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

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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 (NOₓ), and sulfur oxides (SOₓ) by the heavy industry sector in North Korea were 22, 73, and 31%, respectively, of those in South Korea’s air pollutant emissions. Moreover, the CO, NOₓ, and SOₓ 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 NOₓ emissions were concentrated in the western part of North Korea, while CO and SOₓ were concentrated in North Hamgyong Province.

Keywords: North Korea, Heavy industry, Air pollutant emissions

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 (SOₓ) 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 (PM₂.₅) 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 (NOx), SOx, 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 NOx and SOx emitted due to fuel combustion in North Korea derives from the industrial sector. Although the transportation sector accounts for a significant portion of NOx 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).

\[ E = \text{Fuel} \times EF \times (100 - CF) \] (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).

\[
E_{NK} = E_{SK} \times \frac{A_{NK} \times 100 - CF_{NK}}{A_{SK} \times 100 - CF_{SK}}
\]

(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.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Unit</th>
<th>Production Capacity (PC)</th>
<th>Production Output (PO)</th>
<th>Ratio (%)</th>
<th>PO data:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SK</td>
<td>NK</td>
<td>SK</td>
<td>NK</td>
</tr>
<tr>
<td>Steel &amp; Nonferrous Metal Processing Industry</td>
<td>Steel industry</td>
<td>kt yr⁻¹</td>
<td>–</td>
<td>13,720</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Pb (lead)</td>
<td>kt yr⁻¹</td>
<td>–</td>
<td>93</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Zn (Zinc)</td>
<td>kt yr⁻¹</td>
<td>–</td>
<td>305</td>
<td>–</td>
</tr>
<tr>
<td>Machinery Manufacturing Industry</td>
<td>Machine tool</td>
<td>thousands yr⁻¹</td>
<td>–</td>
<td>35</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Precision machinery industry</td>
<td>thousands yr⁻¹</td>
<td>–</td>
<td>32</td>
<td>–</td>
</tr>
<tr>
<td>Chemical Industry</td>
<td>Inorganic chemistry</td>
<td>kt yr⁻¹</td>
<td>6,980</td>
<td>3,150</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Petrochemical</td>
<td>kt yr⁻¹</td>
<td>61,420</td>
<td>190</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>thousand BPSD</td>
<td>3,060</td>
<td>70</td>
<td>2.3</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>thousand barrels yr⁻¹</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1,118,170</td>
</tr>
<tr>
<td></td>
<td>Chemical fertilizer</td>
<td>kt yr⁻¹</td>
<td>3,930</td>
<td>2,870</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>Fine chemical</td>
<td>kt yr⁻¹</td>
<td>58</td>
<td>15</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>thousands yr⁻¹</td>
<td>103,600</td>
<td>1,170</td>
<td>11</td>
<td>–</td>
</tr>
<tr>
<td>Building Materials Industry</td>
<td>Cement</td>
<td>kt yr⁻¹</td>
<td>61,470</td>
<td>9,090</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Plate glass</td>
<td>thousand boxes yr⁻¹</td>
<td>35,000</td>
<td>2,780</td>
<td>7.9</td>
</tr>
<tr>
<td></td>
<td>Refractory</td>
<td>kt yr⁻¹</td>
<td>1,090</td>
<td>2,500</td>
<td>229</td>
</tr>
<tr>
<td></td>
<td>Bricks and construction porcelain</td>
<td>billion sheets yr⁻¹</td>
<td>–</td>
<td>18</td>
<td>–</td>
</tr>
<tr>
<td>Shipbuilding Industry</td>
<td>Tonnage</td>
<td>thousand GT yr⁻¹ (NK)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Ship building</td>
<td>thousand CGT yr⁻¹ (SK)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Automotive Industry</td>
<td>thousand cars yr⁻¹</td>
<td>4,590</td>
<td>63</td>
<td>–</td>
<td>4,110</td>
</tr>
</tbody>
</table>

Capacity: iron making, steel making, rolling; Output: cast steel, Nitric acid, sulfuric acid, Petrochemical products, Oil refining ability, Crude oil intake, Tire, Calculated in terms of 2 mm flat glass, PO data: 2017, PO data: 2018, PO data: 2019 (SK), 2017 (NK), PO data: 2020.
Table 2. Carbon monoxide (CO), nitrogen oxides (NOx) and sulfur oxides (SOx) 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.

<table>
<thead>
<tr>
<th></th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO (%)</td>
<td>NOx (%)</td>
<td>SOx (%)</td>
</tr>
<tr>
<td>Steel &amp; Nonferrous</td>
<td>9.73 (28.1)</td>
<td>77.48 (50.0)</td>
<td>80.59 (50.0)</td>
</tr>
<tr>
<td>Processing Industry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical Industry</td>
<td>21.94 (63.4)</td>
<td>16.46 (9.1)</td>
<td>60.69 (37.6)</td>
</tr>
<tr>
<td>Building Materials</td>
<td>1.83 (5.3)</td>
<td>83.29 (46.1)</td>
<td>19.41 (12.0)</td>
</tr>
<tr>
<td>Industry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical and</td>
<td>0.45 (1.3)</td>
<td>1.23 (0.7)</td>
<td>0.01 (0.0)</td>
</tr>
<tr>
<td>Electronic Industry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shipbuilding</td>
<td>0.23 (0.7)</td>
<td>1.13 (0.6)</td>
<td>0.60 (0.4)</td>
</tr>
<tr>
<td>Industry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automotive Industry</td>
<td>0.40 (1.2)</td>
<td>1.13 (0.6)</td>
<td>0.00 (0.0)</td>
</tr>
<tr>
<td>SUM</td>
<td>34.58 (100)</td>
<td>180.72 (100)</td>
<td>161.30 (100)</td>
</tr>
</tbody>
</table>

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, NOx, and SOx 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, NOx, and SOx 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 NOx, the building materials industry generated the highest emissions, followed by the steel and non-ferrous metal, and chemical industries. The release of SOx 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, NOx, and SOx 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, NOx, and SOx emissions, respectively.
It is reported that North Korea did not install or operate air pollutant reduction facilities \cite{Chu2018}, 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\textsubscript{x},

![Fig. 1.](https://example.com/fig1.png)  
**Fig. 1.** The proportion of the equivalent heavy industry sector in the Clean Air Policy Support System (CAPSS) in South Korea (unit: kt yr\textsuperscript{-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.](https://example.com/fig2.png)  
**Fig. 2.** Estimate of emissions of (a) carbon monoxide (CO), (b) nitrogen oxides (NO\textsubscript{x}), and (c) sulfur oxides (SO\textsubscript{x}) by the heavy industry sector in North Korea by CUR (Capacity Utilization Ratio) case when CF (Control Factor) is 0%.
and SO\textsubscript{x}, the minimum and maximum annual emissions were 3.20, 105.76, and 28.93 kt yr\textsuperscript{-1}, and 8.39, 132.52, and 77.59 kt yr\textsuperscript{-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\textsubscript{x}, and SO\textsubscript{x} emissions were 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\textsubscript{x}, and SO\textsubscript{x} by North Korea were 23.36, 159, 22, and 151.66 kt yr\textsuperscript{-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\textsubscript{x} emissions, and the steel industry for its SO\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{x} emissions in South Korea, which was the greatest proportion of the total emissions (Table 2). However, the sources of North Korea’s SO\textsubscript{x} emissions were similar to those for NO\textsubscript{x}.

![Fig. 3. Comparison of emissions of CO, NO\textsubscript{x}, and SO\textsubscript{x} in the North (NK) and South Korean (SK) heavy industry sectors (CUR 40%, CF 0% case).](image-url)
Fig. 4. Comparison of emissions of CO, NO\textsubscript{x}, and SO\textsubscript{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\textsubscript{x}, and SO\textsubscript{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\textsubscript{x}, in North Korea, where the plate glass sector emitted the greatest quantity of SO\textsubscript{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\textsubscript{x} were concentrated in Nampo, Pyongyang, and South Pyongan Province, and SO\textsubscript{x} were concentrated in Nampo and North Hamgyong Province. All three pollutants are precursors to fine particles, and the PM\textsubscript{2.5} concentration in North Korea is elevated in the west of the country (Yeo and Kim, 2019). NO\textsubscript{x} emissions were also concentrated in the west, whereas CO and SO\textsubscript{x} emissions were concentrated...
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\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{x} emissions. In Pyongyang, the presence of Sangwon cement complex is expected to have had a substantial impact on NO\textsubscript{x} emissions.

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

Fig. 6 compares CO, NO\textsubscript{x}, and SO\textsubscript{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\textsubscript{x} were both overestimated in REAS v3, whereas EDGAR v5.0 emissions were similar to the North Korean data. SO\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{x} emissions in EDGAR-data (Fig. 7) differing from the regional distributions of equivalent heavy industries (Fig. 5). Unlike CO and SO\textsubscript{x}, NO\textsubscript{x} emissions from the equivalent heavy industries in North Korea were responsible for a significant share of the total NO\textsubscript{x} emissions, which were 93.07 kt in 2015. The predicted NO\textsubscript{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\textsubscript{x} emissions and equivalent heavy industry (Fig. 5) are both more concentrated near South Pyongan Province. Additionally, considering that the NO\textsubscript{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\textsubscript{x}, and SO\textsubscript{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) NOx, and (c) SOx.

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.

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**SUPPLEMENTARY MATERIAL**

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