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Air Pollution from Global Steel Industry

An International Benchmarking of Criteria Air Pollutants Intensities

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Global Efficiency Intelligence

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Executive Summary

The world's steel demand is projected to increase from 1,880 Mt (million tonnes) in 2020 to up to 2,500 Mt in 2050. India will lead the production growth and Africa and the Middle East are the other two regions with the highest projected growth rate in steel production over this period. This growth in steel consumption and production will drive a significant increase in the industry's greenhouse gas (GHG) emissions, as well as criteria air pollutant and other hazardous emissions in the absence of substantial effort to abate these emissions.

Air pollution contributes to a wide variety of adverse health effects (see section 1.1). According to the U.S. Environmental Protection Agency (EPA), exposure to criteria air pollutants can cause a variety of respiratory health effects, including inflammation of the lining of the lungs, reduced lung function, and respiratory symptoms, increased susceptibility to respiratory infection, premature mortality, aggravation of cardiovascular disease, decreased lung function growth, exacerbation of allergic symptoms, neurodevelopmental effects such as lowered IQ and behavioral problems, reduction in the capacity of the blood to carry oxygen, thereby decreasing the supply of oxygen to tissues and organs such as the heart, and many other negative health effects.

In addition to being one of the most energy-intensive industries, iron and steel manufacturing also involves processing raw materials that typically contain heavy metals and cause dust emissions. In addition, its heavy dependence on fossil fuels (especially on coal) as the primary source of energy causes iron and steel production to be one of the major air polluting industries. This report focuses on comparing the criteria air pollutants emissions intensities for the steel industry in selected countries.

The aim of the international benchmarking is to offer a means of comparing the performance of a given industry across countries. Benchmarking can also be used to estimate the potential for the abatement of air pollutants through the implementation of pollution control technologies. At the national level, benchmarking of criteria air pollutants emissions intensities can help policymakers prioritize abatement of specific criteria air pollutants and design policies for the curtailment of their emissions.

In this study, we performed the benchmarking for each of the four major criteria air pollutants (Sulfur dioxide (SO_2), Nitrogen oxide (NOx), Particulate matter (PM), and non-methane volatile organic compounds (NMVOC)) emitted from the production of steel in 12 countries/regions. We have considered both direct and indirect sources of emissions i.e., onsite emissions related to process and fuel combustion in steel plants (direct emissions) and offsite emissions associated with electricity use by steel plants (indirect emissions). Emissions related to the rest of the steel value chain are beyond the scope of this project.

Our results show that amongst the criteria air pollutants analyzed in this study, sulfur dioxide (SO_2) was the highest emitted criteria air pollutant from the steel industry globally, whereas the

NMVOCs are the lowest emitted criteria air pollutants from this industry (Figure ES1). Although the shares of direct emissions vary for each criteria air pollutant and country, the majority of emissions of criteria air pollutants can be characterized as direct emissions that happen onsite at steel plants and affect local communities near these plants. To provide a sense of scale, we have also compared the global steel industry's criteria air pollutants emissions with EU-27's total emissions in 2019 in Figure ES1. The SO_2 emissions from the global steel industry in 2019 were 300% higher than the overall total SO_2 emissions of the entire EU-27 region. Emissions of NOx from the global steel industry were 63% lower than the EU-27's overall NOx emissions in 2019. The PM emissions of the global steel industry were 3% higher than the overall PM emissions from the EU-27 region in 2019. The NMVOC emissions from the global steel industry in 2019 were 91% lower than NMVOC emissions from EU-27 region.

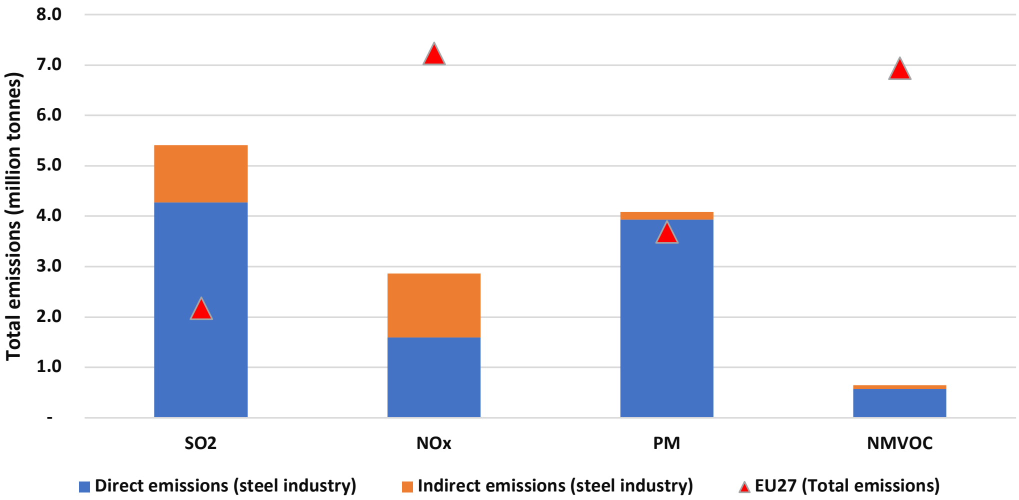

Figure ES1. Global steel industry's criteria air pollutants emissions compared with EU-27's total emissions in 2019 (source: this study, CEIP 2021).

Steel industries from Ukraine, China and Russia have the highest emission intensities for almost all criteria air pollutants analyzed in this study. Steel industries from the United States, Sweden, Belgium and Austria have the lowest emission intensities for most criteria air pollutants. This can be primarily explained by the share of electric arc furnace (EAF) steelmaking in countries, fuel mix of the steel industry and uptake of pollution control technologies. Figure ES2 shows SO_2 emissions intensity of steel industry for countries studied in 2019. Similar figures for NOx, PM, and NMVOC emissions can be found in chapter 4 of the report. Other factors influencing criteria air pollutants emissions in the steel industry are explained in chapter 5 of this report.

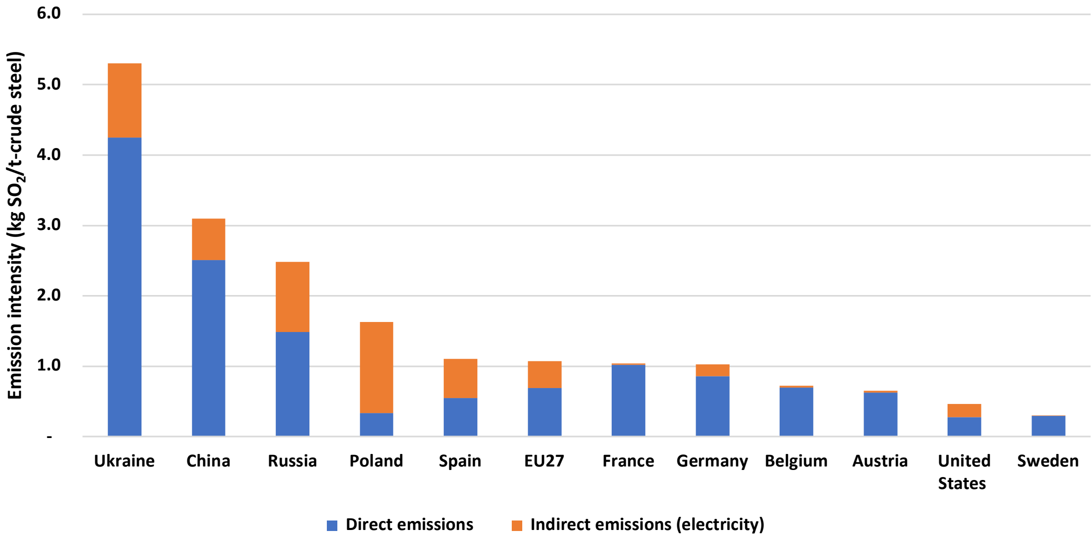

Figure ES2. SO_2 emissions intensity of the steel industry in countries studied in 2019.

Industrial manufacturing facilities such as steel plants are often located close to low-income, disadvantaged communities exposing them to significant pollution. For example, in the United States, manufacturing generated 89% of all chemical waste in the country including 285 thousand tons of criteria air pollutants and over 40 thousand tons of hazardous waste from cement production according to Toxics Release Inventory data maintained by the United States Environmental Protection Agency. Lowering or eliminating criteria air pollutants can help mitigate the health risk and improve the quality of life for the communities located close to steel plants.

In view of the projected continuing increase in absolute steel production and the need for reduction in pollution emissions, future reductions in criteria air pollutant emissions will require a combination of adoption of pollution control technologies in steel plants as well as in the power sector, efficiency improvement for fuel consumption and electrification of the steel industry. Stricter air pollution control regulations and their enforcement for the steel industry are needed in China and other countries with high criteria air pollutant intensities to ensure the reduction of these emissions from the steel industry in these countries. This will result in cleaner and safer air for the people and the environment in these countries.

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1 Introduction

Iron and steel manufacturing is one of the most energy-intensive industries worldwide. The global steel industry emitted around 3.6 billion tons of CO_2 in 2019 (Hasanbeigi 2022). Steel production typically involves processing of raw materials that contain heavy metals and cause dust emissions. The steel industry globally depends on fossil fuels and especially use of coal as the primary fuel. All the aforementioned factors lead to steel production being one of the major air polluting industries. The present report mainly focuses on comparing the criteria air pollutants[1] emission intensities for the steel industry in selected countries and regions.

The six most common criteria air pollutants emitted from the iron and steel industry include; Sulfur dioxide (SO_2; acidic gaseous pollutant), Nitrous oxides (NOx; acidic gaseous pollutant), Carbon monoxide (CO; result of incomplete combustion), Non-methane organic volatile compounds (NMVOCs; ground level ozone[2] precursors), Lead (Pb; toxic heavy metals) and Particulate matter (PM) (US EPA, 2021). Air pollution contributes to a wide variety of adverse health effects. The U.S. EPA (2015) provides a brief description of health effects that have been associated with each of the criteria pollutants.

The major sources of these emissions during the steelmaking process are produced in the Coke oven, sinter plant and the blast furnace. Combustion also accounts for part of these overall emissions. SO_2, NOx and PM are demonstrated to be major conventional air pollutants in the manufacturing of iron and steel.

The world's steel demand is projected to increase from 1,880 Mt in 2020 to up to 2,500 Mt in 2050. (IEA, 2020). India will lead the production growth and Africa and the Middle East are the other two regions with the highest projected growth rate in steel production over this period (IEA, 2020). This significant increase in steel consumption and production will drive a significant increase in the industry's criteria air pollutant emissions in the absence of substantial effort in abating these emissions. Figure 1 shows a simplified flow diagram of steel production using Blast Furnace (BF) – Basic Oxygen Furnace BOF, Direct Reduced Iron (DRI)- Electric Arc Furnace (EAF) and scrap-EAF production routes.

Iron ore is chemically reduced to produce steel by one of these three process routes: BF/BOF, smelting reduction, or direct reduction. Steel is also produced by direct melting of scrap in an EAF. BF-BOF and EAF production routes are the most common today. In 2020, the BF-BOF production route accounted for approximately 72% of the crude steel manufactured worldwide, and EAF production accounted for approximately 28% (Worldsteel 2021). Iron and steel can be produced at separate facilities or in an integrated steel mill, where the iron ore is reduced into pig iron/hot metal or direct reduced iron (DRI) and then processed into steel at the same site.

1 Criteria Air Pollutants means an air pollutant for which acceptable levels of exposure can be determined and for which an ambient air quality standard has been set.

2 Ozone itself is not emitted. According to EPA: "Tropospheric, or ground level ozone, is not emitted directly into the air, but is created by chemical reactions between oxides of nitrogen (NOx) and volatile organic compounds (VOC). This happens when pollutants emitted by cars, power plants, industrial boilers, refineries, chemical plants, and other sources chemically react in the presence of sunlight." (US EPA 2022).

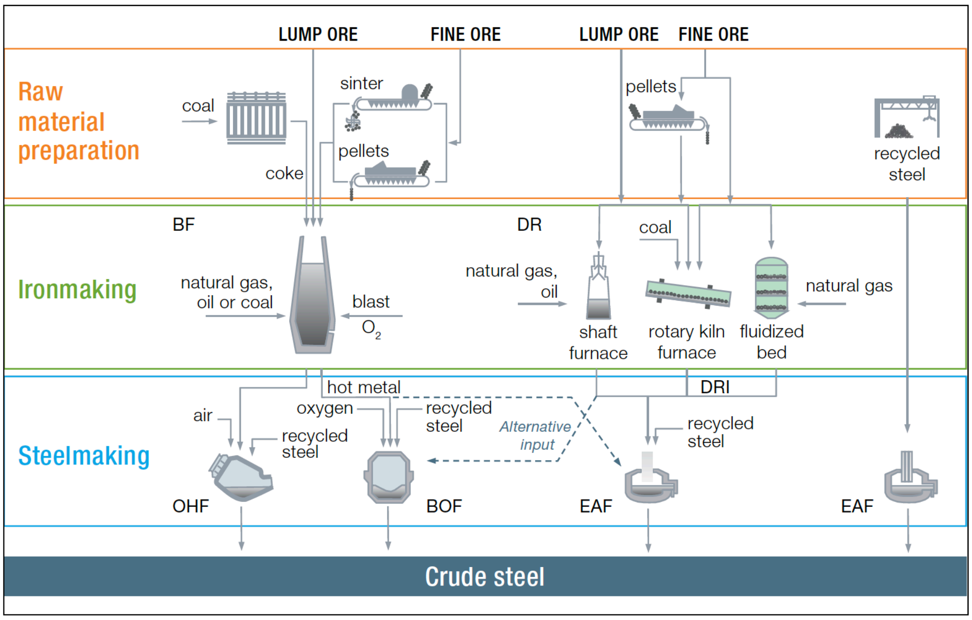

Figure 1. Crude steel production routes (Worldsteel 2019).

According to estimates based on typical criteria air pollutants emissions factors (EEA, 2019), the sintering process is responsible for approximately 90% of SO_2 emissions and over 50% of NOx emissions. As a result, sintering is the largest contributor to air pollution during the BF/BOF steel manufacturing process. Steel manufacturing via electric arc furnace produces substantially lower quantities of criteria air pollutants (EEA, 2019) due to the elimination of sintering, coking, and BF processes as well as use of electricity instead of fossil fuels for the most energy-intensive step within steel manufacturing.

The emission control mechanisms for the pollutants vary by country and depend on their environmental policies. Limited information is available about the penetration of pollution control technologies implemented in steel manufacturing plants in the countries included in this report. However, evidence of steel manufacturing establishments implementing technologies like wet scrubbers, electrostatic precipitators, cyclone cleaners, fabric filters, etc. can be found (EEA, 2019).

In this study, we have conducted benchmarking for four of the six major criteria air pollutants (SO_2, NOx, PM and NMVOC) emitted from the iron and steel industry in 12 steel producing countries/regions. The countries studied represent about 73% of the world's steel production in 2019. The study methodology compares emission intensities for criteria air pollutants (kg/t-crude steel) of the entire steel industry for each country. Since we did not find adequate and reliable data for carbon monoxide (CO) and lead (Pb), these two criteria air pollutants are not included in this study. We have considered both direct and indirect sources of emissions i.e., onsite emissions related to process and fuel combustion in steel plants (direct emissions) and offsite emissions associated with electricity use by steel plants that is caused due to electricity generation in the power sector (indirect emissions). Emissions related to the rest of the steel value chain are beyond the scope of this project.

1.1. Adverse health effects of criteria air pollutants

Air pollution contributes to a wide variety of adverse health effects. The U.S. EPA (2015) provides a brief description of health effects that have been associated with each of the criteria pollutants some of which are listed below:

•**Particulate Matter (PM):** Effects associated with exposures to both $PM_{2.5}$ and $PM_{10-2.5}$ include premature mortality, aggravation of respiratory and cardiovascular disease, and changes in sub-clinical indicators of respiratory and cardiac function. Such health effects have been associated with short- and/or long-term exposure to PM. Exposures to $PM_{2.5}$ are also associated with decreased lung function growth, exacerbation of allergic symptoms, and increased respiratory symptoms (U.S. EPA 2015).

•**Sulfur Dioxide (SO_2):** People with asthma are especially susceptible to the effects of SO_2. Short-term exposures of asthmatic individuals to elevated levels of SO_2 while exercising at a moderate level may result in breathing difficulties, accompanied by symptoms such as wheezing, chest tightness, or shortness of breath. Studies also provide consistent evidence of an association between short-term SO_2 exposures and increased respiratory symptoms in children, especially those with asthma or chronic respiratory symptoms. Short-term exposures to SO_2 have also been associated with respiratory-related emergency department visits and hospital admissions, particularly for children and older adults (U.S. EPA 2015).

•**Nitrogen Dioxide (NOx):** Exposure to NOx has been associated with a variety of health effects, including respiratory symptoms, especially among asthmatic children, and respiratory-related emergency department visits and hospital admissions, particularly for children and older adults (U.S. EPA 2015).

•**Ground-level ozone (O_3):** Ground-level ozone, is not emitted directly into the air, but is created by chemical reactions between oxides of nitrogen (NOx) and volatile organic compounds (VOC). Exposure to ground-level ozone can cause a variety of respiratory health effects, including inflammation of the lining of the lungs, reduced lung function, and respiratory symptoms such as cough, wheezing, chest pain, burning in the chest, and shortness of breath. Ozone exposure can decrease the capacity to perform exercise. Exposure to ozone can also increase susceptibility to respiratory infection. Exposure to ambient concentrations of ozone has been associated with the aggravation of respiratory illnesses such as asthma, emphysema, and bronchitis, leading to increased use of medication, absences from school, doctor and emergency department visits, and hospital admissions. Short-term exposure to ozone is associated with premature mortality. Studies have also found that long-term ozone exposure may contribute to the development of asthma, especially among children with certain genetic susceptibilities and children who frequently exercise outdoors. Long-term exposure to ozone can permanently damage lung tissue (U.S. EPA 2015).

•**Lead (Pb):** Lead accumulates in bones, blood, and soft tissues of the body. Exposure to lead can affect development of the central nervous system in young children, resulting in neurodevelopmental effects such as lowered IQ and behavioral problems (U.S. EPA 2015).

•**Carbon Monoxide (CO):** Exposure to CO reduces the capacity of the blood to carry oxygen, thereby decreasing the supply of oxygen to tissues and organs such as the heart. People with several types of heart disease already have a reduced capacity for pumping oxygenated blood to the heart, which can cause them to experience myocardial ischemia (reduced oxygen to the heart), often accompanied by chest pain (angina), when exercising or under increased stress. For these people, short-term CO exposure further affects their body's already compromised ability to respond to the increased oxygen demands of exercise or exertion. Thus, people with angina or heart disease are identified as at greatest risk from ambient CO. Other potentially at-risk populations include those with chronic obstructive pulmonary disease, anemia, diabetes, and those in prenatal or elderly life stages (U.S. EPA 2015).

Industrial manufacturing facilities such as steel plants are often located close to low-income, disadvantaged communities exposing them to significant pollution. The air pollution has a disproportionate effect on communities of color in the United States. The average exposure to industrial air toxins among low-income African Americans is 47% higher than that of low-income whites (Political Economic Research Institute, 2014). Communities of color are not only more likely to be exposed to industrial air pollution, but also less likely to reap the economic benefits of good manufacturing jobs. One study found that African Americans and Hispanics in communities neighboring industrial facilities receive 33% of the pollution exposure from those facilities, but just 21% of total jobs (PNAS, 2018).

2 Global Steel Production and Trade

World steel production has more than doubled between 2000 and 2020 (Figure 2). In 2020, China accounted for 53% of global steel production while its share was only 15% in 2000. The 2008 drop in world steel production was because of the global economic recession. The 2014 drop was mainly caused by a slowdown in the Chinese economy and chronic overcapacity, which resulted in shutting down illegal induction furnaces and old steel plants in China. In 2020, global crude steel production decreased by about one percent because of the global COVID 19 pandemic.

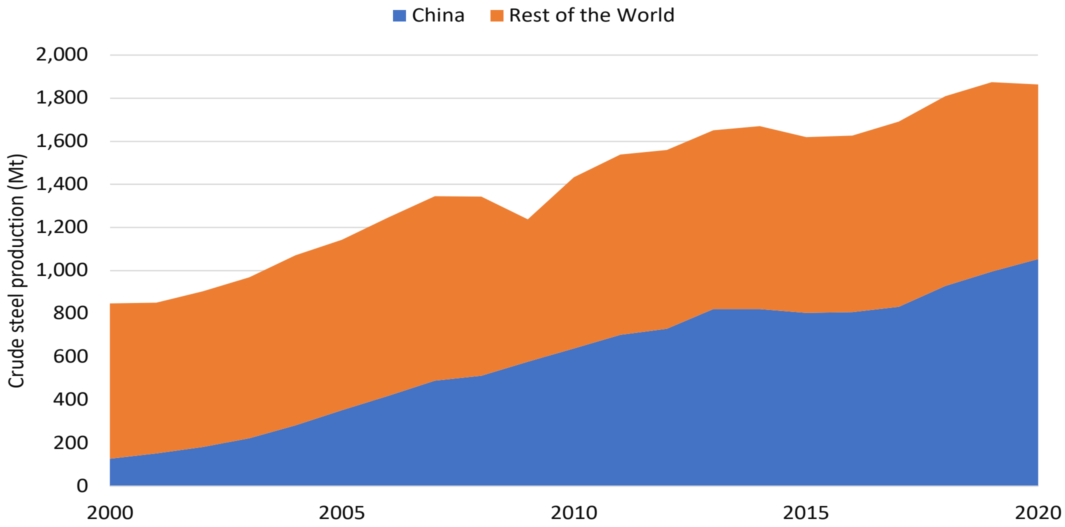

Figure 2. Crude steel production in China and rest of the world, 2000-2020 (Worldsteel 2020, 2021).

In 2020, blast furnace (BF)/basic oxygen furnace (BOF) production accounted for approximately 72% of the steel manufactured worldwide, and electric arc furnace (EAF) production accounted for approximately 28% of global steel production (Worldsteel 2021). Figure 3 shows the top 10 steel producing countries in the world. In 2020, these top 10 producing countries accounted for 86% of world steel production (Worldsteel 2021).

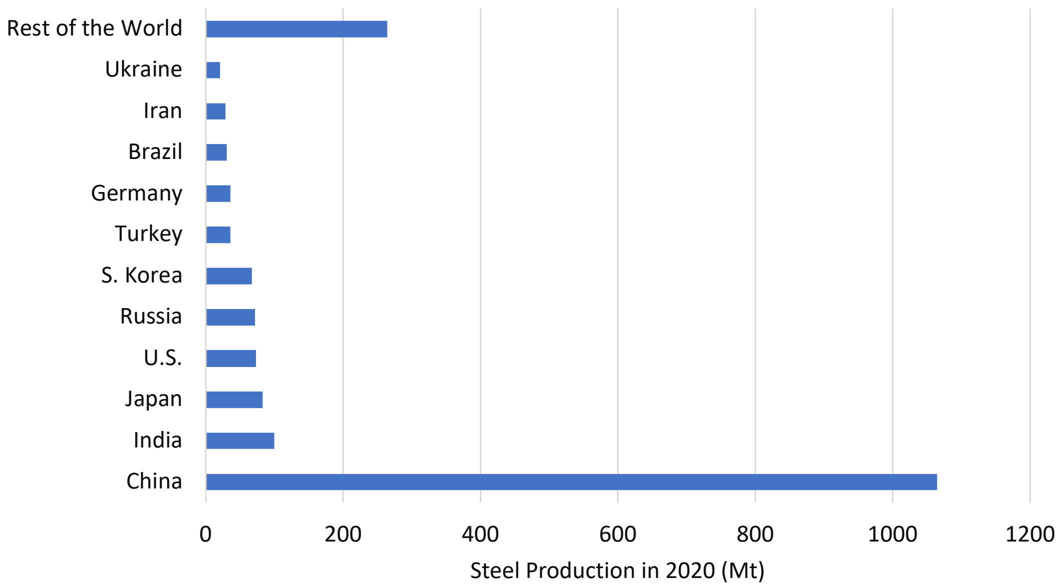

Figure 3. Top 10 steel producing countries in 2020 (Worldsteel 2021).

The top 20 exporting countries account for over 90% of total world steel exports. According to Worldsteel (2021), Russia, Japan, South Korea, Ukraine and China are top five net exporters (export minus import) and the U.S., Thailand, EU, Philippines, and Vietnam are top five net importers (import minus export) of steel in 2020. The significant global trade of such a carbon-intensive commodity has substantial implications for the embodied carbon in traded steel as shown in our recent study (Hasanbeigi et al. 2018). This embodied carbon in traded steel often is not accounted for in national and international carbon accounting and climate policies.

Table 1. Top 20 net exporters and importers of steel in 2020 (Worldsteel 2021)

Rank	Net exports (exports-imports)	Mt
1	Russia	26.4
2	Japan	24.8
3	South korea	16.1
4	Ukrain	13.9
5	China	13.5
6	India	12.1
7	Brazil	8.7
8	Turkey	6.0
9	Egypt	4.2
10	Germany (2)	3.0
11	Taiwan, China	2.7
12	Austria (2)	2.6
13	Malaysia	2.6
14	Belgium (2)	2.5
15	Oman	1.8

Rank	Net exports (imports-exports)	Mt
1	United states	13.6
2	Thailand	11.9
3	European Union (28) (1)	10.0
4	Philippines	6.6
5	Vietnam	6.0
6	Saudi Arabia	5.7
7	Poland (2)	5.6
8	Mexico	4.5
9	Indonesia	4.2
10	Israel	3.3
11	Bangladesh	2.5
12	Myanmar	2.5
13	Uzbekistan	2.5
14	Pakistan	2.3
15	Kenya	2.2

(1) Excluding intra-regional trade
(2) Data for individual European Union (28) countries include intra-European trade

3 Global Steel Industry's Criteria Air Pollutants Emissions

3.1. Sources of criteria air pollutants emissions in the steel industry

Various criteria air pollutants are emitted during each process step involved in steel manufacturing accompanied by the emissions due to fuel combustions. The following sections briefly discuss the sources of these criteria air pollutants during the steel manufacturing process.

Sinter plants account for more than 90% of the SO_2 emissions along with over 50% of NOx emissions from the steel industry mostly as a result of fuel consumption. Blast furnaces (BFs) account for approximately half of the PM emissions from the steel industry, followed by the sintering process, basic oxygen furnace (BOF), and electric arc furnace (EAF).

Emissions from sintering

Emissions from sinter plants are generated from the raw material handling, windbox exhaust, discharge end (associated sinter crushers and hot screens), cooler, and cold screen processes. The windbox exhaust is the primary source of particulate emissions, mainly iron oxides, sulfur oxides, carbonaceous compounds, aliphatic hydrocarbons, and chlorides. At the discharge end, emissions are mainly iron and calcium oxides. The SO_2 emissions from sinter plants mainly originate from the combustion of sulfur compounds in sinter feed such as coke breeze. NOx emissions are mainly caused by combustion of organic nitrogen compounds in sinter feed, reaction of decomposing components with molecular nitrogen, and reaction of molecular N_2 with molecular O_2 (European Commission, 2013). Sinter strand windbox emissions commonly are controlled by cyclone cleaners followed by a dry or wet electrostatic precipitator, high pressure drop wet scrubber, or bag filters (U.S. EPA 2009).

Emissions from coke making

Coke oven emissions are complex mixtures of solid, liquid, and gaseous pollutants. The three main sources of emissions from the coke oven are direct emissions from stack for the off gases, diffused emissions that occur during regular operations such as coke and coal handling and quenching and fugitive emissions occurring through irregularities such as leakages at oven doors (European Commission, 2013). Pushing of coke in the quenching car is the significant source of PM emissions. PM is also emitted during coke unloading, crushing, mixing, screening as well as through fugitive emissions via oven leakages. A majority of VOCs (including NMVOCs) are emitted as fugitive emissions from door leakages. Coke oven leaks are also responsible for NOx, SO_2 and CO emissions. SO_2 emissions are substantially high if non-desulfurized coke oven gas is consumed for the coke making. Emissions from coke making are commonly controlled by periodic repairs and maintenance practices to eliminate leaks. PM emissions are controlled by techniques like wet suppression and hooded quench cars during the initial coke handling and pushing. Stack emissions are controlled by the implementation of ESPs or Baghouse filters. Quenching towers are typically fitted with baffles to curtail the emissions of entrained PM. SO_2 emissions are controlled by desulfurizing the coke oven gas (U.S.EPA 2009)

Emissions from a blast furnace

Significant emissions occur from the blast furnace process. Because of the high input of reducing agents (mainly coke and coal), this process consumes most of the overall energy input of an integrated primary steel plant (European Commission, 2013). The primary source of blast furnace emissions is the casting operation. Particulate emissions are generated when the molten iron and slag contact air above their surface. Casting emissions also are generated by drilling and plugging the taphole. The occasional use of an oxygen lance to open a clogged taphole can cause heavy emissions. During the casting operation, iron oxides, magnesium oxide, and carbonaceous compounds are generated as particulate. Casting emissions at existing blast furnaces are controlled by evacuation through retrofitted capture hoods to a gas cleaner, or by suppression techniques. Emissions controlled by hoods and an evacuation system are usually vented to a bag filter. Another potential source of emissions is the blast furnace top (U.S. EPA 2009).

Emissions from a basic oxygen furnace

Emissions from various sources such as primary and secondary dedusting, hot metal pretreatment and secondary steelmaking, and various solid process residues are the main environmental issues in BOF steelmaking (European Commission, 2013). The most significant emissions from the BOF process occur during the oxygen blow period. The predominant compounds emitted are iron oxides, although heavy metals and fluorides are usually present. Charging emissions will vary with the quality and quantity of scrap metal charged to the furnace and with the pour rate. Tapping emissions include iron oxides, sulfur oxides, and other metallic oxides, depending on the grade of scrap used. Hot metal transfer emissions are mostly iron oxides. Basic oxygen furnaces are equipped with a primary hood capture system located directly over the open mouth of the furnaces to control emissions during oxygen blow periods (U.S. EPA 2009).

Emissions from an electric arc furnace

The air emissions from EAF furnaces consist of a wide range of inorganic compounds (iron oxide dust and heavy metals) and organic compounds such as persistent organic pollutants such as polychlorinated biphenyls (PCBs) and dibenzofurans (PCDD/F) (European Commission 2013). The operations which generate emissions during the electric arc furnace steelmaking process are melting and refining, charging scrap, tapping steel, and dumping slag. Iron oxide is the predominant constituent of the particulate emitted during melting. During refining, the primary particulate compound emitted is calcium oxide from the slag. Emissions from charging scrap are difficult to quantify, because they depend on the grade of scrap utilized. Scrap emissions usually contain iron and other metallic oxides from alloys in the scrap metal. Iron oxides and oxides from the fluxes are the primary constituents of the slag emissions. During tapping, iron oxide is the major particulate compound emitted. Emissions control techniques involve an emissions capture system and a gas cleaning system (U.S. EPA 2009).

3.2. Global Steel Industry’s criteria air pollutants emissions

The 12 steel-producing countries/regions included in this study account for about 73% of total world steel production, 86% of BF-BOF and 58% of EAF steel production. Although the countries selected for the analysis include some of the largest steel producing countries, the country selection is also influenced by the data availability.

The four criteria air pollutants analyzed in this report together amount to a total of 13 million tonnes of emissions from the global steel industry (see Figure 4). These estimations are based on the emission intensities of criteria air pollutants for the countries analyzed in the study. A weighted average of emissions intensities of the countries analyzed in this study is assumed to represent the emissions intensities for all the countries not included in the analysis (i.e., world average intensities). The total emissions for each criteria air pollutant from the rest of the world are then estimated using the world average intensities and steel production from the rest of the world. However, this assumption inherently causes a level of uncertainty for the estimated emissions for the rest of the world.

Sulfur dioxide is the highest emitted air pollutant from the steel production process globally amongst the pollutants analyzed in this study, whereas volatile organic compounds have the lowest emissions. Approximately two thirds of criteria air pollutant emissions analyzed in this study can be characterized as direct emissions (i.e., onsite emissions from steel plants). While direct emissions represent more than 90% of PM and NMVOC emissions from the global steel industry, for SO_2 and NOx, direct emissions represent around 65% of their total respective emissions from the global steel industry in 2019. To get the perspective of order of magnitude of the global steel industry's emissions of criteria air pollutants, we compare the emissions with total criteria air pollutants emitted from the EU-27 region. The SO_2 emissions from the global steel industry in 2019 were 300% higher than the overall total SO_2 emissions of the EU-27 region. Emissions of NOx from the global steel industry were 63% lower than the EU-27's overall NOx emissions in 2019. The PM emissions of the global steel industry were 3% higher than the overall PM emissions from the EU-27 region in 2019. The NMVOC emissions from the global steel industry in 2019 were 91% lower than NMVOC emissions from the EU-27 region.

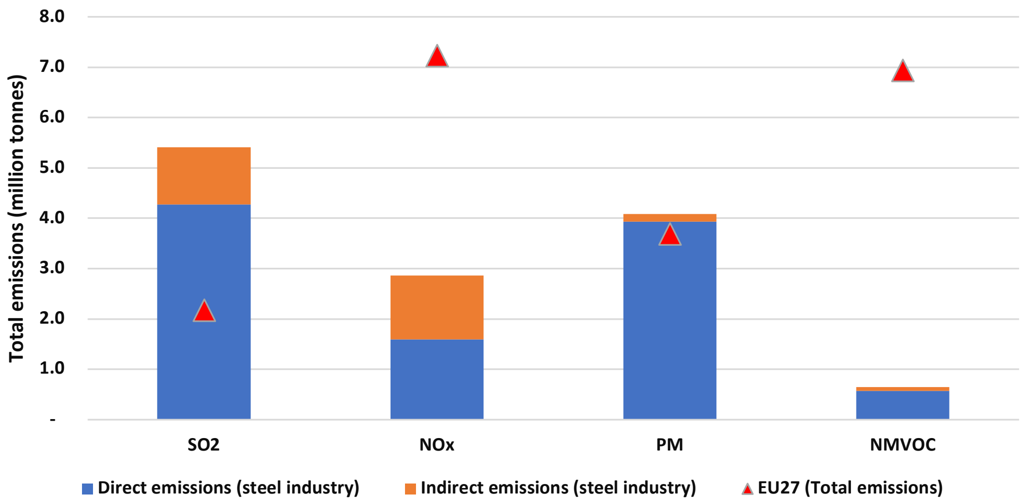

Figure 4. Global Steel industry's criteria air pollutants emissions compared with EU-27 total emissions in 2019 (source: this study, CEIP, 2021).

4 Benchmarking Criteria Air Pollutants Emissions Intensities of the Steel Industry

The aim of the international benchmarking is to offer a means of comparing the performance of a given industry across countries. Benchmarking can also be used to estimate the potential for the abatement of air pollutants through the implementation of pollution control technologies. At national level, benchmarking of criteria air pollutants emissions intensities can help policy makers prioritize emission abatement of specific criteria air pollutant and design policies for the curtailment of their emissions.

The following sections present the results of benchmarking analysis for 12 countries and four criteria air pollutants (SO_2, NOx, PM, and NMVOC) emitted from the steel industry (direct and indirect emissions). Countries included in this study represent about 73% of total steel production for the year 2021.

For this study, we compared the emissions intensity of criteria air pollutants arising from processes and fuel combustion (onsite i.e., direct emissions) and electricity consumption (offsite i.e., indirect emissions) in the steel industry. Direct emission intensities are estimated using the emissions of criteria air pollutants reported in the respective national air pollution inventories, whereas indirect emission intensities are based on the criteria air pollutant emission factors estimated for the electricity generation and the electricity consumption intensities for steel production of the countries included in this study (detailed methodology presented in the Appendix 1).

4.1. Benchmarking of SO_2 emissions intensity

Figure 5 below presents emissions intensity for SO_2 during crude steel production. A large variation in SO_2 emission intensities can be observed. The steel production in Ukraine is the most SO_2 intensive amongst the countries included in this study. This could be because of the low share of EAF steelmaking (7.4%, World steel 2019) in addition to relatively large shares of coal in the fuel mix of iron and steel production processes (56%, IEA 2021) as well as for electricity generation (35%, IEA 2021). The United States, Austria, and Sweden have the lowest SO_2 emissions intensity amongst the countries included in the benchmarking study. As a result of the low emissions intensity of grid electricity used for steel production (Figure 6), almost all the SO_2 emissions from steel production in France, Belgium, Austria and Sweden can be attributed to direct emissions. On the other hand, power sectors in Poland, Spain, and Russia have relatively higher intensities of SO_2 emissions consequently resulting in larger shares of indirect SO_2 emissions from steel production for the countries included in this study.

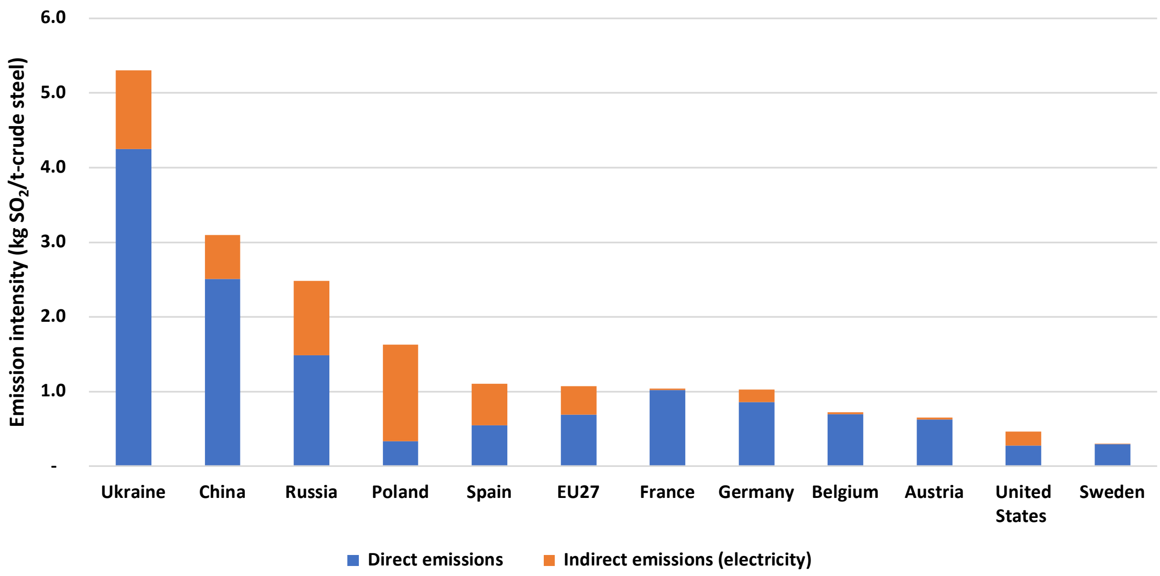

Figure 5. SO_2 emissions intensity of the steel industry in countries studied in 2019.

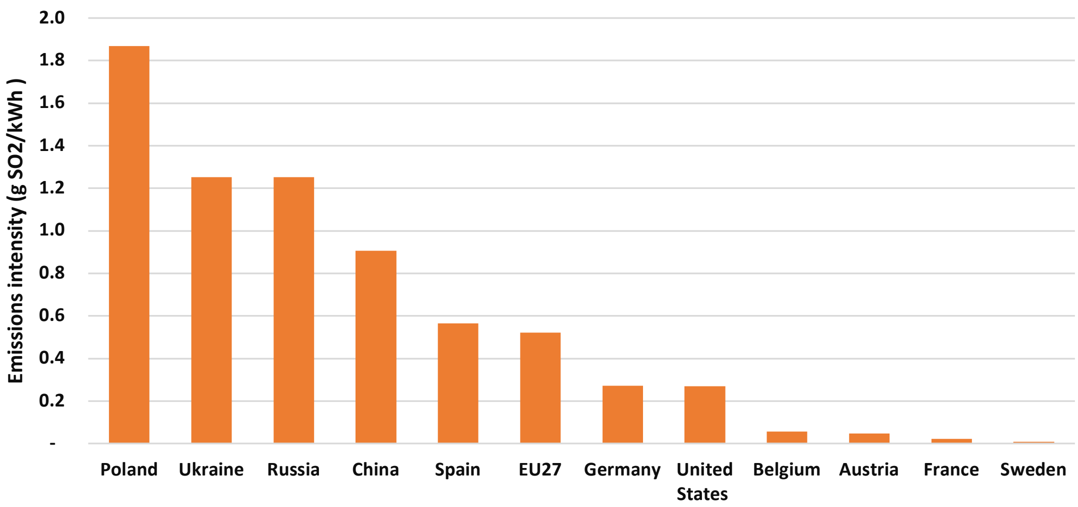

Figure 6. SO_2 emissions intensity of power sector in countries studied in 2019.

4.2. Benchmarking of NOx emissions intensity

Figure 7 shows the NOx emissions intensity for the steel industry in countries studied. Similar to SO_2 emission intensities, a large variation can be observed for the NOx emission intensities. Russia, Ukraine and China have the highest NO_x emission intensities amongst the countries analyzed in this report. However, because of high NOx emission intensities from the power sector (Figure 8), Russia and Ukraine have relatively larger shares of indirect emissions. Sweden has the lowest share of indirect NOx emissions for steel production along with the lowest NOx emissions intensity amongst the countries analyzed in this study.

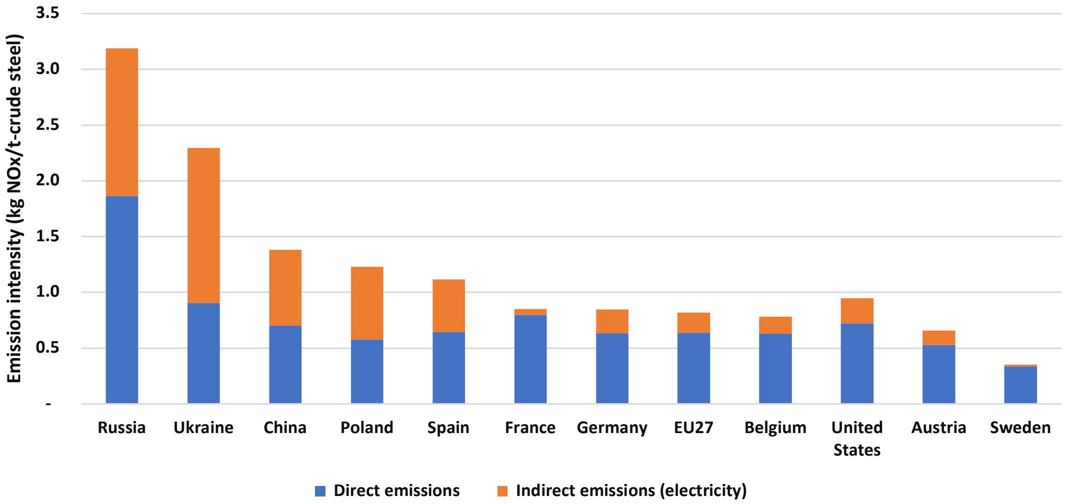

Figure 7. NOx emissions intensity of the steel industry in countries studied in 2019.

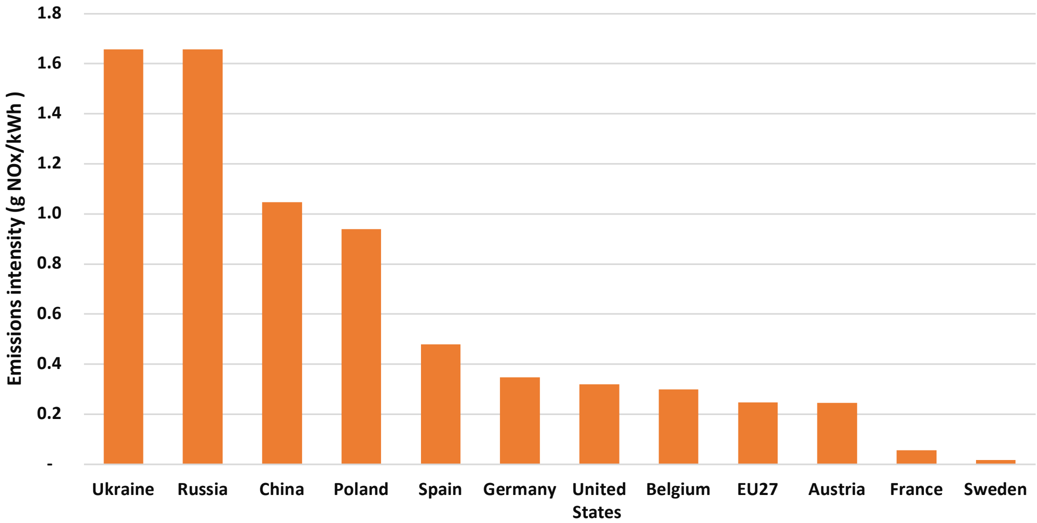

Figure 8. NOx emissions intensity of power sector in countries studied in 2019.

4.3. Benchmarking of PM emissions intensity

A majority of particulate matter arising from steel manufacturing can be attributed to direct emissions for the countries included in this study (see Figure 9). Steel production in China has the highest particulate emissions intensity. This can be partially explained by the fact that the vast majority of steel production in China takes place via the BF/BOF production route (90%, Worldsteel, 2020). Based on the typical emission factors for steel production technologies estimated for the particulate matter emission inventory program (Visschedijk et al., 2004), steel production via BF/BOF production route can cause substantially higher emissions of PM as compared to production via EAF. China is followed by Ukraine and Russia which have relatively low shares of steel production via BF/BOF production route. Steel manufacturing in Poland has approximately 46% share of EAF (WorldSteel,2021) and highest intensity of PM emissions from the power sector (Figure 10) resulting in Poland having the highest share of indirect PM emissions. As a result of implementation of PM control technologies (electro filter and wet scrubbers) in both of their steel manufacturing plants (Environment Agency Austria, 2021), Austria has the lowest intensity for the PM emissions despite having a structure similar to that of China's steel manufacturing sector.

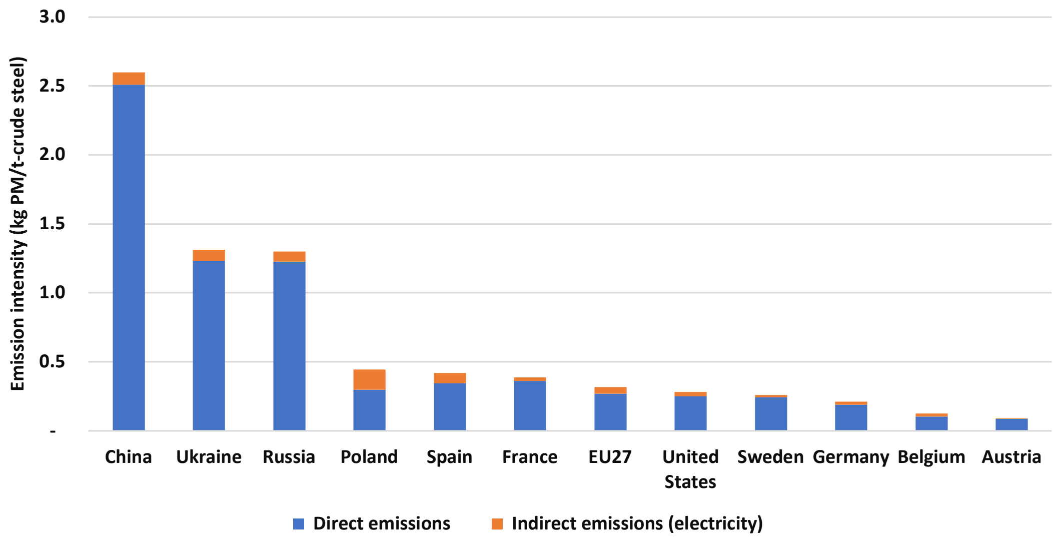

Figure 9. PM emissions intensity of the steel industry in countries studied in 2019.

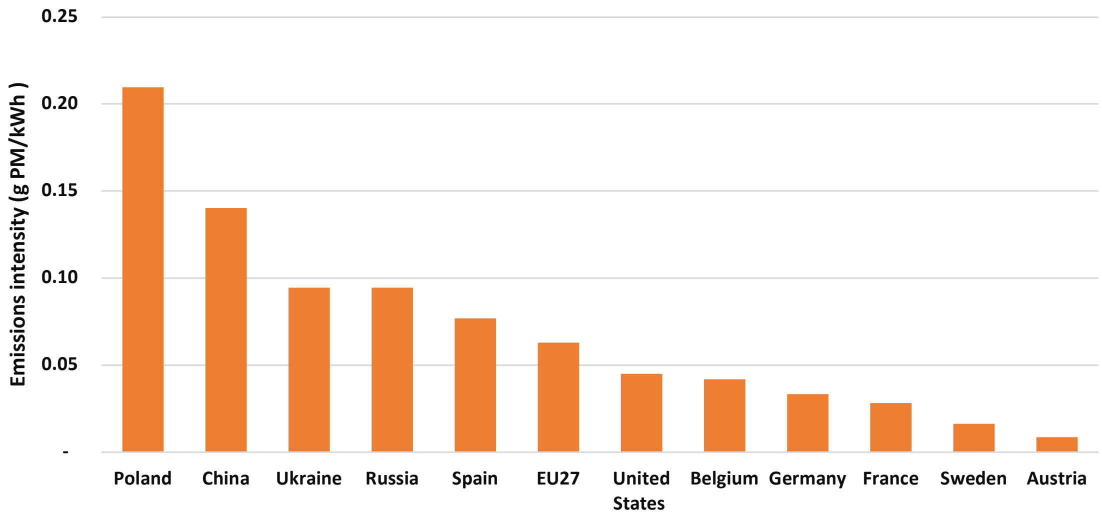

Figure 10. PM emissions intensity of power sector in countries studied in 2019.

4.4. Benchmarking of NMVOC emissions intensity

Non-methane volatile organic compounds (NMVOC) is the lowest emitted for both direct and indirect emissions as compared to the other three criteria air pollutants included in this analysis. Ukraine and China have the highest intensity for the NMVOC emissions (see Figure 11). This is due to the relatively larger share of steel production via the BF/BOF route, and the large share of coal used in the steel industry in these two countries. Spain, Belgium, and Sweden on the other hand have lowest intensities for NMVOC emissions. Despite having overall low emissions intensities, due to relatively higher emissions intensity of NMVOC from the power sector (Figure 12), larger shares of emissions from steel manufacturing in Belgium and Spain can be characterized as indirect emissions.

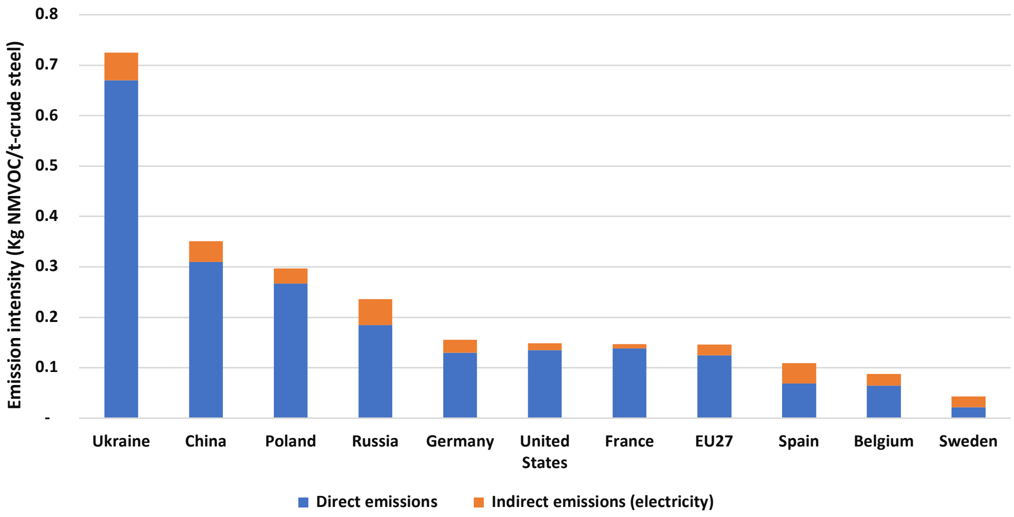

Figure 11. NMVOC emissions intensity of power sector in different countries in countries studied in 2019.

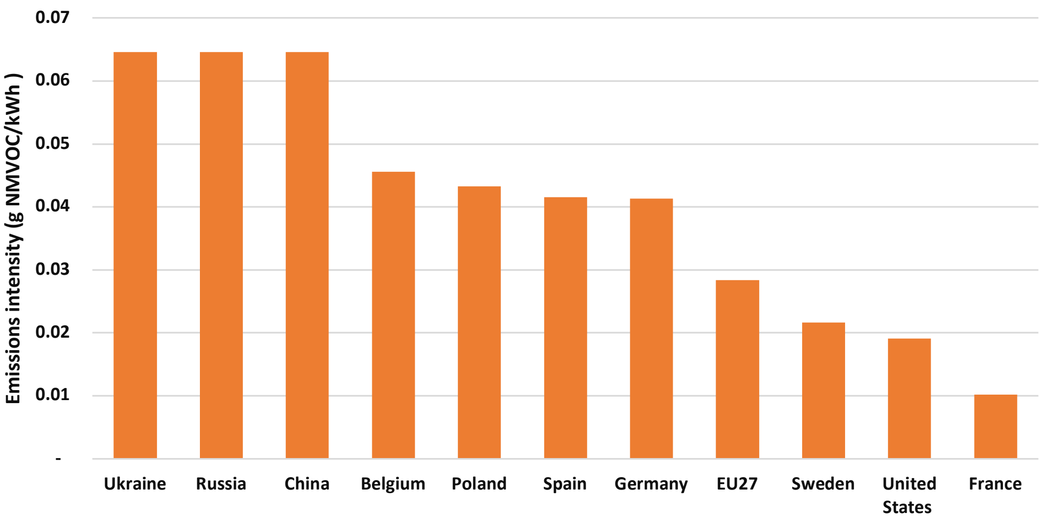

Figure 12. NMVOC emissions intensity of power sector in countries studied in 2019.

5 Key Factors Influencing Criteria air Pollutant Emissions from the Steel Industry

In this sub-section we discuss the following ten factors that could explain why the steel industry's criteria air pollutant emissions intensity values differ among the countries:

1) The level of penetration of pollution control technologies
2) The share of EAF steel in total steel production
3) The fuel mix in the iron and steel industry
4) The electricity grid criteria air pollutant emissions factor
5) The type of feedstock and fuels
6) The steel product mix in each country
7) Share of sintering Vs pelletization
8) Capacity utilization
9) Environmental regulations
10) Cost of energy and raw materials

While a combination of several factors can explain variations in criteria air pollutant emission intensities of the steel industry across countries, some factors have larger impacts than others. It is often difficult to quantify the impact of each factor on the total criteria air pollutant emissions intensity of steel production across different countries. Nonetheless, even a qualitative discussion of these influencing factors can help the reader to better understand the reasons behind variations in criteria air pollutant emissions intensity among the countries studied.

The level of penetration of pollution control technologies

Data on penetration of pollution control technologies in the countries included in this study is very limited. The level of information available for these countries differs, so direct comparison of the penetration of certain technologies is not possible. One direct comparison that is possible is the share of EAFs, which was used to explain some of the variation observed in the emission intensities. Some of the commercially available pollution control technologies include electro filters (99% capture efficiency), fabric filters (99% capture efficiency), wet scrubbers (99% capture efficiency), and Electrostatic precipitator (96% capture efficiency) (EEA, 2019).

The share of EAF steel in total steel production

The structure of the steel manufacturing sector is one of several factors that explains the difference in criteria air pollutant emissions intensity. EAF is a secondary steel production process that primarily uses steel scrap. Because it consumes electricity for its operation, EAF emits much lower amounts of criteria air pollutants related to fuel consumption such as NOx and SO_2 as compared to BF/BOF production route. Steel production via EAF completely eliminates the criteria air pollutants emissions related to sintering, coking, and BF processes. In other words, the higher share of EAF production can help to reduce the overall emissions intensity of fuel combustion related criteria air pollutants for the steel industry in a country.

The fuel mix in the iron and steel industry

The share of different fuels used in the iron and steel industry in the countries studied is an important factor that influences the industry criteria air pollutant emissions intensity because some fuels are more polluting than others. For example, higher shares of coal used in steel production could result in much higher SO_2 emissions intensity. On the other hand, natural gas has a significantly lower emissions factor per unit of energy compared to coal and coke which are the primary types of energy used in the steel industry in many countries.

The electricity grid criteria air pollutants emissions factor

In addition to the share of fuels used directly in the iron and steel industry, the criteria air pollutants emissions factor of power generation in each country is also an important factor to explain the differences in the steel industry's criteria air pollutant emission intensities. This becomes even more important in light of the significant difference in the share of EAF steel production among countries. Because the share of EAF steel production in Spain and the U.S. is much higher than in the other countries included in this analysis, the share of steel-industry electricity use in total energy use is also higher in these countries than in the other countries. In this case, the electricity grid criteria air pollutants emissions factor in the country plays an important role when comparing the air pollutant emissions of the iron and steel industry in these countries.

The type of feedstock and fuels

Criteria air pollutant emissions depend on the feedstock used for processes like sintering and pelletizing. For example, in case of SO_2 emissions, the volatilization of sulfur depends on the basicity of sinter feed. The more the basicity, the lower the SO_2 emissions from the sintering process. Reduction in the quantity of coke breeze in the fuel can also result in lower SO_2 emissions. The grain size of coke breeze also has a substantial effect on SO_2 emissions. Coarser coke breeze results in lower SO_2 emissions. NOx emissions mainly depend on the amount of organic nitrogen present in sinter feed as well as the amount of nitrogen in the fuel consumed (European Commission, 2013).

Share of sintering vs pelletizing

Sinter and pellets both are agglomerated forms of iron ore used as blast furnace feed material. Sinter plants emit relatively larger amounts of criteria air pollutants than the pelletizing plants (Table 2). In most countries, pelletizing plants are not located at the integrated steel facility but rather at the iron ore mine site. Thus, a larger share of steel production via pelletizing will result in lower emissions of criteria air pollutants for the steel industry.

Table 2. Typical emission factors for sintering and pelletizing plants (European Commission, 2013)

	SO_2	NOx	PM	NMVOC
Sinter plant (kg/tonne sinter)	0.31 - 0.97	0.30 - 1.03	0.06 - 0.17	0.001 - 0.20
Pelletizing plant (kg/tonne pellets)	0.01 - 0.21	0.15 - 0.55	0.01 - 0.15	0 - 0.04

The steel product mix in each country

Different steel products have different fuel combustion intensities in the rolling/casting/ finishing processes. Therefore, the product mix is another key factor that could influence the criteria air pollutant intensities among countries. Worldsteel shows the differences in the production of some steel products in the studied countries (e.g., hot rolled bars, concrete reinforced bars, wire rods, hot rolled plates, tubular products, etc.) (Worldsteel, 2020).

Capacity utilization

Capacity utilization of plants also affects energy intensity, and consequently could affect the criteria air pollutant emissions intensity related to steel production. Lower capacity utilization will result in reduced process related emissions. However, inefficient consumption of fuels will lead to higher intensities for fuel combustion-related criteria air pollutant emissions. On the other hand, higher capacity utilization leads to improvement of overall energy efficiency and could help in reducing fuel-related criteria air pollutant emissions intensity.

Environmental regulations

There are differing environmental requirements from country to country. Environmental regulations can affect criteria air pollutant emissions intensity by incentivizing different operational and equipment choices. Overall, the steel industry in countries with stricter air pollution control regulations adopt more advanced air pollution control technologies that can help to reduce criteria air pollutant emissions intensity in the steel industry in those countries.

Cost of energy and raw materials

Low-cost energy and raw materials are key components of managing costs in the steel industry. Changing energy and materials sources can have a substantial effect on the emissions of criteria air pollutants and fuel consumption intensities of a plant. Also, the lower cost of energy in some countries provides fewer incentives for fuel consumption efficiency improvement and increases the payback period for efficiency projects and as a result reducing incentives for curtailment of air pollutants.

6 Conclusions

The current study presents a benchmarking analysis for each of the four major criteria air pollutants emitted from the production of steel in 12 selected steel producing countries/ regions. The countries/regions selected for this study represent about 73% of global steel production with 86% for BF/BOF production route and 56% for EAF production route. We have considered both direct and indirect sources of emissions i.e., onsite emissions related to process and fuel combustion in steel plants (direct emissions) and offsite emissions associated with electricity use by steel plants that is caused due to electricity generation in the power sector (indirect emissions). Emissions related to the rest of the steel value chain are beyond the scope of this project.

Our results show that amongst the criteria air pollutants analyzed for this study, sulfur dioxide (SO_2) is the highest emitted criteria air pollutant from the steel industry globally whereas non-methane volatile organic compounds (NMVOCs) were the lowest emitted criteria air pollutants. Although some variation can be observed amongst the countries in terms of shares of direct and indirect emissions, approximately 75% of global criteria air pollutants can be attributed to direct onsite emissions. While Ukraine, Russia and China have the highest emission intensities for most criteria air pollutants, United States, Austria, Belgium and Sweden have the lowest emission intensities for most criteria air pollutants amongst the countries analyzed for this report.

Although it is often difficult to quantify the effects of key influencing factors on the emission intensities for criteria air pollutants, the large variations that are observed for all the criteria air pollutants amongst the countries included in this report can be mainly explained with a combination of factors such as the share of EAF steel production, fuel mix used in the steel manufacturing sector as well as for the power sector and penetration level of air pollution control technologies.

The benchmarking analysis presented in this study thus provides points of comparison to assess the performance of steel manufacturing in terms of air pollution caused by criteria air pollutants across countries. This comparison can be used to estimate the potential available for the emissions reduction of criteria air pollutants. At the national level, it can help policy makers identify, prioritize, and design policies around emission abatement of specific criteria air pollutants, thus helping improve health and quality of life for the low-income, disadvantaged communities that are frequently located close to industrial plants.

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Appendices

Appendix 1. Methodology

For this study, we have conducted benchmarking of the four major criteria air pollutants emissions intensity released from steel manufacturing sites as well as released from the power sector as result of electricity consumption for steel manufacturing. The emissions intensities of criteria air pollutants are estimated for 11 countries as well as the European Union. Most of the countries included in this study are among the top twenty-five steel producing countries in the world and combined accounted for about 73% of the world steel production in 2021. We used 2019 as the base year for our analysis except for the U.S., for which the latest official data available is for 2017.

A1.1. Direct onsite emissions in the steel industry

First, the criteria air pollutants emissions data for the steel industry was obtained from two major data inventories. Primarily, emissions data for the iron and steel industry from the Centre on Emission Inventories and Projections (CEIP) was used for most countries. The emissions data from the process and product use was added to the one from energy use. The CEIP was established in 2007 to provide databases and tools related to air pollutant emission inventories. Secondly, the United Nations Framework Convention on Climate Change (UNFCCC) requires its members to submit national inventory reports (NIR) as well as emissions data in the form of the Common Reporting Format (CRF) table (UNFCCC, 2022). From the CRF tables, here as well, the emissions data from the process and product use (category 2.C.1) as well as the emissions data from energy use (category 1.A.1.c) were extracted and combined to produce the total emissions data. For most countries, the data from CEIP corroborated with the CRFs and thus CEIP data was used to maintain parity as well as due to the greater detailing in the CEIP database.

For the U.S., the U.S. EPA uses the National Emissions Inventory (NEI) to estimate air emissions of criteria pollutants, criteria precursors, and hazardous air pollutants from air emissions sources and the required data was extracted from this source (USEPA, 2021). In a very few cases, a combination of sources was used for criteria air pollutants emissions data of the steel industry that resulted in more accurate intensity values (China; Wang, 2015, Hasanbeigi, 2017).

The availability of criteria air pollutants emissions data were not similar across the four criteria air pollutants studied and the 12 countries/regions included in this study. The countries included in criteria air pollutants emissions intensity results may vary across the four pollutants studied because non-comparable values were removed.

The production data for the steel industry are from World steel Stat Yearbook 2020. For the European Union, the production data from the UK was subtracted from the total given production data for the EU 28.

Next, we calculated the emissions intensity for all the criteria air pollutants after standardizing the units. The emissions intensities were obtained by dividing the emissions by the production and were reported in kg of emission/tonne of product. Finally, the emissions intensities for each criteria pollutant were graphed and compared.

The total emissions for criteria air pollutants are reported in CEIP (and CRF) using the methods outlined in the EMEP/EEA emission inventory guidebook (EEA, 2019). The countries can adopt one of the three methods suggested in the guidebook based on the granularity of data available for that country. Air pollutant reporting methods are as follows:

- Tier 1 method: This method is employed when there is a lack of detailed information about the production routes and technologies used for the given manufacturing sector. For tier 1 method, total emissions of criteria air pollutants are estimated using average emission factors for the entire manufacturing sector provided in the guidebook and the annual production.
- Tier 2 method: This method is recommended when individual criteria air pollution data from production facilities are not available but the information about production technologies employed by those facilities as well as pollution control technologies is available. EMEP/EEA emission inventory guidebook provides technology specific emission factors for all criteria air pollutants. These technology-specific emission factors along with the data for annual production using that technology are used to estimate the total annual emissions of criteria air pollutants.
- Tier 3 method: This method is used for reporting when the most detailed data for criteria air pollutants are available from the production facilities within the country.

The information of the method employed to report the air pollution data can be found in the NIRs of the respective countries. Most countries analyzed for this benchmarking study have employed Tier 3 method or a combination of Tier2 and Tier 3 method.

A1.2. Indirect emissions related to electricity use

Indirect emissions related to the electricity used in the steel industry are calculated by first estimating the emission intensities for criteria air pollutants in the power sector (kg/kWh) in each country analyzed for this study.

Total emissions for all four criteria air pollutants for the power sector (category 1.A.1.a) are obtained from Emission Database for Global Atmospheric research (EDGAR, 2022). The latest data available from this source are for the year 2015. Therefore, emissions intensities for each air pollutant are estimated based on the electricity generation data (kg/kWh) from the years 2010 and 2015 and the trend of this five years (2010-2015) was used to extrapolate the intensities until the year 2019. Electricity generation data for the countries selected in this study were obtained from IEA (IEA 2021).

Emissions intensities for criteria air pollutants for electricity generation are then combined with the electricity consumption intensities (kWh/tonne of crude steel) for the steel industry in each of the countries included in this study. Electricity consumption intensities for steel industry in the countries included in this analysis are obtained from a combination of sources (ODYSSEE-MURE database, 2021; Hasanbeigi, 2019; Hasanbeigi, 2017).