Deep decarbonisation of iron and steel industry in the age of global supply chain – issues and solutions

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Abstract
Deep decarbonisation of the global manufacturing sector is needed to achieve the climate targets under the Paris Agreement. As of September 2019, 77 countries have announced targets to be carbon neutral by 2050. However, in the age of globalisation, countries are concerned that decarbonisation leads to cost increases for industries, companies will move their production bases to countries with less strict energy efficiency and greenhouse gas (GHG) emission regulations. Such relocation of production base can demotivate countries to implement rigorous policies for industry decarbonisation and cause leakage, reducing the global impacts of decarbonisation. This paper uses the iron and steel industry as an example to check: 1) to what extent the above statement is true; and 2) how to address this global chain and cross-border issue in the decarbonisation of industries.

Introduction
During the Climate Action Summit convened by the UN Secretary-General in September 2019, 77 Countries, 100+ Cities Commit to Net Zero Carbon Emissions by 2050 (Kosolapova, 2019). The iron and steel industry is one of the main energy intensive-industrial sectors that provide essential raw material input for key economic sectors of the economy, from buildings, infrastructure, to automobiles and machinery. Despite that new and modern steel products are lighter and stronger, and increases in ferrous scrap, the global demand for steel has almost doubled since 2000, from 850 million tonnes (Mt) in 2000 to 1,808 Mt in 2018 (World Steel Association, 2019). In 2017, the steel industry generated €442 billion (€/US$ = 1.13 in 2017) value-added and hired over 6 million workers, and contributed a further US$1.2 trillion GDP and 39 million jobs through its global supply chain (World Steel Association, 2019). At the same time, despite technology progress, energy efficiency improvement and the shift to clean fuel, the enormous energy consumption and GHG emissions of the sector also attract much attention in the global efforts for clean energy transition and climate mitigation. In 2017, for each tonne of steel production, on average 0.48 tonne of oil equivalent of energy was used, and the 1.83 tonnes of CO_2 were emitted (World Steel Association, 2019).

How to decarbonise this important sector is a topic that is relevant for many countries, local governments, and enterprises in their efforts for realising climate change mitigation, urbanisation, and industrialisation. There are some studies on the technology roadmap for achieving the deep decarbonisation of the iron and steel sector. This paper will focus on the policy perspective for the deep decarbonisation of the iron and steel sector. It will cover the technology options for deep decarbonisation of the iron and steel sector, the future development trends of the sector, the main policies of main countries and regions, the barriers, as well as possible solutions.

About the global iron and steel industry

MAIN TECHNICAL PROCESS

The main technical processes of the iron and steel industry: ore agglomeration and sintering, coke-making, ironmaking, steelmaking, casting, and rolling (Jamison et al., 2015). The iron and steel industry starts with the mining of iron ore, rocks and minerals from which iron can be economically extracted. Iron ore is widely distributed, with production bases in each major region of the world (World Steel Association, 2018). The countries with the biggest iron reserves are Australia, Brazil, Russia, China, and Ukraine (US Geological Survey, 2020). The contents of iron in different irons vary, and in some cases, the ore needs to be processed to improve the grades of the ore. According to the World Steel Association (2020), in 2017, around 76 % of the global iron ore production is exported.

The biggest exporters are Australia and Brazil, Commonwealth of Independent States (CIS), while the top importers are China, the EU, and the US. The iron and steel industry includes multiple processes and products. From iron ore, through adding coke, such fossil fuels as coal, oil, and natural gas, the impurities in the iron ore can be reduced to produce pig iron. Pig iron can be further purified to produce crude steel, after further purification, the steel can be further produced into various shapes through casting, hot rolling, and cold rolling into various shapes and for different purposes. While some finished products can be made from each step of the process, there is also continuous furnace which can directly produce steel from iron ore.

The most import two processes for iron and steel production is the basic oxygen furnace and electric arc furnace. While in developed countries, the majority of production is based on electric arc furnace, in developing countries, there is still some production using blast furnace. In some of the less developed parts of the world, there is still some production using an open furnace.

Iron and steel, many different products. Production processes: The four main technical processes for steel production worldwide are the classic blast furnace/basic oxygen furnace, the direct melting of scrap (electric arc furnace), smelting reduction and direct reduction (DR) (Remus et al., 2013). Except producing steel from scrap, the other three technologies (blast furnace), electric arc furnace (EAF), and direct region iron (DRI) produce crude steel directly from iron ore and uses fossil fuels and additions to eliminate the residues (as indicated in Table 1) at high temperature.

THE COMPLICATED INTERNATIONAL SUPPLY CHAIN OF IRON AND STEEL

The World Steel Association also provides data on iron and steel production, as well as their imports and exports. Globally, foreign trade accounts for about 27 % of the total steel production, which means that the majority of the production is for local consumption. An analysis on the data on iron and steel production and trade indicates that globally, due to lack of market monopoly and global distribution of the production capacity of producing iron and steel from ore, the prices of iron and steel as raw materials fluctuate widely.

The International Energy Agency (IEA) attributes the high energy intensity of steel production in China to two factors. One is that 80 % of the steel production capacity is the basic oxygen furnace, which is more energy-intensive than the electric arc furnace used in Europe and the United States. Another factor is that in China, the main fossil fuel used for iron and steel production is coal, while in developed countries, the fuel used includes some less carbon intensive substitutes of coal and coke, such as natural gas, biogas, or even hydrogen.

Due to globalisation and the extensive use of iron and steel for many different uses, the international supply chain of the iron and steel industry is very complicated. For example, many countries are both exporters and importers of iron and steel raw material, semi-finished and finished products. The World Steel Association's annual publication, the World Steel Statistics, indicates that iron ore trade is a complicated matrix – buyer countries buy iron ore from different countries and sources, meanwhile seller countries also sell to multiple countries.

The iron and steel industry includes multiple technical processes and the products from these processes can be generally grouped as pig iron, Direction Reduction Iron (sponge iron), crude steel, hot-rolled products, semi-finished and finished steel products. Apart from that, steel scraps are imported and exported. As indicated in Table 1, the world statistics on steel export include a long list of different products.

Another issue regarding the complexity of the international supply chain of iron and steel is the large scale of indirect import and export of iron and steel. As iron and steel is widely used in many industrial products, exporting and importing these products lead to the indirect trade of iron and steel. As indicated in Table 2, many countries are both major indirect exporters and importers of iron and steel.

This also means that a country's iron and steel consumption can be for the country's own use; it can also be due to the production and trade of products with high steel content. A country's high per capita steel use can be due to the country's economic structure. One example is South Korea, the country with the highest per capita steel consumption in the world. South Korea has a big industry and produces and sells a large number of automobiles and appliances.

FUTURE PROJECTION – THE IRON AND STEEL PRODUCTS FROM DIFFERENT REGIONS

Generally, as countries develop, the share of manufacturing sector in their GDP declines, while that of the service sector expands; moreover, their industrial output also upgrades and the industrial product mix moves away from primary materials to high-tech and high value-added manufacturing.

The draft IEA technology roadmap for iron and steel industry projected that by 2050, the global steel production would see a 30 % increase from the 2015 level (Levi, 2019). China's production has already peaked and will slightly decline, the production in the EU and North America will see a minor increase, while the production increases will mainly come from other developing regions, especially South Asia and Africa.

Since 2000, a major change in the world iron and steel industry is China's rapid rise in production, consumption, and export. The country in 2018 accounted for 51 % of global steel production (World Steel Association, 2019). As indicated in Figure 1, the majority of China's iron and steel production is for domestic con-

Table 1. World Steel Exports, 2013, 2015, and 2018.

	2013 (Mt)	2015 (Mt)	2018 (Mt)
Angles. shapes and sections	22.1	21.7	22.7
Bars and rods. hot-rolled	18.1	40.7	18.7
Castings	0.7	0.8	1.3
Cold-rolled strip	3.5	3.9	4.5
Cold-rolled sheets and coils	33.0	32.8	35.7
Concrete reinforcing bars	18.9	18.9	18.8
Drawn wire	7.7	8.4	9.0
Electrical sheet and strip	4.0	4.1	4.6
Forgings	0.7	0.8	1.1
Galvanised sheet	37.1	37.6	44.7
Hot-rolled sheets and coils	67.3	77.7	79.0
Hot-rolled strip	3.0	2.9	3.8
Ingots and semi-finished material	54.1	51.8	62.0
Other bars and rods	4.9	5.3	6.4
Other coated sheet	15.4	16.3	17.9
Plates	29.0	30.1	33.3
Railway track material	3.0	2.1	2.6
Steel tubes and fittings	39.7	35.3	41.3
Tinmill products	6.4	6.3	6.8
Wheels (forged and rolled) and axles	0.9	0.8	0.9
Wire rod	24.2	29.0	27.6
Total	393.8	427.0	442.7

Source: World Steel Association, 2019.

Table 2. Major indirect importers and exporters of iron and steel.

Rank	Country	Indirect exports Mt	Rank	Country	Indirect imports (Mt)
1	China	79.4	1	United States	44.2
2	Germany*	35.6	2	Germany*	24.2
3	Japan	21.8	3	France*	12.7
4	South Korea	21.4	4	United Kingdom*	12.0
5	United States	19.8	5	China	11.8
6	Mexico	14.6	6	Mexico	11.5
7	Italy*	14.3	7	Canada	11.1
8	Spain*	9.9	8	Italy*	8.9
9	Poland*	9.0	9	Russia	8.2
10	France*	8.4	10	Belgium–Luxembourg*	8.2

Source: World Steel Association, 2019 (: Data for individual European Union (28) countries include intra-European trade).*

sumption, supporting the country's recent construction boom and the rapid expansion of its manufacturing sector, including automobiles and various machinery. It mainly imports iron ore from Latin America and Australia to meet its domestic demand.

During the process of industrialisation and urbanisation, countries' demand for iron, steel, cement, and other construction materials also surge due to massive construction of buildings, infrastructure, as well as industrial production capacity. The IEA projects that these global trends will continue and projected that from 2020 to 2050, China's iron and steel production would decrease, those of EU and North America will slight grow, while the production in Latin America, Middle East, Africa, and India will see fast increase. The iron and steel production of India, an emerging country in the process of industrialisation and urbanisation, is projected to grow by more than 400 % between 2015 and 2050 (Levis, 2019). By 2050, it is estimated that China's demand for iron and steel will be halved, while that in India will be tripled, that in Africa will multiply ten times (Pee et al., 2018).

Greenhouse gas (GHG) emissions from the iron and steel sector and the technologies for deep decarbonisation

ENERGY CONSUMPTION AND GHG EMISSIONS OF THE IRON AND STEEL SECTOR

Iron and steel industry contribute 5 % to 7 % of global GHG emissions. Apart from oil, iron and steel is the most important industrial raw material, accounting for 97 % of the global metal production.

The GHG intensity of iron and steel production varies, not only due to technology efficiency, but also due to local energy mix (coal or natural gas), energy from renewable sources, such

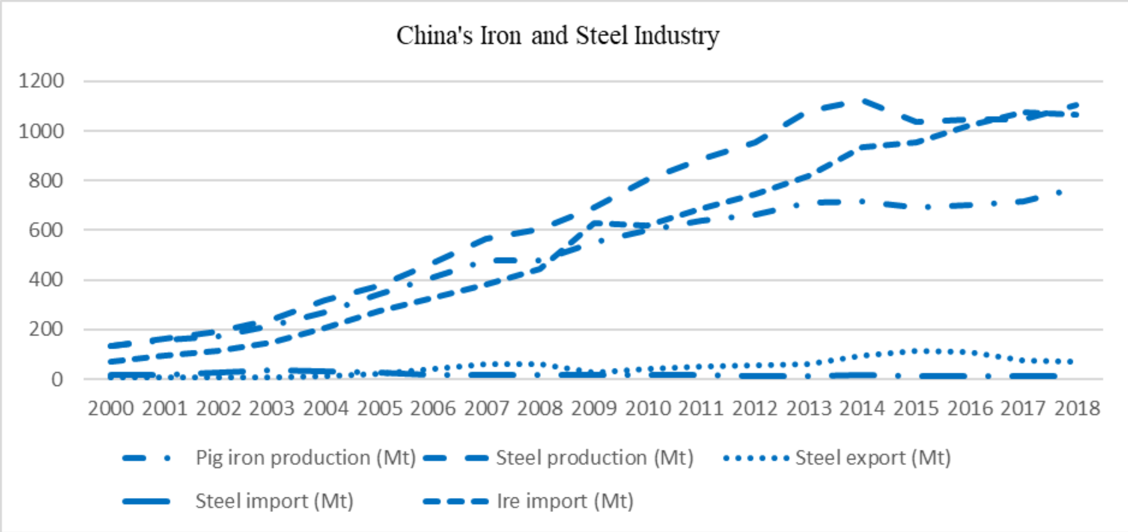

Figure 1. China's Iron and Steel Industry – production and trade. Source: Prepared by the author based on data from the China National Statistical Bureau (CNSB).

as biomass, and; new or old production facility (long use life of production facilities).

INFLUENCING FACTORS OF THE ENERGY AND CO_2 INTENSITIES

Hasanbeigi and Springer (2019) compared the energy and carbon intensities of steel production in different countries and regions and identified the following factors

The main technologies for steel making, whether it is Blast Furnace (BF), Basic Oxygen Furnace (BOF), or Electric Arc Furnace. Many developed countries have a high share of EAF-based steel production, while other countries mainly rely on iron ore to produce iron and steel. For example, in 2016, in China, EAF only contributed 6 % of steel production. This is one of the reasons behind the high energy and CO_2 intensities of China's steel production. Many developed countries' high share of EAF-based steelmaking is the main factor behind the low energy and emission intensity of their steel production.

Compared to coal and coke, natural gas is of higher heat content and less CO_2 intensity. Therefore, countries mainly using natural gas for iron and steel production tends to have lower and GHG intensity for each ton of iron and steel production than those using coal and coke. Canada and Mexico mainly use natural gas for their BF and BOF based steelmaking, which explains their relatively low energy intensity and CO_2 intensity for steel production.

The EAF process can use different stocks, from iron and steel scrap to pig iron from blast furnace, and Direct Reduction Iron (DRI), which uses natural gas to directly using natural gas to reduce the non-iron contents in iron ore in solid state. The EAF processes of China and India have higher energy and GHG energy intensities because they use more pig iron and DRI, while in developed countries, the EFA processes mainly use iron and steel scraps as feedstock.

This technology encompasses a broad group of processes based on different feedstock, furnaces, reducing agents, etc. Natural gas (and in some cases coal) is used as a reducing agent to enable this process. The metallization rate of the end product, called Direct Reduced Iron (DRI) or 'sponge iron', ranges from 85 to 95 per cent (often even higher).

TECHNOLOGIES FOR DEEP DECARBONISATION OF THE IRON AND STEEL SECTOR

The technical solutions for deep decarbonisation for the iron and steel sector include the following directions:

Resource efficiency

Reducing the resource input through stronger and lighter materials, improved quality, and extending the use life of products. One example is that over time, automakers are increasingly using weight reduction initiatives to improve the fuel efficiency performance of their vehicles (Natural Resources Canada, 2014).

Energy efficiency

Improving energy efficiency is another major solution for deep decarbonisation of the industrial sector, including iron and steel. As iron and steel production processes are energy-intensive, energy costs can contribute up to 40 % of the production costs of iron and steel plants. In such a situation, measures for energy efficiency can help industrial plants save energy costs and increase their market competitiveness.

Switch to low-carbon or zero-carbon energy sources

Another group of measures can be called switch to low carbon or renewable energy sources, like from coal to natural gas, biogas, or hydrogen and electricity from renewable or low-carbon sources. Such switches depend on the technology and equipment of the iron and steel production facilities, the availability of alternate low-carbon and zero-carbon energy sources, as well as their prices compared to the original fuel.

The switch to low-carbon or zero-carbon energy sources can reduce low air pollution and contribute to improved national energy security. Therefore the industrial enterprises may get some economic returns or social recognition for such switch, in the form of subsidies, tax reductions, or improved public image as green and clean.

Carbon capture and storage (CCS)

CCS represents one option that allows the continued use of fossil fuels while reducing GHG emissions into the atmosphere and avoiding climate change. In practice, this means the exhaust gases from the chimney has to be collected, purified and sent to underground geographic formations like deserted mines. The process costs money and uses energy. The IEA (2016) report found that 20 years after the Sleipner CCS project starting operation in Norway in 1996, the number of large-scale CCS projects only grew to 15 in 2016, with a further six projects to commence operation before 2018. The report assessed that the main barrier to the deployment of CCS technology is changing in policy and financial support. The total cost of CCS can range from €22/ton CO_2 to €168/ton CO_2 and includes the costs of capturing CO_2 from exhaust gases, transporting captured CO_2 to a storage site, and storing it (IES, 2018).

Recycle and reuse

Ekdahl (2019) from the World Steel Organisation projected that by 2050, the global annual steel scrap could increase from 380 Mt in 2018 to 900 Mt by 2050. The deep decarbonisation can also be achieved through the utilisation of waste heat and waste gases from iron and steel production.

In contrast to the slow development and CCS, China started building its first high-speed railway in 2007, connecting Shenzhen and Guangzhou, with a maximum speed of 250 km/h. By 2018, China's high-speed railway network had expanded to a total length of 29,000 km, and the maximum speed, safety, and comfort have all been improved over the years (Lawrence, Bullock, Liu, 2019).

Similarly, to speed up the research, development, and deployment of deep decarbonisation technologies, strong and effective policy plays a key role. The main success factor behind the high-speed railway technology progress is massive government investment in the technology research and development and well as huge government investments in the technology deployment.

Although developed countries' domestic demand for steel has been stable or slightly decrease and their share of iron and steel production has been decreasing, they are still the main sources of technology innovations in iron and steel sector, due to their strong technology base, high research and development spending, as well as big research teams. Data from the OECD (2015) indicates that in 2012, the An OECD report (2015) indicates that in 2012, globally there were around 3000 steel patents categorised as low carbon, except for the fewer than 100 from China, Chinese Taipei, and India, the majority came from OECD countries, especially the United States, Germany, and Japan. At the same time, the global manufacturing activities, especially heavy and raw material industries, are increasingly moving to emerge countries. In such context, how to provide the necessary technology transfer, capacity building, as well as financing support to speed up the climate change mitigation in developing countries is a key issue that dominates the global climate negotiations (Diringer, 2016).

Table 3. Influencing factors to the energy and GHG intensities of iron and steel industry in different countries.

No.	Influencing factors	Notes
1	The share of EAF (Electric Arc Furnace) steel in total steel production	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 (Blast Furnace) and BOF (Basic Oxygen Furnace), which producers steel from iron ore.
2	The fuel shares in the iron and steel industry	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.
3	The electricity grid CO_2 emissions factor	The grid's CO_2 emission factor is especially relevant for the countries highly depending on EAF for steel making, due to their high electricity consumption in the steel making process.
4	The type of feedstock in BF-BOF and EAF	Iron ores from different mines can be of different iron contents and purity. The quality of the iron ore, and whether the input EAF is iron and steel scrap, or pig iron or DRI, can infect their energy intensity.
5	The level of penetration of energy-efficient technologies	Iron and steel making cover multiple processes and the penetration of energy-efficient technologies and the use of waste heat/furnace gas can influence the overall energy efficiency level from the iron and steel making process.
6	The steel product mix in each country	There are many different steel products of different shapes, sizes, and contents, which can be made through casting/rolling/finishing process, which have much different energy requirements.
7	The age of steel manufacturing facilities in each country	With technology progress, among facilities applying the same technologies, newer ones tend to be more efficient than old ones.
8	Capacity utilisation	Higher capacity utilisation improves overall energy performance compared to lower capacity utilisation if all other factors remain constant.
9	Environmental regulations	Generally, stringent environmental regulations lead to higher energy efficiency and lower GHG emission intensities.
10	Cost of energy and raw materials	Expensive energy and raw materials can motivate enterprises to invest in energy efficiency and raw material saving, while cheap energy and raw materials lead to lower economic returns from energy and raw material saving.
11	Boundary definition for the steel industry	Different countries can have different boundaries on the iron and steel industry. For example, in some countries, coke production is considered part of the iron and steel industry; in other countries, it is not considered.

Source: based on information from Hasanbeigi and Springer, 2019.

The main policies and measures for energy efficiency and GHG emission reduction in the EU, US, China, India

EU – EU ETS AND THE EU ENERGY EFFICIENCY DIRECTIVES

EU's main climate policy for big emitters, like the iron and steel industry, is the EU Emission Trading Scheme (EU ETS). The EU ETS started in 2005 and aimed at helping the energy and industry sectors to cut their CO_2 emissions in a cost-effective way. It requires a cap on emissions for more than 11,000 heavy energy-using installations from the energy and industrial sector and covers 45 % of the EU's greenhouse gas emissions. In 2020, emissions from sectors covered by the system will be 21 % lower than in 2005. The EU is on track to surpass this target. In 2030, emissions from sectors covered by the EU ETS will be cut by 43 % from 2005 levels, as part of the EU's current 2030 climate and energy framework. Under the European Green Deal, which is at the proposal stage, EU set the ambitious targets to be climate neutral by 2050; this will also include further tightening of the EU ETS targets.

In the early days of the EU ETS, the emission allowances were allocated for free to the participating facilities. Over time, the free allocation has been shifting to auctioning. Industrial facilities have to buy allowances for their emissions exceeding the free allocation limit; they can sell the surplus if their emissions are lower than their allowances. The EU ETS prices were below 8 Euros per ton of CO_2 during much of 2012 to 2018, due to accumulation of allowance surplus. After repeated efforts to reduce the surplus and postponing new auctions, the price has been in the range of 20 to 25 Euros per ton of CO_2 since 2018 (Carbon Market Watch, 2019).

The EU ETS, despite its overall success, has achieved limited effects in lowering the GHG emissions from the iron and steel and other carbon-intensive industrial sectors for two reasons. One is the low prices of the emission allowances, which is insufficient to motivate changes in industrial facilities which have long use life. Another reason is due to concerns about carbon leakage and international competition, and stringent requirements in emission reduction and energy efficiency improvement may motivate industries to move their production to areas with cheaper energy and less stringent emission reduction requirements, the EU has been generous in emission allowance allocation to industries. In fact, the Carbon Market Watch (2019) noted that from 2012 to 2018, the annual allowance allocations for industries was between -1.5 % and 0.4 % of the actual emissions; during the same period, the emission allowance allocation for the power sector decreased by 22 %. The report attributed to emission reductions of the EU ETS covered facilities mainly to the shifting from coal to natural gas and renewable energy in the power sector (Carbon Market Watch, 2019).

Even among the energy-intensive industries, the EU ETS attaches importance to the issues of carbon leakage during its allowance allocation. Although the power sector has to obtain their emission allowances through auctioning, steel is one of the sectors that can continue getting free emission allowance allocation until 2030. For example, in 2018, the allocation for cement is 96 % of the actual emissions of the previous year, while that for the iron and steel sector is 116 %. This is because unlike iron and steel, which is traded globally, cement is cheap and heavy, and land transportation costs are high. In Europe, cement is usually produced for local supply, and it is not economically viable to sell cement beyond a radius of 200 or at most 300 km (Cembureau, 2017).

EU's main energy efficiency policy covering the iron and steel sector is the Energy Efficiency Directive, which was first issued in 2012 and then amended in 2018. The 2012 version established a set of binding measures to help the EU achieve its 20 % energy efficiency improvement target by 2020.[1] The 2018 revision further established the goal of 32.5 % energy efficiency improvement by 2030. These targets are also published in terms of primary energy consumption and financial energy consumption for 2020 and 2030. Unlike the EU ETS, whose implementation is mainly at the EU level, the Energy Efficiency Directives are mainly implemented by the member countries; each member country regularly prepares their National Energy Efficiency Action Plan and submit them to the EU for approval and reports its implementation progress to the EU.[2]

US – POLICIES AT THE STATE LEVEL

The US is the third biggest producer of iron and steel in the world. It does not have strong national policies that require its iron and steel sector to take ambitious actions towards energy efficiency improvement and GHG emission reduction. Despite the US federal government never ratified the Kyoto Protocol and had withdrawn from the Paris Agreement, some States had been active in climate change mitigation. For example, California enacted its Global Warming Solutions Act of 2006 and was the first state in the nation to adopt an economy-wide cap-and-trade program. During between 2005 and 2016, the twenty states which are members of the United States Climate Alliance achieved 14 % reduction in GHG emissions through policies that encourage investments in clean energy and energy efficiency (United States Climate Alliance, 2019).

CHINA

China's energy efficiency and climate change mitigation policies for the steel sector include three main components: 1) energy intensity targets for the iron and steel sector; 2) mandatory closure of small and inefficient production capacity; 3) the Top 10,000 Enterprises Programme; and 4) the National Emission Trading Scheme.

1. **Energy intensity targets for the iron and steel sector.** In 2004, China enacted its 2020 Energy Conservation Plan, which set the target for iron and steel industry that by 2020, the energy efficiency for steel making should be close to or reach advanced international standards. In the following five-year plans for 2006–2010, 2011–2015, and 2016–2020, the energy intensity improves targets were further specified and used as a reference for approval of new projects.

1. Baseline of the 20 % energy efficiency improvement in the 2012 EU Energy Efficiency Directive are Projections made in years 2007 for energy consumption in the year 2020. The target was set as 20 % reduction from the projected value.

2. Table 4: The 2020 and 2030 targets for EU-27 are based on a technical adaptation provided by the EU.

Table 4. EU Target for Energy Efficiency Improvement after Brexit.

	2020	2030
EE target	20 %	32.5 %
The upper limit for primary energy consumption for EU-27 after Brexit (Mtoe)	1,312	1,128
The upper limit for final energy consumption for EU-27 after Brexit (Mtoe)	959	846

Source: Eurostat, 2020.

2. **Mandatory closure of the small and inefficient production capacity.** Through establishing energy intensity improvement targets for 2005–2020 and for each five-year period, as well as energy intensity benchmarks and technology catalogue for market entry, the government gives clear signals for investment flow to energy efficiency in the iron and steel sector. Mandatory closure of inefficient and polluting production capacity. The government includes energy efficiency as a criterion in new investment approval, provides fiscal and taxation support for energy efficiency renovation, and set targets for mandatory closure of inefficient and polluting production capacity. For example, in its guidance on the closure of outdated production capacity of the iron and steel sector (NDRC, 2006), the National Development and Reform Commission set the targets that during 2006 to 2010, approximately 100 million ton of iron production capacity had to be closed, and 55 Mt of outdated steel production capacity had to be closed by 2007.
3. **The Top 10,000 Enterprises Programme.** The Top 10,000 Enterprises Programme combines voluntary energy agreement, mandatory energy audit, and annual energy performance assessment. It started with the Top 1,000 Enterprises Programme with annual energy consumption above 180,0000 tons of coal equivalent (tCe) during 2006–2010, and further expanded to the Top 10,000 Enterprise Programme since 2010. The latter actually cover more than 17,000 enterprises with annual energy consumption exceeding 5,000 tCe.
4. **National Emission Trading Scheme.** In 2011, China launched seven local pilot CO_2 emission trading schemes in different parts of China. The national ETS was formally launched in 2018. Although the national ETS has a long-term target of covering both power sector and big industrial energy consumers, so far the enforcement of industrial sector, including iron and steel, has been delayed due to concerns about carbon leakage and international competitiveness.

INDIA

India produced 106 Mt of crude steel in 2018, only second to China. Per capita finished steel consumption in 2017 is placed at 212 kg for the world and 523 kg for China, and for India it was 69 kg as published by World Steel Association. India is the largest producer of sponge iron in the world and the 3rd largest finished steel consumer in the world after China and the US (Drishti, 2019).

In India, the iron and steel industry is covered by the PAT (Perform, Achieve, and Trade) scheme for the power sector and energy-intensive industries. Under PAT, each participating enterprise is allocated a target for energy efficiency improvement, if they overachieve, they get Energy Saving Certificates or ESCerts, each equal to 1 metric tonne of oil (Mtoe) and can sell them. If they underachieve, they have to buy ESCerts. PAT Circle 1 for 2011–2014 covered 101 iron and steel enterprises, each with an annual energy consumption above 30,000 ton oil equivalent (tOe) (Dhingra, 2011). On the basis of success from PAT Cycle I, the PAT coverage has been expanded to new sectors and cover more enterprises. PAT Cycle V will last until 2022 (Bureau of Energy Efficiency, n.d.).

International governance for deep decarbonisation

THE PARIS AGREEMENT

The Paris Agreement sets the global long-term temperature goal of limiting the global average temperature rise to well below 2 °C above pre-industrial levels; to pursue efforts to limit the increase to 1.5 °C. However, it is based on voluntary national pledges for GHG emission reduction – countries propose their own Nationally Determined Contributions and report the progress of their actions. There lacks a compliance system to encourage countries who do more on climate change mitigation and penalise countries who either set insufficient mitigation targets or fail to achieve their targets. Despite repeated record high temperatures around the world, the United Nations' assessment is that globally, the gap for achieving the 2 °C climate target has been widening in the past decades (UNEP, 2019). With the recent waves of nationalism, populations, and protectionism, many countries are concentrating on their own immediate interests, and ignore the scientific community's call for immediate and deep climate action.

Developed countries as a whole lack the strong political will from main countries to take the necessary ambitious targets, and provide the necessary technology, financial, and capacity support to developing countries on climate change mitigation (Tannenberg, 2019).

Even though the EU ETS and the Chinese ETS cover the iron and steel industry, they have not yet provided deep emission reductions from the EU and the Chinese iron and steel sector yet. They are worried about international carbon leakage and moving of iron and steel production to countries without stringent mitigation requirements, the EU. In the United States, the federal government has withdrawn from the Paris Agreement, while some states have their local emission trading system. India's PAT scheme for iron and steel energy efficiency only started in 2014.

CARBON LEAKAGE AND BORDER TAX

Regarding the impacts of international development on the host countries' energy efficiency, GHG emissions, as well as other pollutant emissions, there are two hypotheses: pollution havens and the pollution halo. The pollution halo hypothesis argue that multinational companies through foreign direct investment (FDI) transfer their greener technology to host country. In contrast, the pollution haven hypothesis posits that, when large industrialized nations seek to set up factories or offices abroad, they will often look for the cheapest option in terms of resources and labor that offers the land and material access (Asghari, 2013). In the climate mitigation making, so far the US, the EU, and China seem to believe in the pollution haven hypothesis, i.e. stringent energy and climate regulations will lead to losses of market share, job, and investment. Indriya and Widodo (2011) studied the trade patterns of dirty products in East Asia and found weak evidence of carbon leakage and pollution.

Both the US and the EU have threatened to use border tax to shield their products and enterprises from market share loss and force their main trade partners to adopt equally stringent emission and energy efficiency standards (Morris, A.C., 2018; European Commission, 2019).

In its Green Deal, proposed legislation for achieving climate neutrality by 2050, the EU plans to introduce a carbon border tax, to shield European steel producers and other energy-intensive industries against cheaper imports from countries with less strict climate policies (European Commission, 2019). To follow the WTO principles of national treatment and non-discrimination, the border tax should be the same for the same products from all countries and treat the EU's own production and imported products in the same way. A border carbon tax is a concept attractive to the public, but difficult to implement in practice, as it would require detailed and reliable data to calculate the GHG emissions during all steps before a product reaches the EU border. Zachmann and McWilliams (2020) evaluated the EU border carbon tax proposal and thought it would be very difficult to implement. One issue is the global supply chain makes it very difficult to get accurate data on the energy consumption and GHG emissions during a product's entire supply chain by the time it reaches the importing country.

The EU's failed attempt to enforce an aviation emission tax back in 2012 reflects the difficulties of border tax in implementation. In 2012, the EU started to include civil aviation in its ETS in 2012 and required all flights landing in or departing from EU. to pay aviation emission tax. However, the policy was boycotted by airlines from other countries, including the US, China, Russia, and India. In late 2012, the EU agreed to suspend imposing carbon emission taxes on flights of non-EU airlines in and out of the EU, while continuing to enforce it on flights inside the EU (Liang and Zhang, 2014). Since 2018, the US government has imposed 25% import tariff on its iron and steel import from multiple countries, under the excuse of national security considerations.

SECTORAL APPROACH

Another idea on international cooperation on climate mitigation in specific industrial sectors is the sectoral approach, an idea advocated by multiple international scholars during the designing of the post-2012 international climate regime (CEPS, 2008; Egenhofer & Fujiwara, 2009).

One justification often mentioned by advocators for the sectoral approach is for practical reasons: as many of the small and least developed countries do not have these industries, a sectoral approach can reduce the number of participating countries, hence make it easier to reach an agreement and implement the agreed mitigation.

In the international climate negotiations, there are two successful examples of using a sectoral approach to put climate change mitigation under special international organisation coordination: international civil aviation and international maritime. Under the UNFCCC, countries only need to report the GHG emissions from their jurisdiction. Therefore, international civil aviation and international maritime, despite the big size and continuous growth of their GHG emissions, are not included in national commitment for emission reductions. How to coordinate international efforts and speed up GHG emission reduction in these two sectors had been an issue much debated in the international climate negotiations. The issue of emissions from international aviation was solved in 2016, putting this under the administration of the International Civil Aviation Organisation (IACO), which include two global aspiration goals. One is 2 % annual fuel efficiency improvement for international aviation through 2050, and the other is carbon-neutral growth from 2020. In 2018, the UN International Maritime Organisation (IMO) committed to peaking the GHG emissions from international shipping as soon as possible, reducing the total annual GHG emissions by at least 50 % by 2050 from the 2008 basis, and pursuing efforts towards zero-emission.

The difference between the iron and steel industry is that international aviation and international maritime are never included in national GHG inventories, and there exist strong international coordination bodies. The World Steel Association mainly focuses on data collection and publishing, is not as powerful as the UN agencies IMO and IACO. There is also the question of whether to limit the sectoral approach to iron and steel industry, or to all energy-intensive sectors, such as cement, petrochemicals, metallurgy, fertiliser. The United Nations Industrial Development Organisation (UNIDO) is the UN agency specialising in clean development of industry. Moreover, UNIDO and UNEP jointly host the 'Climate Technology Centre & Network', the main mechanism for providing support to developing countries in climate technology issues.

Conclusions

The iron and steel industry is one of the main energy-intensive industries with high GHG emissions. As the majority of world iron ore reserve concentrate in a few countries, the international iron ore export rate is quite high. As for the production and consumption of iron and steel, international data indicates that the majority of the global production is for domestic consumption, international trade only accounts for around one-fourth of the total production.

Iron and steel are basic materials used in many industries, from materials for buildings and infrastructure, parts and components for automobiles, trains, equipment, and appliances. Countries' consumption for iron and steel tend to increase rapidly during urbanisation and industrialisation, while developed countries' per capita iron and steel production remains stable or gradually decline. A big change in the world iron and steel industry is the rapid growth of iron and steel production and consumption in China. China's iron and steel production have peaked, and it is projected that the global growth in iron and steel production and consumption will mainly take place in India and some African countries, which will undergo rapid industrialisation and urbanisation.

Developed countries still own the majority of the patents for low-carbon technologies for the iron and steel sector. How to enable big developing country producers of iron and steel production gain access to and deploy the low-carbon technologies is key for deep decarbonisation of the iron and steel sector worldwide. In countries, strong and effective policies are needed to motivate enterprises to invest in low-emission technologies.

Carbon leakage and market share and job loss are main concerns that prevent countries from requiring deep decarbonisation of the iron and steel sector. One of the solutions the EU and the US have resort to is border tax. Although border tax is politically attractive, they are difficult to implement. Another option is the sectoral approach for international governance of steel and iron industry decarbonisation.

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