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Steel Climate Impact

An International Benchmarking of Energy and CO_2 Intensities

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Foreword by the author

This report is an update to our previous report titled "How Clean is the U.S. Steel Industry? An International Benchmarking of Energy and CO_2 Intensities". In the previous report the energy and CO_2 intensities were calculated using 2016 data. In this report, the intensities are calculated using 2019 data. The energy and CO_2 intensities presented in this report might be different from the previous report not only because a different base year is use, but also because different sources of primary data as well as refined analysis and assumptions are used in this new update. These changes are explained in detail in chapter 4 as well as the methodology section. *It should be noted that the purpose of this update was not trend analysis but to refine the data and method used in our previous analysis based on the latest information available.*

Acknowledgments

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Executive Summary

The iron and steel industry accounts for around 7% of global greenhouse gas (GHG) emissions and 11% of global carbon dioxide (CO_2) emissions. Global steel production has more than doubled between 2000 and 2020. China accounted for 53% of global steel production in 2020. Under the current policy and technology regime, the energy use and GHG emissions of the steel industry is likely to continue increasing because the increased demand for steel, particularly in developing countries, is outpacing the incremental decreases in the energy and CO_2 emissions intensity of steel production happening.

International benchmarking of energy intensity and CO_2 emissions intensity can provide a comparison point against which a company or industry's performance can be measured to that of the same type of company or industry in other countries. Benchmarking can also be used for assessing the energy and emissions improvement potential that could be achieved by the implementation of energy efficiency or CO_2 reduction measures. Also, on a national level, policy makers can use benchmarking to prioritize energy saving and decarbonization options and to design policies to reduce energy and GHG emissions.

In this study we conducted a benchmarking analysis for energy and CO_2 emissions intensities of the steel industry among the largest steel-producing countries. Because of the difference in the composition of the steel industry across countries and the variation in the share of electric arc furnace (EAF) steel production, a single intensity value for the overall steel industry is not a good indicator of efficiency of the steel industry in a country. Therefore, in addition to calculating CO_2 intensities for the entire steel industry, we also calculated separately the CO_2 intensities associated with the EAF and blast furnace–basic oxygen furnace (BF-BOF) production routes in each country.

> The iron and steel industry worldwide accounts for around a 11% of global CO_2 emissions.

Our results show that when looking at the entire steel industry, Italy, U.S., and Turkey have the lowest and Ukraine, India, and China have the highest CO_2 emissions intensities among the countries/region studied. Among several reasons, this is primarily because of a significantly higher share of EAF steel production in total steel production in Italy, U.S., and Turkey. Figures ES1 shows the CO_2 emissions intensities for the steel production for the 16 countries/region studied.

Some key factors that could explain why the steel industry's energy and CO_2 emissions intensity values differ among the countries are: the share of EAF steel in total steel production, the fuel mix in the iron and steel industry, the electricity grid CO_2 emissions factor, the type of feedstocks for BF-BOF and EAF, the level of penetration of energy-efficient technologies, the steel product mix in each country, the age of steel manufacturing facilities in each country, the capacity utilization, environmental regulations, cost of energy and raw materials, and the boundary definition for the steel industry. These are discussed later in the report.

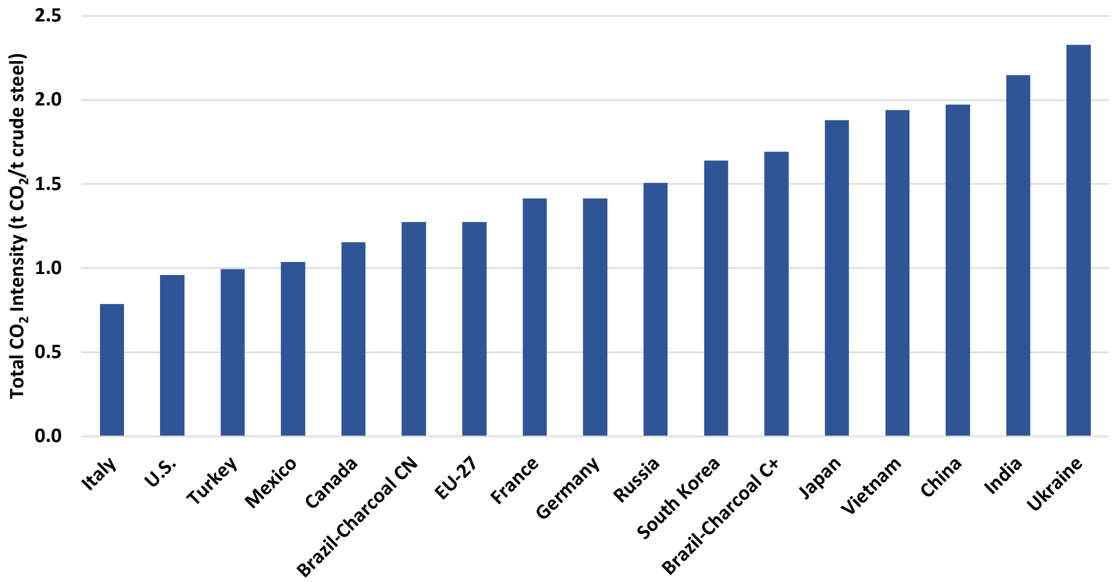

Figure ES1. The CO_2 intensity of the steel production in the studied countries/region in 2019
Note: Brazil-Charcoal CN refers to when charcoal is considered carbon neutral. Brazil-Charcoal C+ refers to when charcoal is not considered carbon neutral because of questions and concerns regarding the sustainability of biomass used in the steel industry in Brazil. See methodology in Appendix for more information.

In view of the projected continuing increase in absolute steel production and the need for deep decarbonization of the steel industry to meet the Paris Agreement targets, future reductions in absolute energy use and CO_2 emissions will require innovation beyond technologies that are widely used today. New developments will likely include different processes, fuels, and materials as well as technologies that can economically capture, use, and store the industry's CO_2 emissions. This report sheds light on the relative performance of today's steel industries around the world, highlighting where these future developments can and should take place.

It should be noted that top ten steel producing countries account for 86% and top five countries (China, India, Japan, U.S., and Russia) account for 74% of global steel production. Therefore, substantial actions are needed by these few countries in near, medium, and long term in order to achieve net-zero carbon emissions by 2050. In recent years, some countries and several major steel companies have announced their carbon-neutrality targets. While this is a positive step, these steel companies will need to take concrete actions in the near term and start deploying deep decarbonization and low carbon steel production technologies by 2030 in order to avoid stranded carbon-intensive assets and to meet Paris Agreement targets.

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1 Introduction

Iron and steel manufacturing is one of the most energy-intensive industries worldwide. In addition, the use of coal as the primary fuel for iron and steel production globally means that iron and steel production has among the highest carbon dioxide (CO_2) emissions of any industry. The iron and steel industry accounts for around a quarter of greenhouse gas (GHG) emissions from the global manufacturing sector (IEA 2019).

The world's steel demand is projected to increase from 1,880 Mt in 2020 to up to 2,500 Mt in 2050, (IEA 2020a). 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 2019). This significant increase in steel consumption and production will drive a significant increase in the industry's absolute energy use and CO_2 emissions in the absence of substantial effort in decarbonizing the iron and steel industry.

Figure 1 shows a simplified flow diagram of steel production using blast furnace - basic oxygen furnace (BF-BOF), direct reduced iron - electric arc furnace (DRI-EAF), and scrap-EAF production routes.

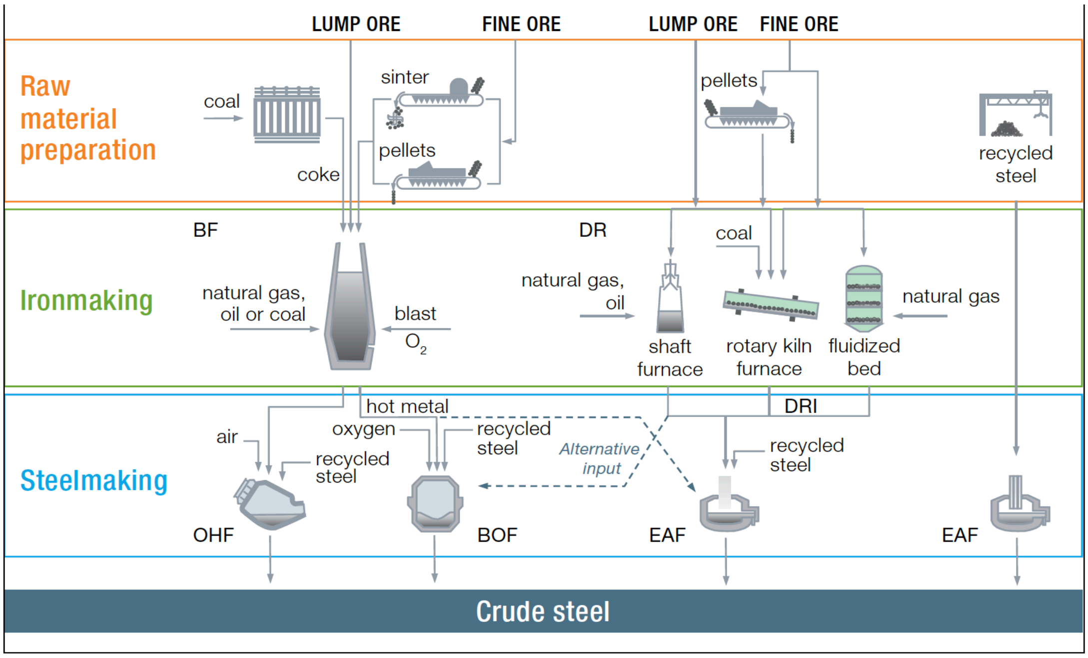

Figure 1. Steelmaking production routes (Worldsteel 2019)

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 DRI and then processed into steel at the same site.

There are emerging technologies that aim to reduce energy use and emissions from the steel industry such as the ones described in IEA (2020a) and Hasanbeigi et al. (2013). For example, hydrogen DRI-based EAF steelmaking where hydrogen is produced by electrolysis using renewable electricity is one of the key deep decarbonization technologies that is being piloted (SAAB 2021) and is being seriously considered by both industry as policymakers.

For this study, we have conducted benchmarking of the energy intensity and CO_2 emissions intensity of the iron and steel industry in 16 major steel producing countries/region.
The countries studied are among the top 20 steel producing countries in the world and represent 87 percent of world's steel production in 2019. The study methodology compares energy and CO_2 emissions intensity of the entire steel industry for each country. In addition, we assessed BF-BOF and EAF steel production separately to provide more in-depth insight and account for the differences in steel industry structure in terms of types of steelmaking technologies used. To provide a more accurate comparison, we also added the embodied energy in imported and exported pig iron and DRI when calculating energy and CO_2 emissions intensity for each country. We estimated the embodied energy in pig iron and DRI that is traded and subtracted that amount from total energy use of the steel industry for exporting countries and added that amount to total energy use of the steel industry in importing countries. Since the energy and CO_2 emissions intensities are calculated for production of one tonne of crude steel, this approach will ensure that the intensities are not overestimated for countries exporting pig iron and DRI and not underestimated for countries importing these intermediary products. See Appendix 1 for more details about the study methodology.

The study boundaries include coke making, pelletizing, sintering, iron making, steel making, steel casting, hot rolling, cold rolling, and processing such as galvanizing or coating. The embodied energy and CO_2 emissions associated with scrap used in the iron and steel industry and the CO_2 emissions associated with mining have been excluded. While results are presented on a "crude steel" basis, the energy and CO_2 emissions intensities shown in this report also include the energy use and associated CO_2 for the steel rolling and finishing processes, the result of which is sometimes referred to as "semi-finished steel". The documentation of IEA (2021) which was the main energy consumption data source used in this study shows that these steel rolling and finishing processes are included in the scope of its steel industry energy use data reported. In addition, we confirmed with IEA that sintering is included in the scope of steel industry energy use data they have reported.

Countries that produce a higher share of hot-rolled, cold-rolled, and coated products (vs. long products), like the U.S., may show higher energy and CO_2 emissions intensities than countries with a lower share using this approach than they would in a study focused only on crude steel production and would not include steel rolling and finishing processes.

This report is an update to our previous report titled "How Clean is the U.S. Steel Industry? An International Benchmarking of Energy and CO_2 Intensities". In the previous report the energy and CO_2 intensities were calculated using 2016 data. In addition to calculating energy and CO_2 intensities for the entire steel industry, we also calculated separately the intensities associated with the EAF and BF-BOF production routes in each country. In this current report, the intensities are calculated using 2019 data. The energy and CO_2 intensities presented in this report are different from the previous report not only because a different base year is use, but also because different sources of primary data as well as refined analysis and assumptions are used in this new update. These changes are explained in detail in chapter 4 as well as the methodology section (see Appendix 1). *It should be noted that the purpose of this update was not trend analysis but to refine the data and method used in our previous analysis based on the latest information available. As such, the results of the previous analysis are not directly comparable to the results presented herein.*

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, the global crude steel production decreased by about 1% because of the global COVID 19 pandemic.

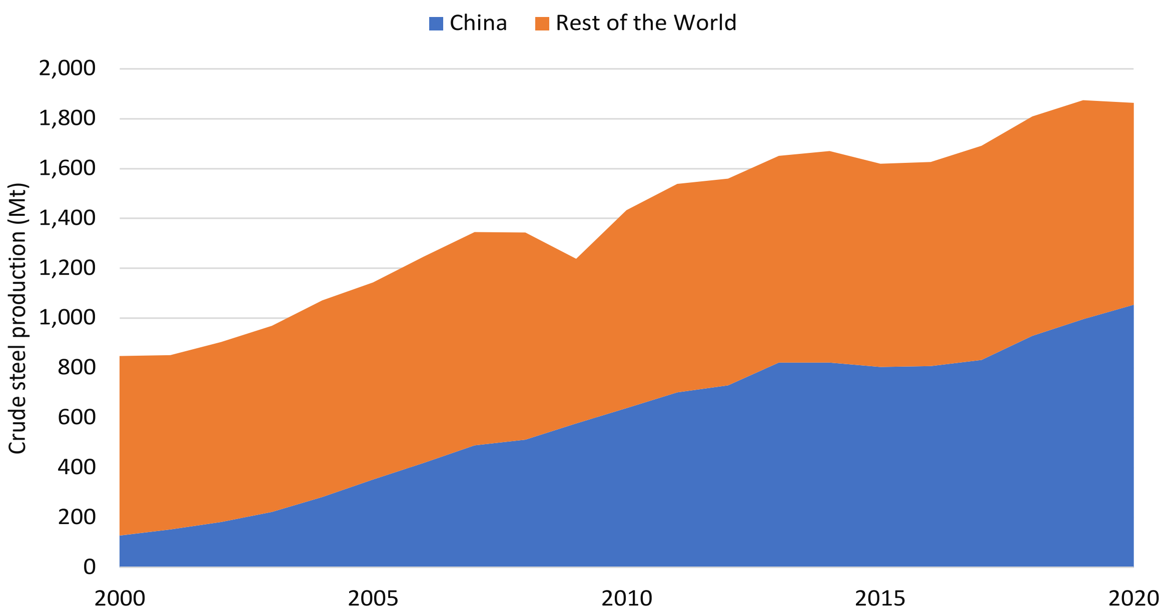

Figure 2. Crude steel production in China and rest of the world, 2000-2020 (Worldsteel 2020, 2021)

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).

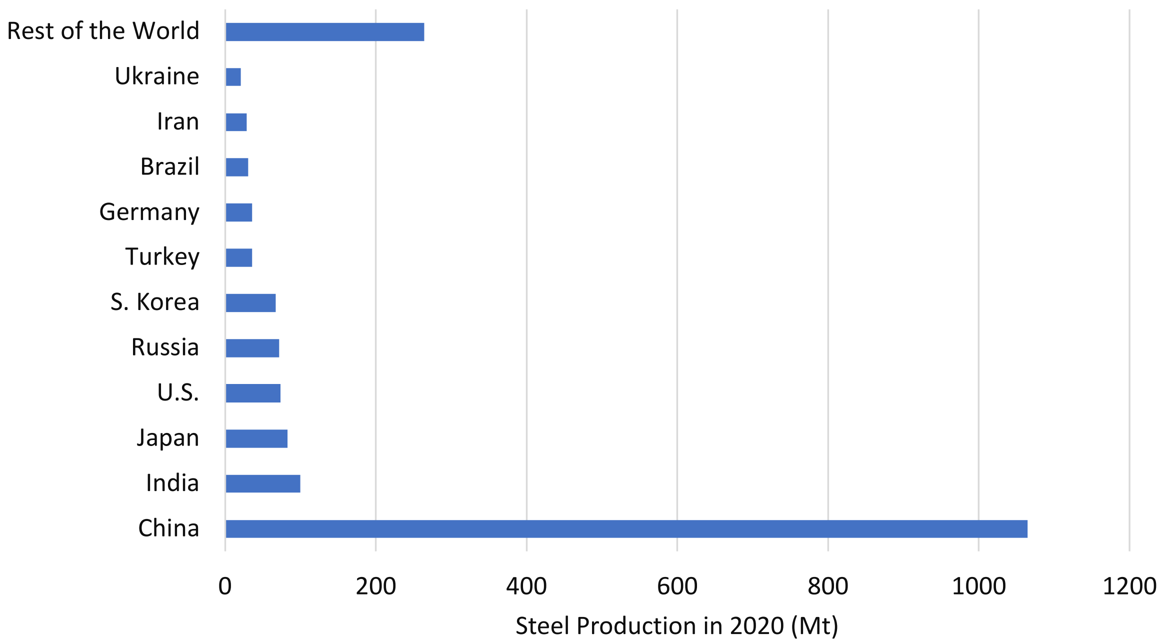

Figure 3. Top 10 steel producing countries in 2020 (Worldsteel 2021)

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 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	Ukraine	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 imports (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 CO_2 Emissions

The Global steel industry emitted around 3.6 gigaton of CO_2 (Gt CO_2) emissions in 2019 (Figure 4). We used IEA (2021) energy use data to estimate total steel industry CO_2 emissions and the weighted average CO_2 intensities of BF-BOF and EAF steelmaking from countries/region included in this study to estimate total global emissions for each steel production route. These 16 major steel-producing countries/region included in this study account for 87% of total world steel production, 92% of BF-BOF and 75% of EAF steel production. Therefore, we have a high coverage of global steel production in our study.

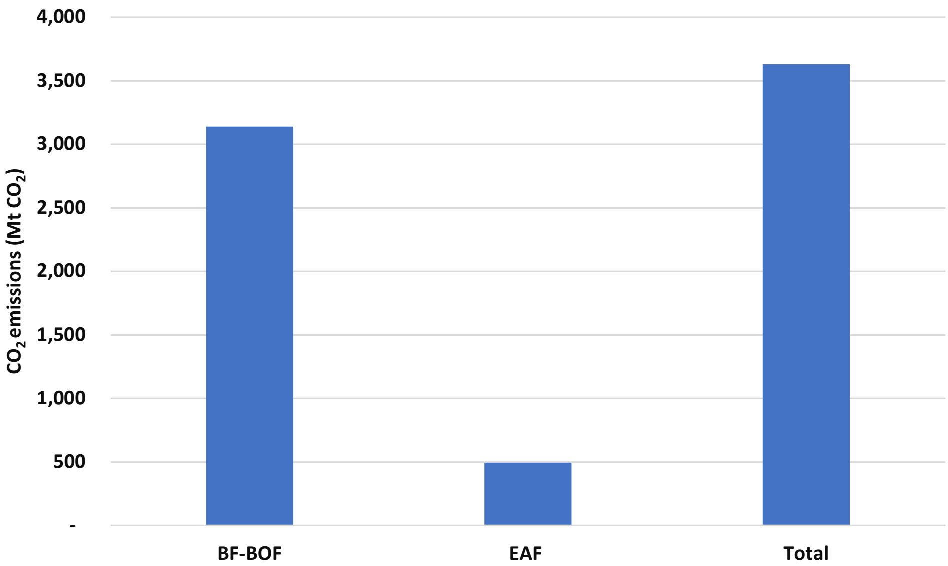

Figure 4. Global steel industry CO_2 emissions in 2019 by process type (source: this study)

Global BF-BOF steel production emitted around 3.1 Gt CO_2 and global EAF steel production emitted around 0.5 Gt CO_2 in 2019. The high CO_2 intensities of EAFs in China and India because of their use of large share of pig iron or coal-based direct reduced iron (DRI) as feedstock instead of steel scrap in EAFs causes an increase in global EAF's CO_2 emissions.

We also estimate the total CO_2 emissions from the steel industry in each of the countries studied, based on our estimated CO_2 intensities for BF-BOF and EAF by country and the amount of production in each country. Table 2 shows the results of this analysis, with China standing out as responsible for 54% of global steel industry's CO_2 emissions.

Based on total steel industry emissions presented above and the global GHG emissions of 52 Gt $CO_{2\text{-}e}$ in 2019 (includes non- CO_2 GHG emissions as well) reported in UNEP (2020) the global steel industry accounts for around 7% of total global GHG emissions.

Based on the total steel industry emissions presented above and the global CO_2 emissions of 33 Gt CO_2 in 2019 reported in IEA (2020c) the global steel industry accounts for around 11% of total global CO_2 emissions.

It is worth highlighting that only the annual GHG emissions of China and the U.S. are higher than the annual CO_2 emissions of the global steel industry.

Table 2. Total CO_2 emissions from steel production in the countries studied and rest of the world in 2019 (in Mt CO_2)

Countries	Total CO_2 emissions from steel industry (Mt CO_2)	Share from total emissions (%)
China	1,967	54.1%
Rest of the World	634	17.4%
India	239	6.6%
Japan	187	5.1%
South Korea	117	3.2%
Russia	108	3.0%
U.S.	84	2.3%
Germany	56	1.5%
Brazil	55	1.5%
Ukraine	49	1.3%
Vietnam	34	0.9%
Turkey	34	0.9%
France	20	0.6%
Mexico	19	0.5%
Italy	18	0.5%
Canada	15	0.4%

4 Benchmarking Energy and CO_2 Emissions Intensities of the Steel Industry

International benchmarking of energy intensity and CO_2 emissions intensity can provide a comparison point against which a company or industry's performance can be measured to that of the same type of company or industry in other countries. Benchmarking can also be used for assessing the energy and emissions improvement potential that could be achieved by the implementation of energy efficiency or CO_2 reduction measures. Also, on a national level, policy makers can use benchmarking to prioritize energy saving and decarbonization options and to design policies to reduce energy and GHG emissions.

For this study, we have conducted benchmarking of the energy intensity and CO_2 emissions intensity of the iron and steel industry in 16 major steel producing countries/region (14 countries plus EU-27). We used 2019 as the base year for our analysis. A few countries that were included in the previous report are missing in this new study (e.g. Poland and Spain) mainly because of lack of reliable quality data. Instead, we included a few other top steel producing countries as well as the EU-27 region in this new study.

For the benchmarking study, we compared the energy and CO_2 emissions intensity of the entire steel industry in these 16 countries/region. In addition, to provide more in-depth insight and take into account the differences in steel industry structure in terms of type of process used, we conducted CO_2 emissions intensity benchmarking for BF-BOF and EAF steel production, separately. To have a more accurate and fair comparison, we also took into account the embodied energy in net imported pig iron, DRI, and coke when calculating energy and CO_2 emissions intensity for each country. The energy and CO_2 emissions intensities shown in this report also include the energy use and associated CO_2 for the steel rolling and finishing processes.

See Appendix 1 for a description of the methodology. The subsections below show the results of these benchmarking analysis.

There are some differences between the energy and CO_2 emissions intensity results presented in this reported compared to those of our previous report, "How Clean is the U.S. Steel Industry? An International Benchmarking of Energy and CO_2 Intensities". Some of the primary reasons for these differences are:

- The use of different sources of data for energy use in the steel industry in selected countries. Unlike the previous study, in this study, we mainly relied on energy use reported by International Energy Agency (IEA 2021). This helps to have a more similar boundary for energy use reported for the steel industry for different countries. The boundary will define which sources of energy and what processes are included in the reported data. Therefore, using the same source of data will help to have a fairer comparison. In a few cases where IEA data was missing or resulted in unreasonably low or high intensity values we used energy use reported by countries and published in their energy balances.
- A refined method to better account for energy use in coke making and embodied energy in net import coke.
- A refined method of calculating energy intensity by process route and better allocation of overall energy intensity and calibration of historical data
- The use of a different source for electricity grid emissions factor. We used the same source in this study for grid emissions factor of all countries, while in the previous report we obtained grid emissions factor from various sources. The emissions factors used in this analysis for some countries (e.g. China) are substantially different from the previous analysis contributing to differences in calculated CO_2 emissions intensity between this study and previous report.

4.1. Benchmarking the Total Steel Industry's Energy and CO_2 Emissions Intensities

Figure 5 shows the total final energy intensity of the entire steel industry in these 16 countries/ region in 2019. Italy, Turkey, Mexico, and the U.S. have the lowest energy intensity among the countries studied. This is primarily because of a significantly high share of EAF steel production in total steel production in these countries (Figure 6). EAF is a secondary steel production process that primarily uses steel scrap and therefore uses less energy to produce a ton of steel compared to BF-BOF. In other words, a higher share of EAF production helps reduce the overall energy intensity of the steel industry in a country. It should be noted that EAF can also use DRI or even pig iron which are energy-intensive feedstock to EAF. In some countries like India a high amount of DRI is used in EAF and in China a large amount of pig iron that is produced by blast furnaces is used in EAF, both resulting in significantly higher energy and emissions intensity for the steel produced by EAF in those countries. However, other factors also impact the energy and CO_2 emissions intensity of the steel industry, as is discussed in the rest of this report.

On the other hand, Ukraine, India, China, and Brazil have the highest energy intensity among the countries studied. Ukraine, China, and Brazil also have the lowest share of EAF steel production (Figure 6). While India's steel industry has a high share of EAF steel production (56 percent), its energy intensity is relatively high. This is mainly because unlike many other countries, a substantial amount of DRI is used as the feedstock to EAFs in India (around 50% of total EAF feedstock). Unlike recycled steel scrap, DRI is produced from iron ore using the direct reduction process (Figure 1), which is an energy- and carbon-intensive process. In addition, India is one of the few countries in the world that uses coal-based DRI technology instead of natural gas-based DRI used in most countries around the world. This contributes to higher energy intensity and emissions for DRI-EAF steel produced in India.

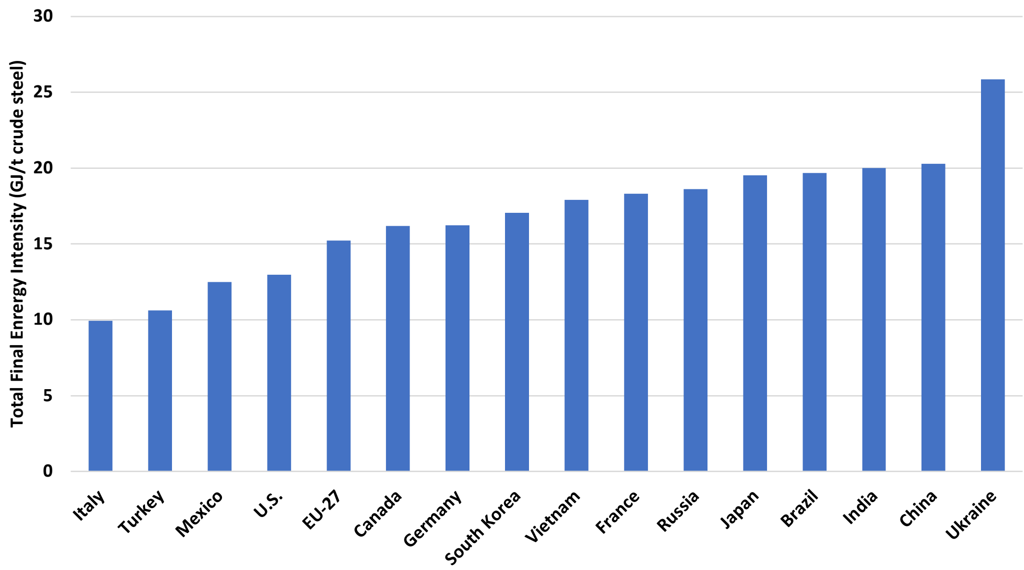

Figure 5. Total final energy intensity of the steel industry in the studied countries/region in 2019

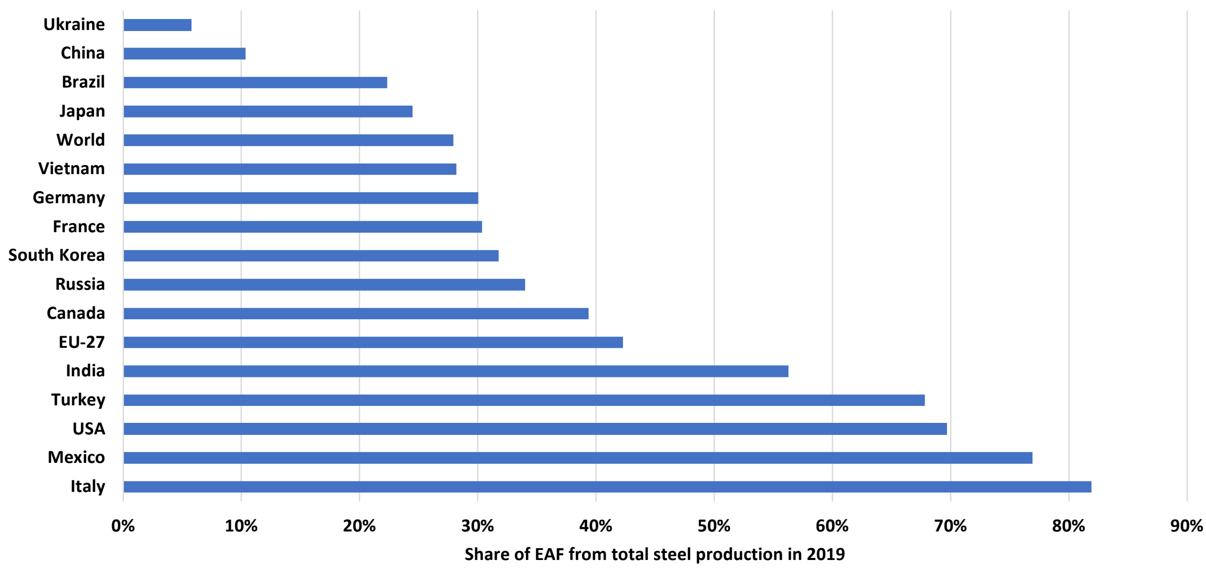

Figure 6. The share of EAF from total steel production in the studied countries/region in 2019

The ranking of the CO_2 emissions intensity of the steel industry among the countries studied (Figure 7) is slightly different from the energy intensity ranking. Italy, U.S. and Turkey have the lowest and Ukraine, India, and China have the highest CO_2 emissions intensity. The U.S. ranks better for its CO_2 emissions intensity. This is partly because of high share of natural gas used in the U.S, steel industry (54% of total fuel used in steel industry in the U.S.). Natural gas has a significantly lower emissions factor per unit of energy compared to coal and coke, which are the primary type of energy used in the steel industry in many countries. The U.S. also has a lower CO_2 grid emissions factor than Turkey and Mexico. Other factors affecting the CO_2 emissions intensity of the steel industry are discussed at the end of this chapter.

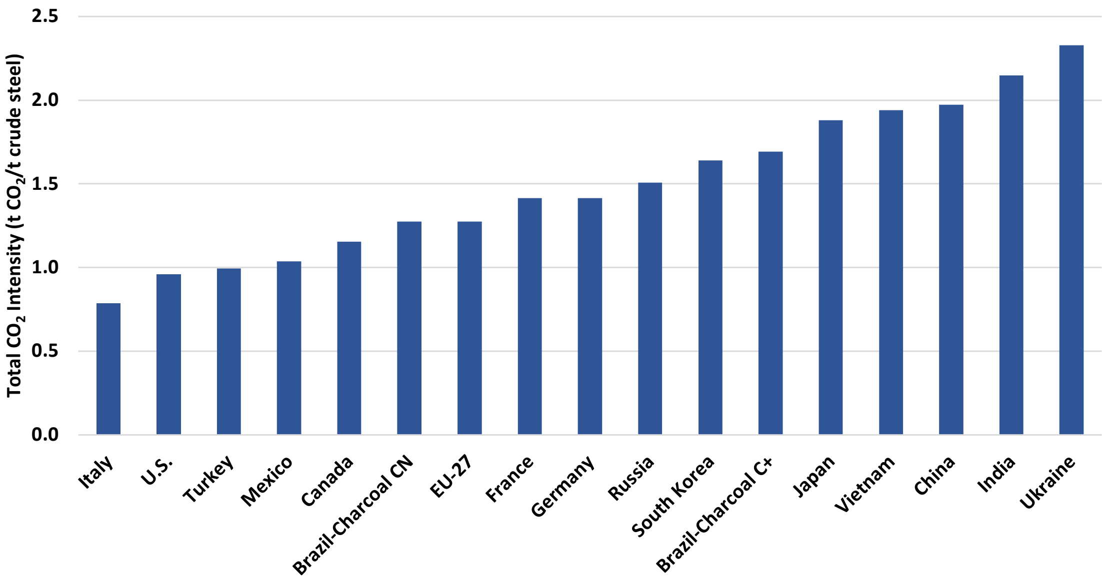

Figure 7. Total CO_2 emissions intensity of the steel industry in the studied countries/region in 2019
Note: Brazil-Charcoal CN refers to when charcoal is considered carbon neutral. Brazil-Charcoal C+ refers to when charcoal is not considered carbon neutral because of questions and concerns regarding the sustainability of biomass used in the steel industry in Brazil. See methodology in Appendix for more information.

4.2. Benchmarking BF-BOF Steel Production's CO_2 Emissions Intensities

Because BF-BOF and EAF steel production routes are quite different and thus their CO_2 emissions intensity are also significantly different from each other, it is crucial to dive deeper and benchmark the steel production in each country for each production route. That gives a more fair and accurate view of the efficiency of the steel production in each country.

Figure 8 shows the CO_2 intensity of BF-BOF steel production in the studied countries in 2019. It worth highlighting that even though China has the 3rd highest CO_2 intensity for its entire steel industry (Figure 7), its ranking improved for the CO_2 intensity for the BF-BOF steel production route. Although the very low share of EAF steel production in China results in a high total CO_2 intensity for its entire steel industry, more than 80% of the BF-BOF steel production capacity in China was built after the year 2000, with average age of plants around 13 years (IEA 2020b). Many of these new plants are using more efficient production technology. In addition, in the past ten years, China has been aggressively shutting down old and inefficient steel plants.

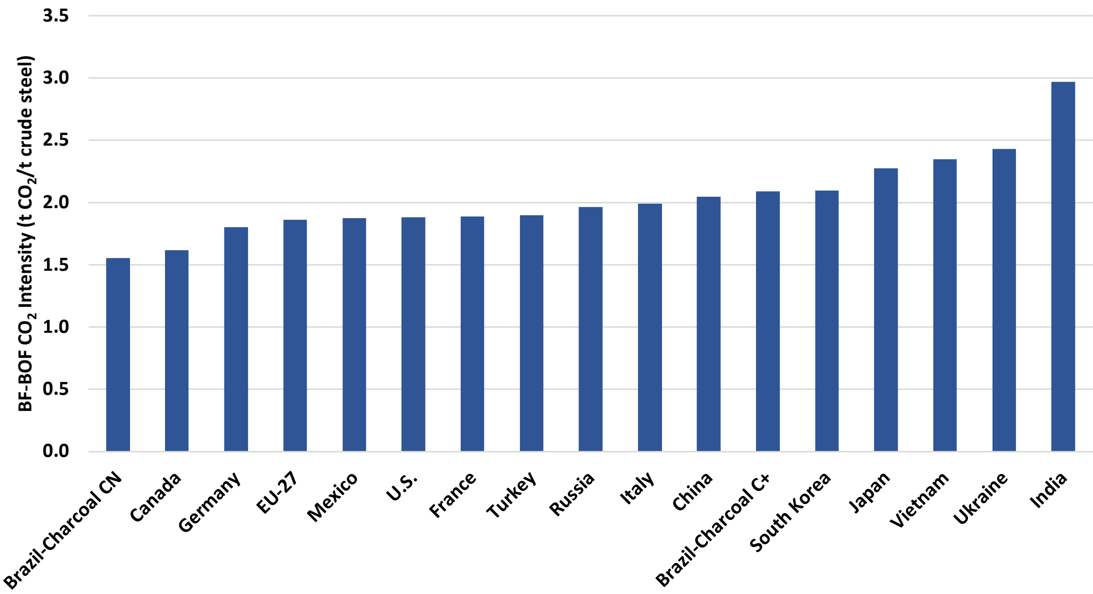

Figure 8. The CO_2 intensity of BF-BOF steel production in the studied countries/region in 2019
Note: Brazil-Charcoal CN refers to when charcoal is considered carbon neutral. Brazil-Charcoal C+ refers to when charcoal is not considered carbon neutral because of questions and concerns regarding the sustainability of biomass used in steel industry in Brazil. See methodology in Appendix for more information.

India has the highest CO_2 intensity of BF-BOF steel production mainly because of many old and inefficient BF-BOF plants still operating in India. It should be noted, however, that some of the newly built steel plants in India are among the world's most efficient.

Key factors influencing energy and CO_2 emissions intensity of the steel industry are explained in section 4.4. It should be noted that no single factor could be used to explain the variations in energy and CO_2 intensity among countries. In addition to energy intensity of BF-BOF plants, one key factor affecting CO_2 intensity of BF-BOF steel production is the mix of fuel used in BF-BOF plants in each country. Figure 9 shows the weighted average CO_2 emissions factors of fuels in the steel industry in the studied countries in 2019. As can be seen U.S., Mexico and Canada have among the lowest and India, Vietnam, and China have among the highest weighted average CO_2 emissions factors of fuels in the steel industry. If charcoal is considered carbon neutral, the Brazil have the cleanest fuel mix and if charcoal is not considered carbon neutral, then Brazil have the highest carbon-intensive fuel mix for the steel industry.

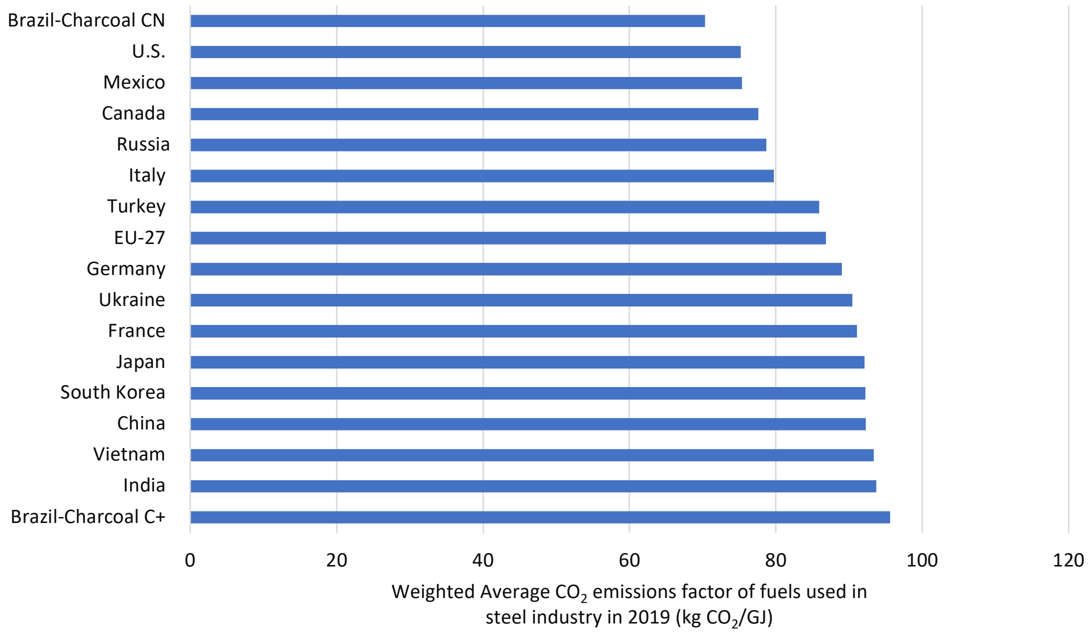

Figure 9. Weighted average CO_2 emissions factors of fuels in the steel industry in the studied countries/ region in 2019

Note: Brazil-Charcoal CN refers to when charcoal is considered carbon neutral. Brazil-Charcoal C+ refers to when charcoal is not considered carbon neutral because of questions and concerns regarding the sustainability of biomass used in steel industry in Brazil. See methodology in Appendix for more information.

Another important factor that influences CO_2 intensity of BF-BOF steel production is electricity grid CO_2 emissions factor. Around 20% of the energy used in BF-BOF steel production (including rolling and finishing) is electricity. Therefore, if the emissions factor of the electricity used in the primary steelmaking is lower, it will help to reduce the CO_2 intensity of BF-BOF steel production. It should be noted that some of this electricity is produced onsite using off gases from coke oven, BF, and BOF and some is purchased from the grid. We have accounted for the onsite power generation in our analysis and only applied the grid emissions factor to the portion of electricity purchased from the grid. As can be seen in Figure 10, France and Brazil have the lowest electricity grid CO_2 emissions factors thanks to large nuclear (in France) and hydro (in Brazil) power generation. India, China, and Vietnam have the highest electricity grid CO_2 emissions factors among studied countries due to large share of coal used in their power generation. Other factors affecting the CO_2 emissions intensity of BF-BOF steel production are discussed at the end of this chapter.

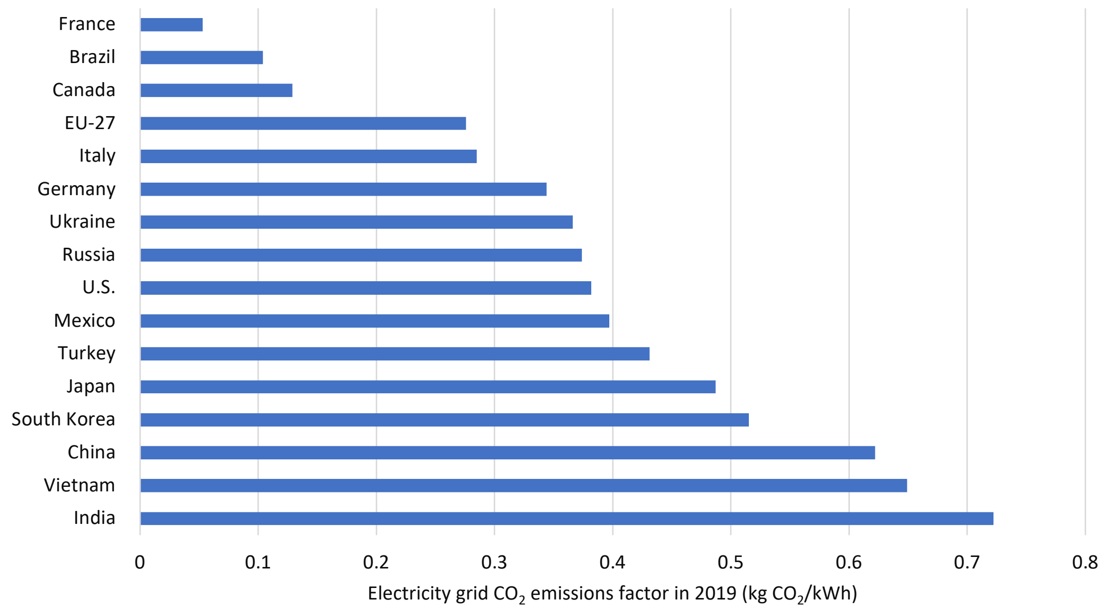

Figure 10. Electricity grid CO_2 emissions factors in the studied countries in 2019 (IEA 2021)

4.3. Benchmarking EAF Steel Production's CO_2 Emissions Intensities

EAF steel production is less energy- and carbon-intensive than BF-BOF steel production, especially when most or all of EAF feedstock is recycled steel scrap. (Note: the embodied energy and carbon in recycled steel scrap are usually not included in EAF energy and emissions intensities calculation).

Figure 11 shows the CO_2 intensity of EAF steel production in the 16 countries/region studied. Brazil and France have the lowest and India and China have the highest CO_2 intensity of EAF steel production. A key reason why the CO_2 intensity of EAF steel production in India, China, and Mexico are significantly higher than that in other countries is the type of feedstock used in EAF in these countries. In most countries, steel scrap is the primary feedstock for EAF. In India and Mexico, however, a substantial amount of DRI (around 50% in India and 40% in Mexico) is used as feedstock in EAFs (Worldsteel 2020). In China, instead of DRI, a significant amount of pig iron (around 50% of EAF feedstock), which is produced via blast furnace, is used as feedstock in EAFs (Wang 2017). Both DRI and pig iron production are highly energy-intensive processes, which result in higher energy and CO_2 intensity of EAF steel production when used as feedstock in EAFs. Vietnam's high CO_2 intensity of EAF steelmaking can be mainly attributed to its very high electricity grid CO_2 emissions factor (see below).

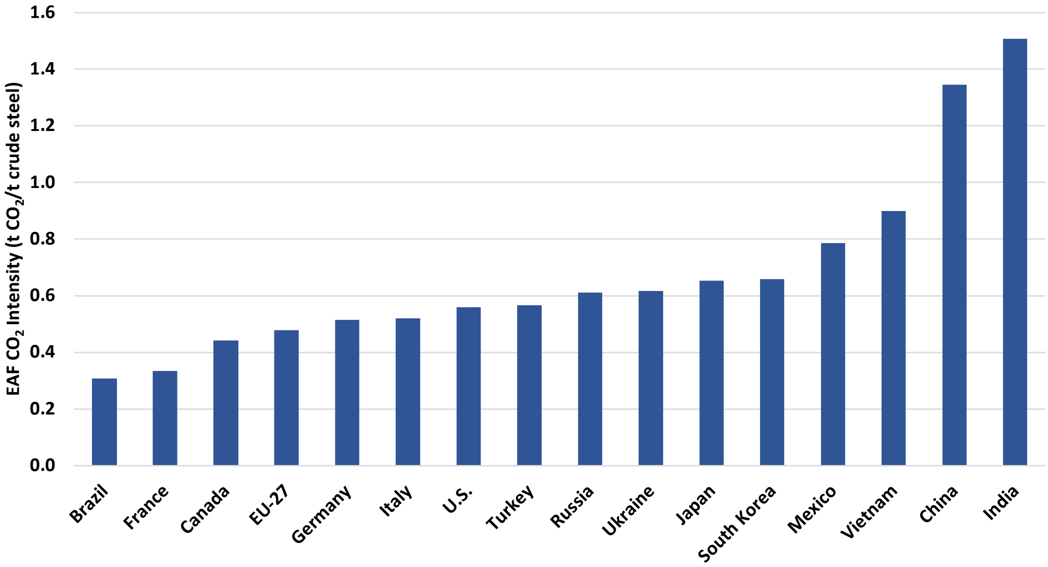

Figure 11. The CO_2 intensity of EAF steel production in the studied countries/region in 2019

Another important factor that influences CO_2 intensity of EAF steel production is electricity grid CO_2 emissions factor (Figure 10). Around half of the energy used in EAF steelmaking (including rolling and finishing) is electricity. The share of electricity from total energy use decreases as the share of DRI used in the EAF steelmaking increases. Therefore, if the emissions factor of the electricity used in the steel industry is lower, it will significantly help to reduce the CO_2 intensity of EAF steel production. France, Brazil, and Canada have the lowest electricity grid CO_2 emissions factors thanks to large nuclear (in France) and hydro (in Brazil and Canada) power generation. India, Vietnam, and China have the highest electricity grid CO_2 emissions factors among studied countries due to large share of coal used in their power generation.

4.4. Key Factors Influencing Energy and CO_2 Emissions Intensity of the Steel Industry

In this sub-section we discuss the following eleven factors that could explain why the steel industry's energy and CO_2 emissions intensity values differ among the countries:

1) The share of EAF steel in total steel production
2) The fuel mix in the iron and steel industry
3) The electricity grid CO_2 emissions factor
4) The type of feedstocks in BF-BOF and EAF
5) The level of penetration of energy-efficient technologies
6) The steel product mix in each country
7) The age of steel manufacturing facilities in each country
8) Capacity utilization
9) Environmental regulations
10) Cost of energy and raw materials
11) Boundary definition for the steel industry

While a combination of several factors can explain variations in energy and CO_2 emissions intensity of the steel industry across countries, some factors have larger impacts than other. It is difficult and sometime not possible to quantify the impact of each factor on energy and CO_2 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 energy and CO_2 emissions intensity among the countries studied.

The share of EAF steel in total steel production

The structure of the steel manufacturing sector is one of the key variables that explains the difference in energy and CO_2 emissions intensity. EAF is a secondary steel production process that primarily uses steel scrap and therefore uses less energy per unit of final product compared to BF-BOF. In other words, the higher share of EAF production help to reduce the overall energy intensity of the steel industry in a country. Figure 6 shows the differences in EAF steel production ratio across countries.

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 CO_2 emissions intensity because some fuels are more carbon intensive than others. For example, the higher share of natural gas used in Mexico and Canada (66% and 50% of total fuel used in the steel industry, respectively) has helped lower the CO_2 emissions intensity of BF-BOF steel production in these two countries. Natural gas has a significantly lower emissions factor per unit of energy compared to coal and coke which are the primary type of energy used in the steel industry in many countries.
Figure 9 shows the weighted average CO_2 emissions factors of fuels in the steel industry in the studied countries in 2019.

The electricity grid CO_2 emissions factor

In addition to the share of fuels used directly in the iron and steel industry, the fuel mix for power generation in each country is also an important factor, especially when we compare the CO_2 emissions of the steel industry in the countries. The fuel mix 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 Italy, Mexico, Turkey, and the U.S. is much higher than in the other countries, the share of steel-industry electricity use in total energy use is also higher in these four countries than in the other countries. In this case, the fuel mix for power generation in the country, and as the result the emissions factor of the grid (kg CO_2/kWh), plays an important role when comparing the CO_2 emissions of the iron and steel industry in these countries. Figure 10 shows the electricity grid CO_2 emissions factors in the studied countries in 2019.

The type of feedstocks in BF-BOF and EAF

The main reason why the energy intensity of EAF steel production in India and China and Mexico are significantly higher than that in other countries is the type of feedstock used in EAF in these countries. In most countries, steel scrap is the primary feedstock to EAF. In India and Mexico, however, a substantial amount of DRI (around 50% of feedstock in India and 40% in Mexico) is used as feedstock in EAFs (Worldsteel 2020). In China, instead of DRI, a significant amount of pig iron (around 50% of feedstock), which is produced by blast furnace, is used as feedstock in EAFs (Wang 2017). When high quality scrap is not available in sufficient quantities, DRI or pig iron are used in EAFs as a source of iron ore for production of (high-grade) steel. Both DRI and pig iron production are highly energy-intensive processes, which result in higher energy intensity of EAF steel production when used as feedstock in EAFs. Finally, the quality of iron ore (Fe content, impurities, etc.) could also influence the energy use of the steel production.

The level of penetration of energy-efficient technologies

Data on penetration of energy-efficient and CO_2 emissions reduction technologies and practices in countries are scarce and not fully comparable. The types of information available in these countries differ, so direct comparison of the penetration of certain technologies is not possible. One direct comparison that is possible is the penetration of EAFs, which was presented above. The application of energy-efficient and CO_2 emissions reduction technologies depends on factors such as raw materials used, energy sources, energy and operation costs, product mix, and the regulatory regime in the country.

For example, in China, the penetration of waste-heat and waste-energy recycling technologies and other energy efficient technologies such as coke dry quenching (CDQ) for the coking process, top-pressure recovery turbines (TRTs) for BFs, pulverized coal injection, and continuous casting has helped to reduce the energy intensity of BF-BOF steel production in China. CDQ is a heat-recovery technology that produces electricity. Other technologies, such as low-temperature waste-heat recovery, are also being adopted in China. Many Chinese steel companies benefited from the Kyoto Protocol's Clean Development Mechanism (CDM) and government financial incentives for additional funding to support CDQ and TRT projects in their plants. Such financial incentives may not be available in some of the countries studied.

The steel product mix in each country

Different steel products have different energy requirements in the rolling/casting/finishing processes. Therefore, the product mix is another key factor that could influence the CO_2 intensities among countries. Worldsteel (2020) shows the differences in the production of some iron and steel industry products in the studied countries.

The age of steel manufacturing facilities in each country

The average age of BF vessels in the U.S. is over 30 years. Even though the BF vessels in the U.S. have been relined and other upgrades have been made, they are overall older than most of the steel production facilities in China, which has an average age of around 13 years (IEA 2020b), and therefore could be less energy-efficient than the Chinese facilities. India has the highest energy intensity of BF-BOF steel production mainly because of many old and inefficient BF-BOF plants and coal-based smelting reduction plants still in operation. It should be noted, however, that some of the newly built steel plants in India are among the world's most efficient, as they use latest state-of-the-art technologies.

Capacity utilization

Capacity utilization of plants also affects the energy intensity and CO_2 emissions intensity of steel production. Higher capacity utilization improves overall energy performance compared to lower capacity utilization if all other factors remain constant. Because it takes a long time and is costly to shut down and restart BFs, operators avoid shutting down for short periods and instead reduce production so that the BFs continue to work at less than full capacity. This reduces BF energy efficiency and productivity and increases overall energy and CO_2 intensities of steel production.

Environmental regulations

There are differing environmental requirements from country to country. Environmental regulations can affect industry CO_2 emissions intensity by incentivizing different operational and equipment choices. At the same time, operation of some pollution control equipment requires additional energy, which can also add CO_2 emissions.

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 in order to optimize costs can affect the CO_2 and energy intensities of a plant. Also, the lower cost of energy in some countries provides less incentive for energy optimization and increases the payback period for energy efficiency projects.

Boundary definition

The boundary definition for the steel industry might vary from country to country in their energy statistics. For example, some countries may report the energy use of coke-making within the steel industry while some others may report it separately. That is the main reason why for this study we decided to primarily rely on the IEA data since IEA uses the same boundary and definition when reporting the energy use data. The steel industries in each country also vary in the amount of auxiliary/intermediary products such as sinter, coke, pig iron, DRI, oxygen, lime that they import from outside the industry (either domestically or internationally). See Appendix 1 for description of steel industry boundary used in this study. Fortunately, for the main intermediary products, pig iron, DRI, and coke we obtained the data for their net imports for each country. To have a more accurate and fair comparison, we took into account the embodied energy in net imported pig iron, DRI, and coke when calculating energy and CO_2 emissions intensity for each country. For some other auxiliary/intermediary products, the net import data was not available for most countries and we could not include those in our analysis, but their impact on total energy and CO_2 emissions intensity is not significant based on our earlier studies. Finally, the consumption of pellets in BFs can affect energy consumption. Pellets are produced at the iron ore mine sites and have a high iron content. If pellets replace sinter in BFs, the energy consumption decreases, since energy consumption for sinter making is omitted and also the higher iron content of the pellets. The differences in the share of pellets and sinter used in BFs in different countries can slightly affect the energy intensity of BF-BOF steel production across countries.

5 Conclusions

In this study we conduct a benchmarking analysis for energy and CO_2 emissions intensity of the steel industry among the largest steel-producing countries. Because of the difference in structure of the steel industry among countries and variation in the share of EAF steel production, a single intensity value for the overall steel industry is not a good indicator of the efficiency of the steel industry in a country. Therefore, in addition to calculating energy and CO_2 intensities for the entire steel industry, we also calculated separately the intensities associated with the EAF and BF-BOF production routes in each country.

Our results show that when looking at the entire steel industry, Italy, Turkey, Mexico, and the U.S. have the lowest and Ukraine, India, and China have the highest energy and CO_2 emissions intensities among the countries studied. Among several reasons, this is primarily because of significantly higher share of EAF steel production from total steel production in Italy, Turkey, and the U.S. and a very low share of EAF steel production in Ukraine and China (only 6% and 10 percent, respectively in 2019).

For CO_2 emissions intensity of BF-BOF steel production, Canada has the lowest and India has the highest CO_2 emissions intensity. Canada has one of the lowest and India has one of the highest weighted average CO_2 emissions factors of fuels in the steel industry.

For the CO_2 emissions intensity of EAF steel production, India and China still have the highest intensity, while Brazil and France have the lowest CO_2 emissions intensity of EAF steel production. One key factor that explains this is that the primary type of energy used in EAFs is electricity and France and Brazil have the lowest electricity grid CO_2 emissions factors. Also, in China and India, a substantial amount of energy-intensive pig iron (in China) and DRI (in India) are used as feedstock in EAFs, which results in higher energy and CO_2 emissions intensity steel produced by the EAF route in these two countries.

In view of the projected continuing increase in absolute steel production and the need for deep decarbonization of the steel industry to meet Paris Agreement targets, future reductions in absolute energy use and CO_2 emissions will require innovation beyond technologies that are available today. New developments will likely include different processes, fuels, and materials (e.g. hydrogen-direct reduction steelmaking using renewable energy to produce hydrogen and use it in DRI process) as well as technologies that can economically capture and store steel industry's CO_2 emissions. Deployment of these new technologies in the market will be critical to the industry's climate change mitigation strategies for the mid and long term. It should be noted that top ten steel producing countries account of 86% and top five countries (China, India, Japan, U.S., and Russia) account for 74% of global steel production. Therefore, substantial actions are need by these countries in near, medium, and long term in order to achieve net zero carbon emissions by 2050.

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Appendices

Appendix 1. Methodology

For this study, we have conducted benchmarking of the energy intensity and CO_2 emissions intensity of the U.S. iron and steel industry against that of the steel industry in fourteen other major steel producing countries. All the countries included in this study are among the top twenty steel producing countries in the world and combined accounted for 87% of world's steel production in 2019. We used 2019 as the base year for our analysis.

For the benchmarking study, we compared the energy and CO_2 emissions intensity of the entire steel industry in these 16 countries. In addition, to provide more in-depth insight and take into account the differences in steel industry structure in terms of type of process used, we conducted CO_2 emissions intensity benchmarking for BF-BOF and EAF steel production, separately. To have a more accurate and fair comparison, we also took into account the embodied energy in net imported pig iron and DRI when calculating energy and CO_2 emissions intensity for each country. The energy and CO_2 emissions intensities shown in this report also include the energy use and associated CO_2 for the steel rolling and finishing processes.

There are some differences between the energy and CO_2 emissions intensity results presented in this report compared to those of our previous report, "How Clean is the U.S. Steel Industry? An International Benchmarking of Energy and CO_2 Intensities". Some of the primary reasons for these differences are:

- The use of different sources of data for energy use in the steel industry in selected countries. Unlike the previous study, in this study, we mainly relied on energy use reported by International Energy Agency (IEA 2021). This was to have a similar boundary for energy use reported for the steel industry as much as possible. In a few cases where IEA data was missing or result in unreasonably low or high intensity values we used energy use reported by countries and published in their energy balances.
- A refined method to better account of energy use in coke making and embodied energy in net import coke.
- A refined method in calculating energy intensity by process route and better allocation of overall energy intensity and calibration of historical data
- The use of different sources for electricity grid emissions factor. We used the same source in this study for grid emissions factor of all countries, while in the previous report we obtained grid emissions factor from various sources. The emissions factors used in this analysis for some countries (e.g. China) are substantially different from the previous analysis contributing to differences in calculated CO_2 emissions intensity between this study and previous report.
- The primary source of energy use data published in IEA energy balances are the data that are reported by each country to IEA. It should be noted that some countries refine their data collection and reporting system over time. For example, every few years, China publishes a revised industrial energy use statistics for the previous years based on their refined data or revised method of accounting. Such changes in countries energy data reporting may impact the energy intensities calculated for different years.

Unlike the previous study, in this study, we mainly relied on energy use reported by International Energy Agency (IEA 2021). This was to have a similar boundary for energy use reported for the steel industry as much as possible. In a few cases where IEA data was missing or result in unreasonably low or high intensity values we used energy use reported by countries and published in their energy balances. In a few cases (e.g. India (NSO 2021) and Russia (FSS 2021)), a combination of sources was used for energy use data of the steel industry that resulted in more accurate intensity values.

The production and trade data for the steel industry are from Worldsteel (2020). Table A.1 and Table A.2 show the production and trade data for crude steel, pig iron, and DRI in the countries studied in 2019.

Table A.1. Crude steel production in 2019 (Worldsteel 2020)

No.	Country	Crude steel production (Mt)					EAF share
		Total	BOF	EAF	OHF*	Other	
1	China	996.5	893.3	103.2	-	-	10%
2	India	111.4	48.7	62.7	-	-	56%
3	Japan	99.3	75.0	24.3	-	-	24%
4	U.S.	87.8	26.6	61.2	-	-	70%
5	Russia	71.7	45.9	24.2	1.7	-	34%
6	South Korea	71.4	48.7	22.7	-	-	32%
7	Germany	39.6	27.7	11.9	-	-	30%
8	Turkey	33.7	10.9	22.9	-	-	68%
9	Brazil	32.6	24.8	7.3	-	0.5	22%
10	Italy	23.2	4.2	19.0	-	-	82%
11	Ukraine	20.8	14.8	1.2	4.8	-	6%
12	Vietnam	17.5	9.7	4.9	-	2.8	28%
13	Mexico	18.4	4.2	14.1	-	-	77%
14	France	14.5	10.1	4.4	-	-	30%
15	Canada	12.9	7.8	5.1	-	-	39%
16	EU-27	149.9	86.5	63.4	-	-	42%

* OHF: open-hearth furnace

Table A.2. Pig iron and DRI production and trade in 2019 (Worldsteel 2020)

No.	Country	Pig Iron (kt)			DRI (kt)		
		Production	Export	Import	Production	Export	Import
1	China	809,365	1	1,000	-	-	1,365
2	India	74,156	277	20	36,818	861	58
3	Japan	74,907	44	164		-	19
4	U.S.	22,301	11	5,005	3,240	314	1,762
5	Russia	50,707	4,253		8,030	4,092	
6	South Korea	47,521	78	169		-	406
7	Germany	25,520	191	428	470	-	767
8	Turkey	9,869	2	1,232		-	398
9	Brazil	26,280	2,865				
10	Italy	4,606	54	1,412			1,014
11	Ukraine	20,064	2,580	1			3
12	Vietnam	9,836	-	95			
13	Mexico	3,845		345	5,974	-	466
14	France	9,877	126	151		1	361
15	Canada	6,420	55	22	1,440	2	15
16	EU-27	80,069	1,126	3,593	580	340	3,475

Fuel emissions factors are from the IPCC (2006) and electricity grid CO_2 emissions factors in the studied countries in 2019 are from Carbon footprint (2020).

First, we calculated the energy intensity of the entire steel industry in each country in 2019 using the steel industry energy use data we obtained from energy balances (IEA 2021) and production data from Worldsteel (2020). Then, we used the fuel emissions factors and electricity CO_2 emissions factors to convert energy intensities into CO_2 emissions intensities. Because of significant concern related to sustainability of biomass supply, in our main analysis we did not consider biomass fuels (including charcoal) carbon neutral and we applied CO_2 emissions factors provided by IPCC to biomass fuels. The share of biomass from total fuel used in the steel industry is quite small in countries studied except in Brazil where significant amount of charcoal is used in the steel industry. That is why only for Brazil we calculated two CO_2 emissions intensities, one with charcoal is considered carbon neutral (named "Brazil-Charcoal CN") and another one with charcoal is considered not carbon neutral (named "Brazil-Charcoal C+) and IPCC default emissions factor is applied.

Countries do not report the energy use of their steel industry by production route, i.e. BF-BOF and EAF, separately. Therefore, we had to estimate the energy intensity of BF-BOF and EAF steel production in each country using the following method. We used the energy intensity of BF-BOF and EAF steel production reported for different countries in earlier studies such as RITE (2012a, b), Oda et al. (2012) and Hasanbeigi et al. (2019). Then, we adjusted these older energy intensities using overall energy intensity of the steel industry in 2019 calculated above and the share of EAF steel production in 2019. Other adjustments were made to calibrate the older BF-BOF and EAF energy intensities based on 2019 data. In addition, we used the values for net imported pig iron, DRI, and coke to adjust the BF-BOF and EAF intensities by taking into account the embodied energy in the net import.

Boundary of this study

In this study, the boundary of the iron and steel industry is defined to include all of the following: coke making, pelletizing, sintering, iron making, steel making, steel casting, hot rolling, cold rolling, and processing such as galvanizing or coating (Figure A.1). This boundary definition is used for calculating CO_2 emissions and CO_2 intensity in this study. We took net imported pig iron, direct-reduced iron (DRI), and coke into account by adding the energy for production of these products to the total energy and CO_2 emissions of the steel industry.

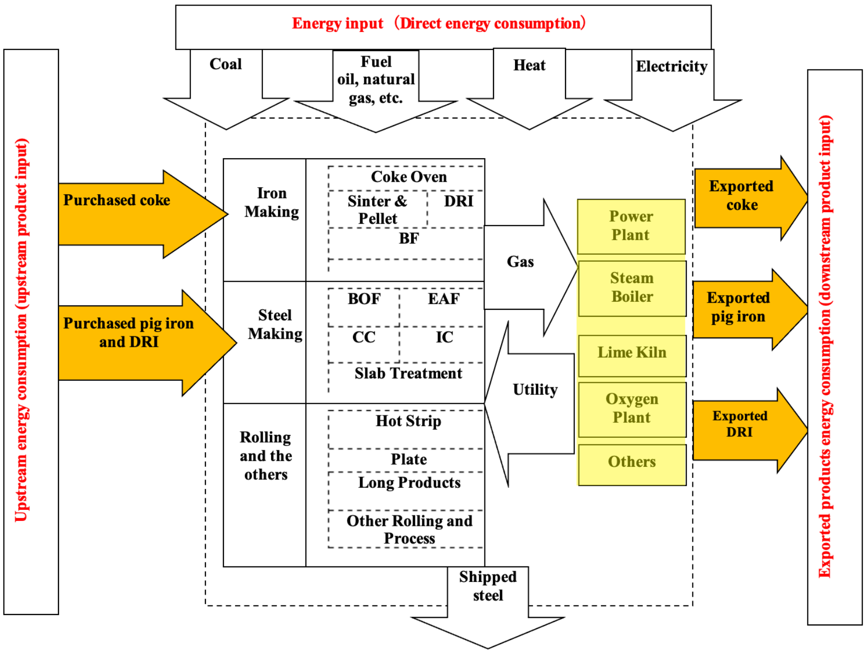

Figure A.1. Flow chart of iron and steel sector boundaries used in this study
Note: BF: blast furnace; BOF: basic oxygen furnace; EAF: electric arc furnace; DRI: direct reduced iron; CC: continuous casting; IC: investment casting

We do not include CO_2 emissions associated with other energy-intensive products manufactured for the iron and steel industry (e.g., electrodes, refractories, etc.). These products could be included in a more extensive, life-cycle analysis study of the industry but are excluded here because the focus of this study is on iron and steel production. The current study also does not take into account the embodied energy and CO_2 of the scrap used in the iron and steel industry or the CO_2 emissions associated with mining. Finally, the energy-related CO_2 emissions from further processing of steel by foundries are also excluded from this analysis.

Appendix 2. List of acronyms

BF	blast furnace
BOF	basic oxygen furnace
CO_2	carbon dioxide
DRI	direct-reduced iron
EAF	electric arc furnace
EIA	Energy Information Administration (U.S. Department of Energy)
EU	European Union
GHG	greenhouse gas
GJ	gigajoule
IEA	International Energy Agency
IPCC	Intergovernmental Panel Climate Change
kton	Kilo tonne (1000 metric tonne)
MJ	megajoule
Mt	million metric tonne
Worldsteel	Worldsteel Association