmosenv.2012.12.040

Kim, I.S., Kim, Y.P. (2019). Characteristics of energy usage and emissions of air pollutants in North Korea. J. Korean Soc. Atmos. Environ. 35, 125–137. https://doi.org/10.5572/KOSAE.2019.35.1.125 (in Korean with English abstract)

Kim, N.K., Kim, Y.P., Morino, Y., Kurokawa, J., Ohara, T. (2014). Verification of NO_x emission inventories over North Korea. Environ. Pollut. 195, 236–244. https://doi.org/10.1016/j.envpol.2014.06.034

Kim, S.M., Kim, S.H., Lee, H.B. (2017). Trends and status of thermoelectric power plant in North Korea. Korean Inst. Electr. Eng. 2017, 364–365. (in Korean with English abstract)

Kim, Y.P. (2006). Air pollution in Seoul caused by aerosols. J. Korean Soc. Atmos. Environ. 22, 535–553. (in Korean with English abstract)

Korea Development Bank (KDB) (2020a). 2020 North Korea's industry I. Korea Development Bank Seoul. (in Korean)

Korea Development Bank (KDB) (2020b). 2020 North Korea's industry II. Korea Development Bank Seoul. (in Korean)

Korean Standard Industry Classification (KSIC) (2017). Korean standard industrial classification. Korean Standard Industry Classification, Korea. https://kssc.kostat.go.kr:8443/ksscNew_web/link.do?gubun=001 (accessed 1 August 2021).

Korean Statistical Information Service (KOSIS) (2020). Major statistical indicators of North Korea. Korean Statistical Information Service, Korea. (in Korean)

Korean Statistical Information Service (KOSIS) (2021a). Primary energy supply (caloric value). Korean Statistical Information Service, Seoul. https://kosis.kr/bukhan/index/index.do (accessed 15 September 2021).

Korean Statistical Information Service (KOSIS) (2021b). Statistical data: capacity utilization rate. Korean Statistical Information Service, Korea. https://meta.narastat.kr/metasvc/index.do?iemInputNo=0000094384319 (accessed 3 September 2021).

Korean Statistical Information Service (KOSIS) (2021c). Statistical data: production capacity. Korean Statistical Information Service, Korea. https://meta.narastat.kr/metasvc/index.do?iemInputNo=0000094384319 (accessed 3 September 2021).

Korean Statistical Information Service (KOSIS) (2021d). Statistical data: production output. Korean Statistical Information Service, Korea. https://meta.narastat.kr/metasvc/index.do?iemInputNo=0000094384319 (accessed 3 September 2021).

Kurokawa, J., Ohara, T. (2020). Long-term historical trends in air pollutant emissions in Asia: regional emission inventory in Asia (REAS) version 3. Atmos. Chem. Phys. 20, 12761–12793. https://doi.org/10.5194/acp-20-12761-2020

Ministry of Unification (MOU) (2021). 2021 Understanding North Korea. Ministry of Unification, Seoul. (in Korean)

National Coordinating Committee for Environment (NCCE) (2012). DPR Korea's second national communication on climate change. National Coordinating Committee for Environment, Pyongyang. https://unfccc.int/sites/default/files/resource/prknc2.pdf

National Institute of Environmental Research (NIER) (2016). National air pollutant emission calculation method handbook (III). National Institute of Environmental Research, Korea. http://airemiss.nier.go.kr/user/boardList.do?command=view&siteId=airemiss&boardId=85&page=1&boardSeq=146&search=&column=&categoryId=&categoryDepth=&id=airemiss_040200000000&parent= (accessed 15 July 2021).

National Institute of Environmental Research (NIER) (2020). Emissions of pollutants by sector and species. National Institute of Environmental Research, Korea. http://airemiss.nier.go.kr/mbshome/mbs/airemiss/index.do (accessed 23 June 2021).

Richter, A., Burrows, J.P., Nüß, H., Granier, C., Niemeier, U. (2005). Increase in tropospheric nitrogen dioxide over China observed from space. Nature 437, 129–132. https://doi.org/10.1038/nature04092

Shaddick, G., Thomas, M., Amini, H., Broday, D.M., Cohen, A., Frostad, J., Green, A., Gumy, S., Liu, Y., Martin, R.V., Prüss-Üstun, A., Simpson, D., van Donkelaar, A., Brauer, M. (2018). Data integration for the assessment of population exposure to ambient air pollution for global burden of disease assessment. Environ. Sc. Technol. 52, 9069–9078. https://doi.org/10.1021/acs.est.8b02864

World Health Organization (WHO) (2017). World health statistics 2017: monitoring health for the SDGs, sustainable development goals. World Health Organization, Geneva, Switzerland. https://apps.who.int/iris/handle/10665/255336

World Health Organization (WHO) (2019). World health statistics 2019: monitoring health for the SDGs, sustainable development goals. World Health Organization, Geneva, Switzerland. https://apps.who.int/iris/handle/10665/324835

Yeo, M.J., Kim, Y.P. (2018). Electricity supply trend and operating statuses of coal-fired power plants in North Korea using the facility-specific data produced by North Korea: characterization and recommendations. Air Qual. Atmos. Health 11, 979–992. https://doi.org/10.1007/s11869-018-0601-5

Yeo, M.J., Kim, Y.P. (2019). The state of the air quality and measures for improving it in North Korea. J. Korean Soc. Atmos. Environ. 35, 318–335. https://doi.org/10.5572/kosae.2019.35.3.318 (in Korean with English abstract)

Yeo, M.J., Seo, J.H., Kim, Y.P. (2019). Temporal and spatial characteristics of visibility in North Korea. J. Korean Soc. Atmos. Environ. 35, 726–740. https://doi.org/10.5572/KOSAE.2019.35.6.726 (in Korean with English abstract)