Institute of Energy Economics
at the University of Cologne

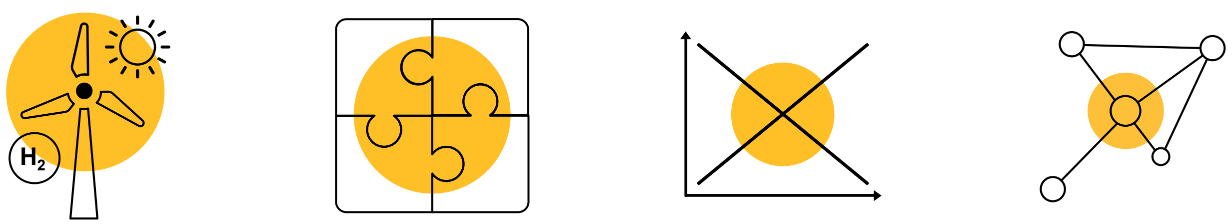
EWI analysis

Low-carbon steel

A global cost comparison

On behalf of:

Gesellschaft zur Förderung des Energiewirtschaftlichen Instituts an der Universität zu Köln e. V.



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Executive Summary

This analysis investigates the long-term production costs and competitiveness of the largest steel-producing countries. It is assumed that energy systems will be green, green hydrogen is available as a traded commodity, and large-scale infrastructure for CO_2 transport and storage exists.

Why is the steel sector important?

Steel is a critical industry for countries worldwide. It is a crucial input for many products of modern societies, such as transport, buildings, infrastructure, and household products. Steel is particularly relevant for the energy transition since it is a critical material for technologies such as solar panels, wind turbines, and electric vehicles. Key facts about steel:

- The steel sector is responsible for 8 % of global greenhouse gas (GHG) emissions
- Steel production relies on coal which makes up 75 % of the sector's energy demand
- Steel demand is expected to increase in the coming decades

The role of steel at the Conference of the Parties (COP)

With each COP, the topic of climate protection and decarbonization comes back into focus worldwide. In 2021 at COP26 in Glasgow, 29 countries representing over 30 % of the global steel production pledged to establish near-zero emissions steel production by 2030. The Steel sector was considered with one of the five goals (the Glasgow Breakthrough):

"Near-zero emission steel the preferred choice in global markets, with efficient use and near-zero emissions steel production established and growing in every region by 2030." (UK, 2021)

The UN Climate Change High-Level Champions (2022) highlight that the global pipeline of conventional steel plants is underway or in the planning stage. A "U-turn" is necessary where coal-based steel production is ramping up or is dominant. The 2022 Breakthrough Agenda launched after COP26 stresses, among others, the following short-term key priorities for the steel sector:

"Governments and companies (…) should collectively agree on common definitions for low emission and near-zero steel…"
"Governments (…) should find agreeing ways to ensure that near-zero steel can compete in international markets."(IEA, 2022b)

The decarbonization of the steel industry in Germany

A wide range of climate neutrality studies assumes that until 2045/2050, primary steel needs to be produced in Germany to a full extent via DRI. In addition, the less energy and emission-intensive secondary steel production is assumed to increase (EWI, 2021b).

The "*Handlungskonzept Stahl*" (steel action plan) of the Federal Ministry for Economic Affairs and Climate Action (BMWK) identifies three main challenges for the transformation of the German steel industry (BMWK, 2020):

Executive Summary

1. Equal opportunities in the global steel market
2. Preventing carbon leakage
3. Driving transformation together

In essence, these challenges indicate that the shift to lower-carbon production processes shall not be at the expense of the competitiveness of individual companies; or entire countries.

Only a quarter of globally produced steel is traded globally

In 2021 a quarter (460 Mt) of crude steel was exported. Only 60 % (277 Mt) of this quarter accounted for extra-regional exports. Hence, steel is mainly produced for domestic or for intra-regional demand today.

Excess capacity is a structural problem of the global steel market

The steel sector faces the structural problem of excess capacity, which undermines the global steel market’s functioning. In 2020 the global crude steel production capacity continued to increase and is expected to increase even further. This study thoroughly overviews the global steel market and its most important players.

Thereinafter, potential options for cutting emission in the steel industry, production costs for various countries, and production routes are calculated and discussed.

Scenario analysis for a transition of the steel industry

In this study, we consider three different scenarios for the transition of the steel industry. The analysis focuses on China, India, Russia, the United States (US), Japan, and Germany. These countries have been responsible for 1,449 Mt of crude steel production, a share of 74 % of the global crude steel production in 2021 (1,951 Mt). We investigate production costs and the cost gap between these countries.

Low-carbon steel requires green hydrogen or CCS

The steel industries' emissions can be decreased substantially using either renewable energies and green hydrogen or fossil energies with carbon capture and storage (CCS). This analysis considers two process routes of integrated iron- and steelmaking plants with different reducing agents and with or without CCS.

The conventional blast furnace – basic oxygen furnace (**BF-BOF**) route is the most emission-intensive steelmaking route. More than 80 % of the emissions stem from iron making in the blast furnace using coke as a reduction agent.

The direct reduction iron - electric arc furnace (**DRI-EAF**) steelmaking routes are significantly less emission-intensive. Using natural gas for syngas production and heating is less emission-intensive than coal.

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The application of CCS further reduces the carbon footprint of these steelmaking routes. For the **BF-BOF+CCS** route, carbon capture reduces the emission intensity by 83 % compared to the unabated process. For the **DRI-EAF+CCS** route, the emission intensity reduces by 84 % compared to the unabated DRI-EAF process using coal and by 80 % compared to the unabated DRI-EAF process using natural gas.

The technology with the lowest emission intensity is **hydrogen steelmaking**. The emission intensity of hydrogen steelmaking is 58 % lower than DRI-EAF+CCS using natural gas or 97 % lower than conventional steelmaking via the BF-BOF route.

Highest production costs in Germany and Japan

Due to high energy and labor costs, steelmaking in Germany and Japan is the costliest of all compared countries. In the case of hydrogen steelmaking, Japan is more expensive than Germany due to high hydrogen costs. The cost gap between the region with the highest and lowest production cost ranges in all case studies between 20 and 26 %.

The cost gap for low-carbon steel is not larger than the historical cost gap

If the same uniform CO_2 price or technology specification applies in all countries , the production cost gap does not increase compared to the historical cost gap of 45 %. Despite the historical cost gap, today, all analyzed countries except the US produce self-sufficient or are net exporters.

Competitiveness is not only determined by production costs

Steel is mainly produced near the demand. Crude steel is traded globally to a lesser extent than raw materials such as iron ore or coal. Thus, potential future cost gaps do not mean that a specific region cannot produce competitively. Other reasons for competitiveness might be the directive of self-sufficient production and spare capacity, steel quality, security of supply, or lower transport costs.

CCS could play a crucial role in the competitiveness of low-carbon steel

In the scenarios, coal-based DRI-EAF is the most economical technology unless natural gas is available for low prices, as in Russia and the US. For a CO_2 price range from approximately 80 to 500 $/t, DRI-EAF+CCS steelmaking is the most economical route in all countries, with the condition that CCS is allowed and that pipeline transport from the steel plant to the storage site exists.

Hydrogen steelmaking requires high CO_2 prices to be competitive

Hydrogen steelmaking has high marginal abatement costs and requires a CO_2 price of at least 500 $/t (India) and up to 750 $/t (Germany) to be economical in the analyzed countries.

Executive Summary

Graphical abstract

Status quo

Steel production

Steel trade

Country-specific cost assumptions

Energy

Raw materials

WACC

Labor

CO_2 transport & storage

Processes

BF-BOF*

DRI-EAF**

Electrolysis

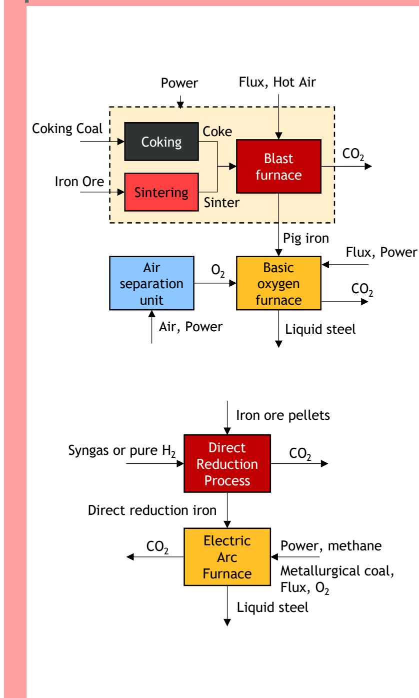
Carbon Capture & Storage

Coal gasification

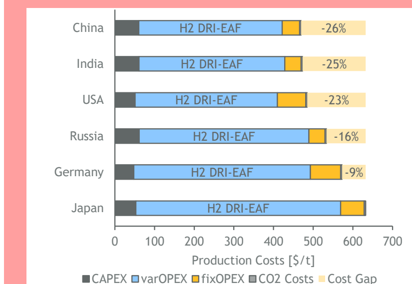
Steam methane reforming

Country-specific estimation of iron- & steelmaking costs based on green electricity

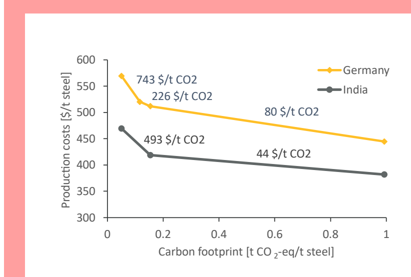
Mass & energy balances of processes



Production costs & cost gap



Marginal abatement costs



Scenarios

Emission reduction scenarios

1. Hydrogen steelmaking
2. Open to all technologies
   – At low CO_2 price
   – At high CO_2 price

Analysed countries

- China
- India
- Japan
- US
- Russia
- Germany

*blast furnace – basic oxygen furnace, **direct reduction iron – electric arc furnace

1 Overview of the global steel market

- The role of steel in the global economy
- The global steel market
- How is iron & steel produced today?
- Global steel trade
- Cutting emissions in the global steel production
- Policy measures reducing emissions in the steel industry
- The role of steel at the Conference of the Parties (COP)

The role of steel in the global economy

The iron & steel sector is a critical industry for countries worldwide. Steel is a crucial input for many industrial products of modern societies, such as transport, buildings, infrastructure, and household products. Steel is particularly relevant for the energy transition since it is a critical material for technologies such as solar panels, wind turbines, and electric vehicles. Thus, steel plays an important role in the global economy, having an annual revenue of over USD 2.5 trillion.

Around 6 million people worldwide are employed in the steel sector (IEA, 2020c). Currently, 330.000 jobs in the EU are directly related to steel production (European Commission, 2021).

Steel production has increased significantly over the last decades, driven primarily by increased steel production in emerging and developing markets.

Steel production is highly energy and emission-intensive. The sector is the largest industrial coal consumer (IEA, 2020c). The steel sector is one of the sectors considered as hard to abate. The growth of global steel consumption, the long investment cycles due to the capital-intensive nature, competitive markets, high costs of low-carbon technologies, and low- to medium technology readiness are reasons for this (MPP, 2022). However, cutting GHG-emissions in the steel sector is crucial for reaching global climate targets.

Global supply chain disruptions and increasing energy prices impact global steel consumption (EUROFER, 2022). Recent developments, such as the significant demand reduction as a result of the COVID-19 pandemic, form a challenge to the European steel sector (European Commission, 2021).

The steel sector faces the problem of excess capacity. This excess capacity undermines the global steel market's functioning. In 2020 the global crude steel production capacity continued to increase. Reduced steel production and demand in 2020, increased global overcapacity in the steel sector. Overcapacity reached 624.9 Mt in 2020. Global crude steel production capacity is also expected to expand further in the upcoming years. This will intensify supply-side pressure for steel-makers worldwide (European Commission, 2021; OECD, 2021). As a result, since 2015, margins have been low in the steel market (IEA, 2020c).

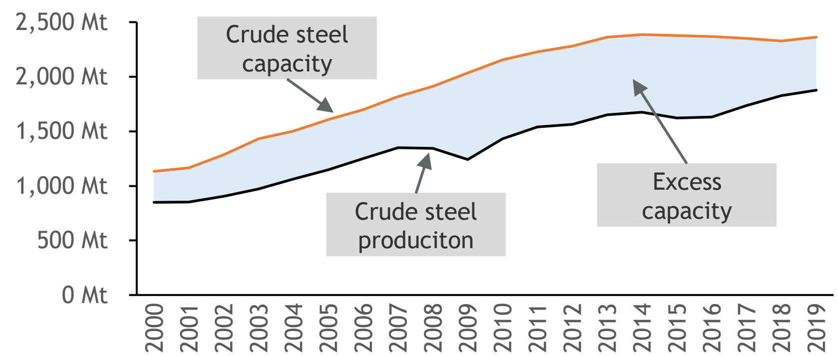


Figure 1: Global crude steel production, capacity, and excess capacity, source: own illustration based on World Steel Association (2022) and OECD (2022)

The global steel market

Since 2001 global crude steel production has doubled (World Steel Association, 2022). In particular, the growing demand for and production of steel in developing and emerging economies is responsible for the sharp increase of production volume from 1,540 Mt in 2011 to 1,951 Mt in 2021 and has driven global production growth. The production volume in advanced economies remained relatively stable over the last decade. Steel production saw a visible decline in 2020 in advanced economies but reached the pre-pandemic level again in 2021 (IEA, 2022e; World Steel Association, 2022).

In 2021 1,951 Mt of crude steel was produced worldwide, with an increase of 3,8 % compared to 2020. More than half of the global steel production is located in China. The country produced 1,032 Mt of crude steel in 2021. Following China by a significant margin, India (118 Mt), Japan (96 Mt), the US (86 Mt), and Russia (76 Mt) have been the largest steel-producing countries in 2021 (World Steel Association, 2022).

In the European Union (EU), Germany (40 Mt), Italy (24 Mt), Spain (14 Mt), and France (14 Mt) have been the dominating steel producers in 2021. The steel sector plays an important role in Germany. In 2021 Germany was the worldwide eighth-largest producer of crude steel (World Steel Association, 2022).

This analysis focuses on China, India, Russia, the United States (US), Japan, and Germany. These countries have been responsible for 1,449 Mt crude steel production, a share of 74 % of the global crude steel production in 2021.

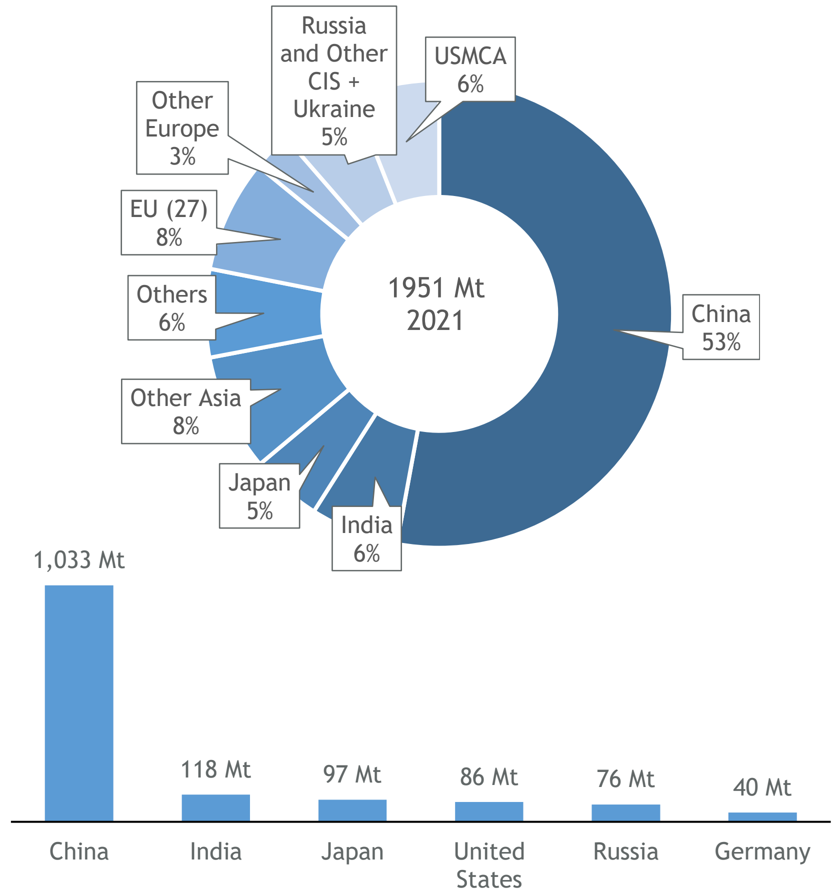


Figure 2: Crude steel production in 2021 globally and for selected countries
Source: own illustration based on World Steel Association (2022)

How is iron & steel produced today?

Steel can be produced via different production processes. The quality of crude steel, the input, and the energy intensity of the production process can differ significantly.

70 % of global steel production uses iron ore as the main iron source. When iron ore is the main input, this is referred to as primary steel production. Recycled steel scrap accounts for the remaining share. When steel is primarily produced with scrap, it is referred to as secondary steel. Nevertheless, also primary steel production typically uses 15-25% of scrap in its production process (IEA, 2020c).

Iron is produced by two major processes today. The **blast furnace process** produces pig iron and accounts for 92 % of the iron produced today. The **direct reduction process** produces direct reduction iron (DRI) or so-called iron sponge, which accounts for 8 % of the iron produced today (World Steel Association, 2022).

A distinction in the steel production processes is primarily made between the **basic oxygen furnace (BOF) route** and the **electric arc furnace (EAF) route**.

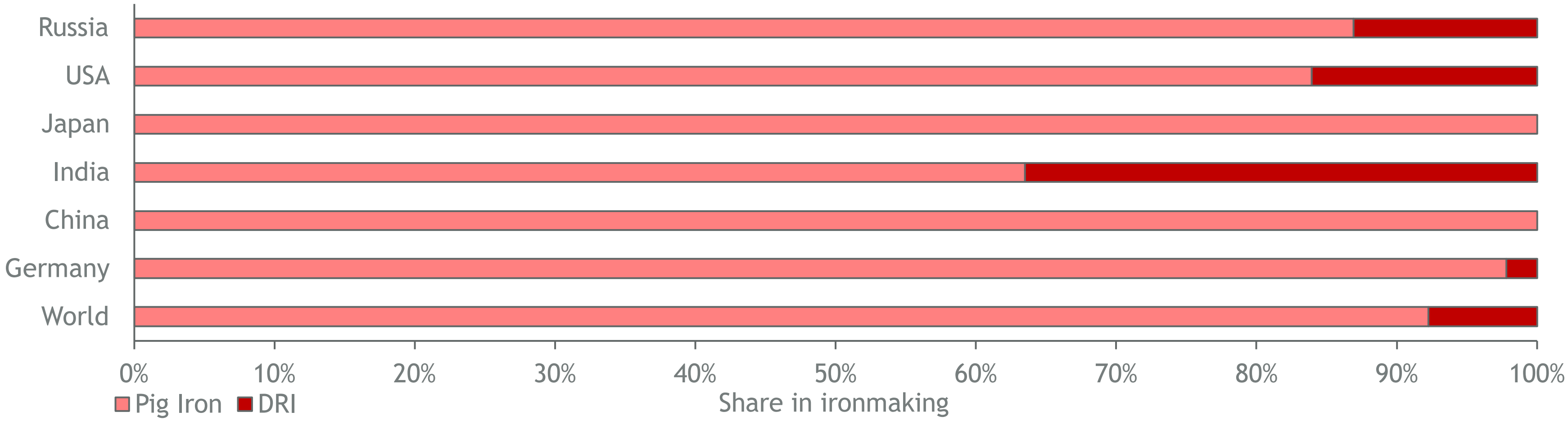
The BOF route produces only primary steel based on coking coal. The EAF route can produce either primary steel with direct reduction (DRI-EAF) or secondary steel using steel scrap. Currently, natural gas is used for the DRI-EAF route. Compared with the BOF route, the DRI-EAF route emits around half the emissions. Even fewer emissions are emitted when secondary steel is produced from steel scrap (World Steel Association, 2022).

Worldwide the BOF route is the dominant production process for crude steel. In 2022 70 % of global crude steel was produced by the BOF route, while 29 % was produced via the EAF route. Other processes, including the highly emission-intensive open-hearth furnace (OHF) route, only made up a marginal share of 0.3% (World Steel Association, 2022).

However, the share of production processes in crude steel production differs among countries and countries (see figure 3) In Germany, 70 % of the crude steel production uses the BOF route. In the EU, 56 % of the crude steel production is produced by the BOF route. However, in some EU countries, e.g., Italy 84 % and Spain 68 %, the EAF route is the primarily used production process.

In China (89 %), Japan (75%), and Russia (59 %), the BOF route is dominating. In India (55 %) and the United States (69 %), the EAF route is the primarily used production process (World Steel Association, 2022).

How is iron & steel produced today?



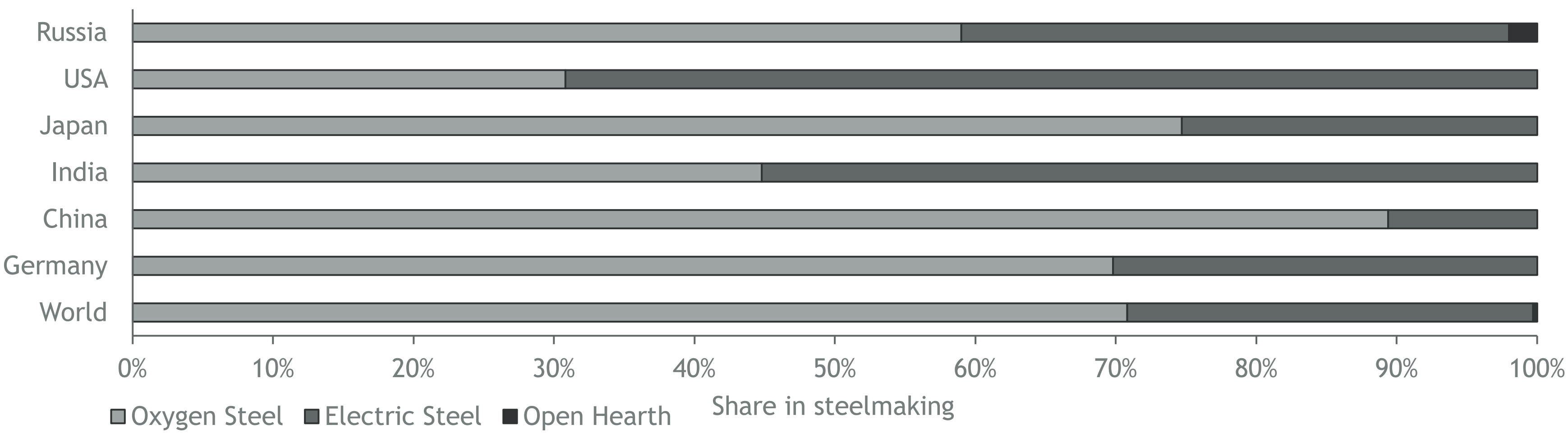


Figure 3: Technology shares for ironmaking (top) and steelmaking (bottom) in 2021 globally and for selected countries.
Source: own illustration based on World Steel Association (2022)

Global steel trade

Steel products are traded globally and are often at the centre of trade negotiations. However, the share of global trade varies significantly for different steel products. Apart from China's dominance, the global steel market is highly competitive and fragmented. None of the countries shown in table 1 has a market share of more than 10 % (IEA, 2020c).

China, the world's largest steel producer, exported 66.2 Mt of steel in 2021. Thus, exports accounted for only 6 % of total production in China. In 2021 the EU exported 134 Mt of steel, while the major share (108 Mt) accounted for intra-regional trade within the EU market. Nevertheless, the EU is a net importer of steel, importing 48 Mt from third countries in 2021 (World Steel Association, 2022).

Steel is mainly produced domestically and near the demand. Of the global crude steel produced in 2021 (1,951 Mt), roughly a quarter (460 Mt) was traded internationally (see Figure 3). From the 460 Mt of traded steel, 183 Mt accounted for trade within a region and 277 Mt for extra-regional global trade (World Steel Association, 2022).

The US (29.7 Mt) and China (27.8 Mt) are the largest importers of steel. Within the EU, Germany was with 23.3 Mt in 2021, the largest importer of steel (World Steel Association, 2022).

China, as the largest exporter, was followed by Japan (33.8 Mt), Russia (32.6 Mt), and Germany (23.9 Mt). The US is the only net importer of the selected countries with 21.5 Mt, and Germany is the only country with balanced trade (World Steel Association, 2022).

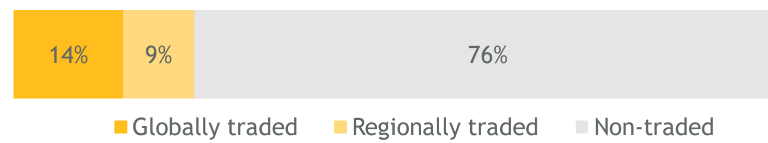


Figure 4: Shares of global crude steel trade and production in 2021
Source: own illustration based on World Steel Association (2022)

Table 1: Exports and imports of crude steel in 2021 for selected countries
Source: own illustration based on World Steel Association (2022)

#	Imports 2021 [Mt]	Total	#	Exports 2021 [Mt]	Total
1	US	29.7	1	China	66.2
2	China	27.8	2	Japan	33.8
3	Germany	23.3	3	Russia	32.6
4	India	5.9	4	Germany	23.9
5	Japan	5.5	5	India	20.4
6	Russia	5.0	6	US	8.2

Cutting emissions in the global steel production

Iron and steel production is highly energy-intensive, accounting for 8 % of global final energy demand and 20 % of industrial energy use. In 2019, the iron and steel sector was responsible for 8 % of global GHG emissions (IEA, 2020c). Due to the growing steel production, the sector's emissions increased over the past decade (IEA, 2022e).

The CO_2 content of production depends on the production process and the input. In 2021, one ton of crude steel production accounted for 1.39 t CO_2 (IEA, 2022e). The BF-BOF route emits 1.78 tCO_2/t crude steel (scope-1). However, this can strongly vary by country and plant. The EAF emits around 0.06 to 0.1 tCO_2/t of scope-1 emissions (JRC, 2022). Depending on the source of electricity, scope-2 emissions range from 0.00 tCO_2/t crude steel (electricity from renewable energy sources, RES) to 0.71 tCO_2/t crude steel (lignite-fired power plant, own calculations).

Coal (74 %) currently makes up the largest share of energy demand in the steel sector. Electricity meets 13 %, and gas accounts for 9 % of the energy demand (IEA, 2020a). To be in line with the net zero scenario of the IEA, the share of electricity in the global steel sector needs to increase by 5 % points between 2022 and 2030 (IEA, 2022e).

The German iron and steel sector accounted for 25 % of Germany's industrial energy demand in 2018 (EWI, 2021a). The steel industry must significantly reduce its emissions to reach net zero. While CO_2 emissions can be reduced in the short term by energy efficiency improvements and increased steel recycling, more is needed to decarbonize the sector.

The emission reduction potential of conventional production processes is limited. New low-carbon steel production technologies must be adopted. Therefore, production processes with CCU or CCS, hydrogen, direct electrification and bioenergy are important (IEA, 2022e).

Various different clean iron and steel technologies have advanced over the last years. Nevertheless, these technologies differ regarding their technology readiness and importance for decarbonization (IEA, 2022a).

The first green steel pilot projects are conducted, while many more, particularly for the direct reduction of hydrogen (H2 DRI), have been announced (IEA, 2022e).

Policy measures reducing emissions in the steel industry

Far-reaching measures by countries worldwide are needed on the demand and supply side to cut emissions in the steel sector. Mandatory targets for emission reduction, energy efficiency targets or carbon pricing (e.g., ETS) are possible policy instruments to cut emissions in the steel sector.

Many countries worldwide have introduced policies to reduce the emissions of the industry sector. Some countries have specifically addressed the steel sector and established roadmaps and targets (IEA, 2022e; IEA, 2020c). The following list gives an overview of national and regional roadmaps, and targets:

- **China** has announced to introduce a steel emission price and to increase the use of scrap steel. However, until today, carbon pricing does not cover the steel sector.
- **India** released a steel recycling policy to extend the use of scrap in steel production.
- The **European** emissions trading system (EU-ETS) plays an important role in reducing industrial emissions. However, to maintain economic competitiveness and avoid carbon leakage, competitive and trade-exposed sectors, such as the steel industry continue to receive free allowances. The European Commission proposed a carbon border adjustment mechanism (CBAM), including, among others, the steel sector.
- **France** has introduced emission reduction targets for the steel sector.
- The **German** government is allocating funding to hydrogen-based steel production.
- **Korea** has an emission trading scheme covering the steel sector.
- **Japan** introduced an energy benchmark system and supports international collaboration and technology transfer.

Although first measures are taken by some countries, global emission reduction efforts in the steel sector are undermined by global excess capacity. In 2016 the “Global Forum on Steel Excess Capacity” was founded to join efforts and find a common solution to this problem. Among others, the European Commission, Russia, the US, Japan and Korea are members. However, the major steel producers China and India do not engage in this initiative (European Commission, 2021; Global Forum on Steel Excess Capacity, 2022).

The role of steel at the Conference of the Parties (COP)

With each COP, the topic of climate protection and climate neutrality comes back into focus worldwide. Due to the high energy and CO_2 intensity, the steel sector is an important topic. In 2021 at COP26 in Glasgow, 29 countries representing over 30 % of the global steel production pledged to establish near-zero emissions steel production by 2030. The steel sector was considered with one of the five goals (named the Glasgow Breakthrough):

"Near-zero emission steel the preferred choice in global markets, with efficient use and near-zero emissions steel production established and growing in every region by 2030." (UK, 2021)

The UN Climate Change High-Level Champions (2022) highlight that the global pipeline of conventional steel plants is underway or in the planning stage. A "U-turn" is necessary where coal-fired steel is ramping up. However, a "U-turn" is also necessary in countries with dominant coal-based steel plants.

At COP26 in 2021, 45 countries launched the Breakthrough Agenda, a commitment to accelerating innovation and deploying green technologies in the 2020s. The Breakthrough Agenda, released annually, tracks developments towards the Breakthrough goals that should be reached by 2030 and identifies where further action is needed. The first Breakthrough Agenda report was released in 2022 and provided a pathway of coordinated international actions and recommendations for reaching the goals in the steel sector. The recommendations for the next 1-2 years are (among others):

"Governments and companies willing to lead the transition in the steel sector should collectively agree on common definitions for low emission and near-zero emission steel, along with a time frame for the adoption of standards by the mid-2020s."

"Governments and companies should increase the scale of near-zero emission steel procurement commitments to cover a significant share of their future demand."

"Governments should urgently launch a strategic dialogue (…) with the purpose of agreeing ways to ensure near-zero emission steel can compete in international markets. This is needed to prevent trade acting as a brake on the transition."

"Governments and companies should urgently identify several commercial-scale pilot projects, in all major steel producing regions, where international collaboration can support shared technology learning, business case development and policy support."

(IEA, 2022b)

Defining *low emission* and *near-zero* is vital for steelmaking technologies as the GHG emission intensity varies significantly between different technologies.

2 Steelmaking technologies

- Blast furnace & blast oxygen furnace (BF-BOF)
- Direct reduction process & electric arc furnace (DRP & EAF)
- Hydrogen production
- Carbon Capture and Storage (CCS)
- Assessment of the Technology Readiness Level (TRL)

Blast furnace & blast oxygen furnace (BF-BOF)

Ironmaking in a blast furnace

The blast furnace (BF) process converts iron ore into pig iron. Inside the blast furnace, the combustion of coke provides heat and forms carbon monoxide. Carbon monoxide is a reducing agent and reacts with the iron ore to pure iron and CO_2.

Coke is typically produced on-site at the blast furnace plant by heating coking coal in the absence of oxygen. By sintering, raw iron ore and fluxes are agglomerated to attain a homogenous ore carrier that can be fed to the blast furnace. Sinter is almost always produced on-site at the blast furnace plant. Flux is necessary to improve fluidity and to drive out impurities from the ore in the form of slag.

Blast furnaces are existing since the mid-1800s and are the most common technology for ironmaking in terms of production quantity. Pig iron from blast furnaces accounted for 92 % of global iron production in 2021 (World Steel Association, 2022).

Steelmaking in a basic oxygen furnace

In the subsequent basic oxygen furnace (BOF), pig iron is converted into steel by burning unwanted elements and adjusting the carbon content of the steel by blowing oxygen into the melt. Oxygen steel accounted for 70 % of the global crude steel production in 2021 (World Steel Association 2022).

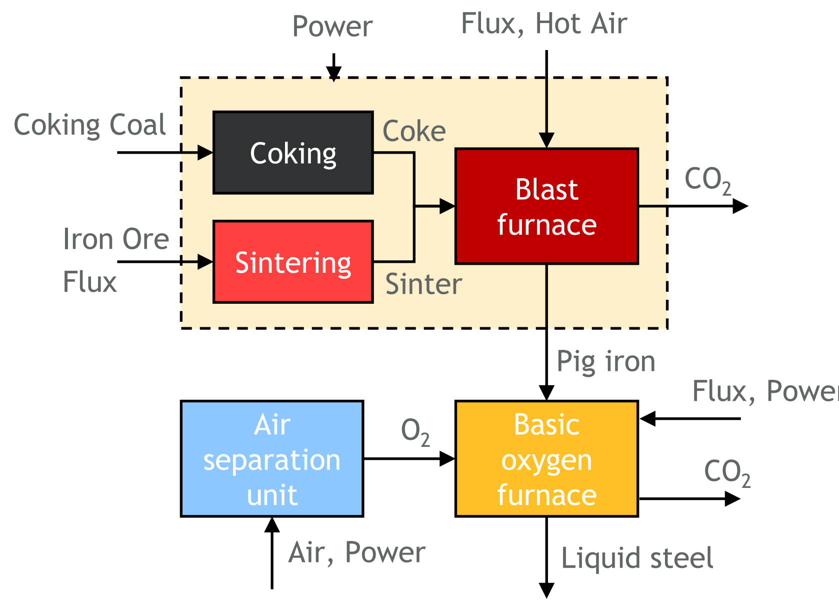


Figure 5: Flowsheet of essential mass and energy flows in an integrated blast furnace & blast oxygen furnace (BF-BOF) steel plant.

Direct reduction process & electric arc furnace (DRP & EAF)

Ironmaking in a direct reduction process

The direct reduction process (DRP) uses syngas or pure hydrogen as reducing agents to produce direct reduction iron (DRI) or the so-called iron sponge. Syngas is a mixture of hydrogen and carbon monoxide. While carbon monoxide reacts with the iron ore to CO_2 and pure iron, hydrogen reacts with the iron ore to pure iron and water. Therefore, the reduction of iron ore with hydrogen produces no GHG emissions. The iron ore reduction with hydrogen is endothermic and cools the reactor (Midrex, 2022). Methane is added to the furnace as fuel gas for temperature control. Therefore, the fuel gas demand increases if hydrogen is used as the only reduction agent.

Moreover, methane is necessary to adjust the carbon content of the DRI in case hydrogen is the only reduction agent. Iron ore pellets are usually the ore carrier used in the direct reduction process. Pellets serve a similar purpose to sinter but are typically produced at the site of the mine or the shipping port (Ecofys, 2009). The commercialization of the DRP started in the 1970s (Smil, 2016). In 2021, DRI accounted for 8 % of global iron production (World Steel Association, 2022).

Steelmaking in an electric arc furnace

DRI can be fed directly into an electric arc furnace which converts the iron into steel. Alternatively, DRI can be converted to hot briquetted iron, which has better transport properties and can be used as iron feedstock for a BOF. An EAF converts DRI, scrap, or a mixture to steel, using electric power as a

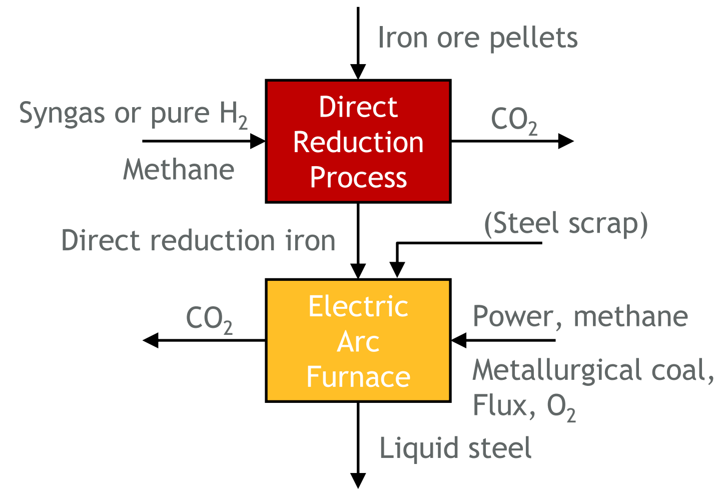


Figure 6: Flowsheet of essential mass and energy flows in an integrated direct reduction process & electric arc furnace steel plant.

primary energy source. As a secondary heat source, methane and oxygen are burned in oxyfuel combustion burners. Flux is added to the furnace to drive out impurities in the form of slag. Metallurgical coal is added to the furnace as charge and injection carbon.

Charge carbon has the purpose of adjusting the carbon content of the melt. Injection carbon is a foaming agent for the slag, which increases the furnace's energy efficiency due to the foam's insulating effects. Direct emissions of the EAF stem from combustion of methane and coal, and the consumption of the graphite electrodes of the furnace.

Hydrogen production

Coal gasification

The primary process of producing hydrogen or syngas (a mixture of carbon monoxide and hydrogen) from coal is partially oxidizing coal with water. The combustion of coal usually covers the heat demand of the process. By its chemical reaction, coal gasification is inherently linked to CO_2 emissions. Coal gasification is a conventional process used since the 1800s. In Germany industrial scaled coal gasification plant are not used (VDI, 2016). In 2020, 19 % of the global hydrogen was produced from coal (IEA, 2021).

Steam methane reforming

Hydrogen from natural gas is primarily produced by steam methane reforming of natural gas and water. The process requires heat, usually generated by the combustion of natural gas. The reforming reactions inherently produce CO_2. Hydrogen production from natural gas accounted for 60 % of global production in 2020 (IEA, 2021).

Water electrolysis

Water electrolysis is based on an electrochemical reaction splitting water into hydrogen and oxygen which requires electric power and heat. If the electricity used for electrolysis is entirely from renewable energies, the produced hydrogen is emission-free, sustainable, and thus called green hydrogen. Water electrolysis is a mature technology (Buttler & Spliethoff, 2017).

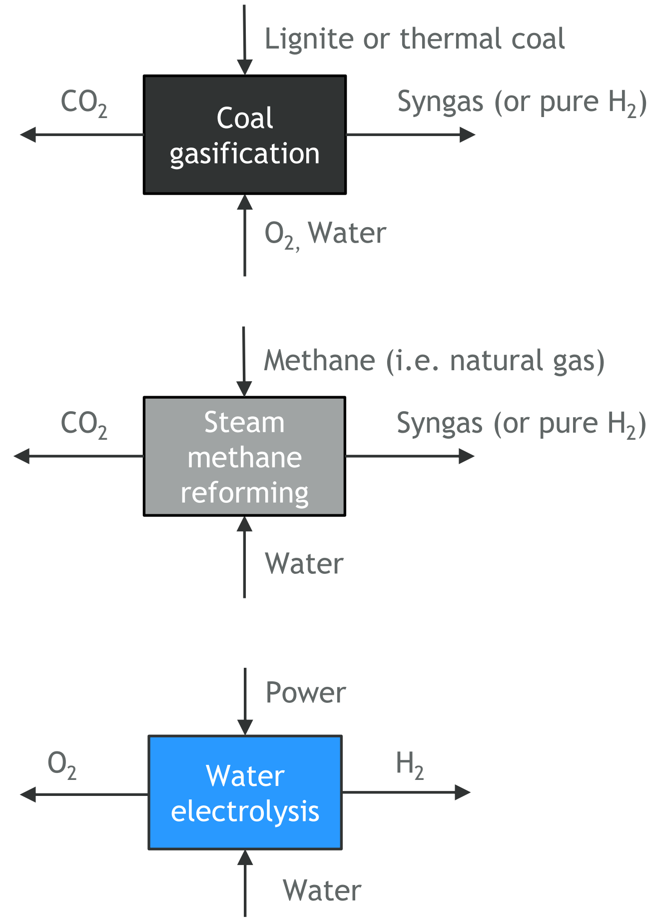


Figure 7: Flowsheet of essential mass and energy flows of a water electrolysis, coal gasification and steam methane reforming process.

Carbon Capture and Storage (CCS)

Carbon Capture and Storage (CCS) intends to capture CO_2 from exhaust gases and sequester them underground (Bui et al., 2018)

Carbon capture

The removal of CO_2 from a flue gas stream is referred to as carbon capture. For most chemical and steel plants, pressure swing adsorption (PSA) is the most economical technology for carbon capture and requires electrical power (Hasan et al., 2012). Typically, PSA captures about 90 % of the CO_2 present in the flue gas (Riboldi & Bolland, 2017). If the flue gas stream contains water, the stream must be dehydrated prior to carbon capture, which requires additional energy. Subsequently, the captured CO_2 stream is compressed up to 150 bar for transport and storage.

Storage & Transport

Sources of CO_2 emissions, like steel mills or waste incineration plants, are usually not located at a suitable CO_2 storage site. Thus, the captured CO_2 needs to be transported. On an industrial scale, pipeline transport is the most economical transport option (Smith et al., 2021). As CO_2 pipeline infrastructure does not yet exist, transport via trailers or trains might be the only transport options in the early use of CCS.

At the storage site, the captured CO_2 is sequestered underground. Saline aquifers or depleted oil and gas fields can be appropriate geological storage sites for CO_2.

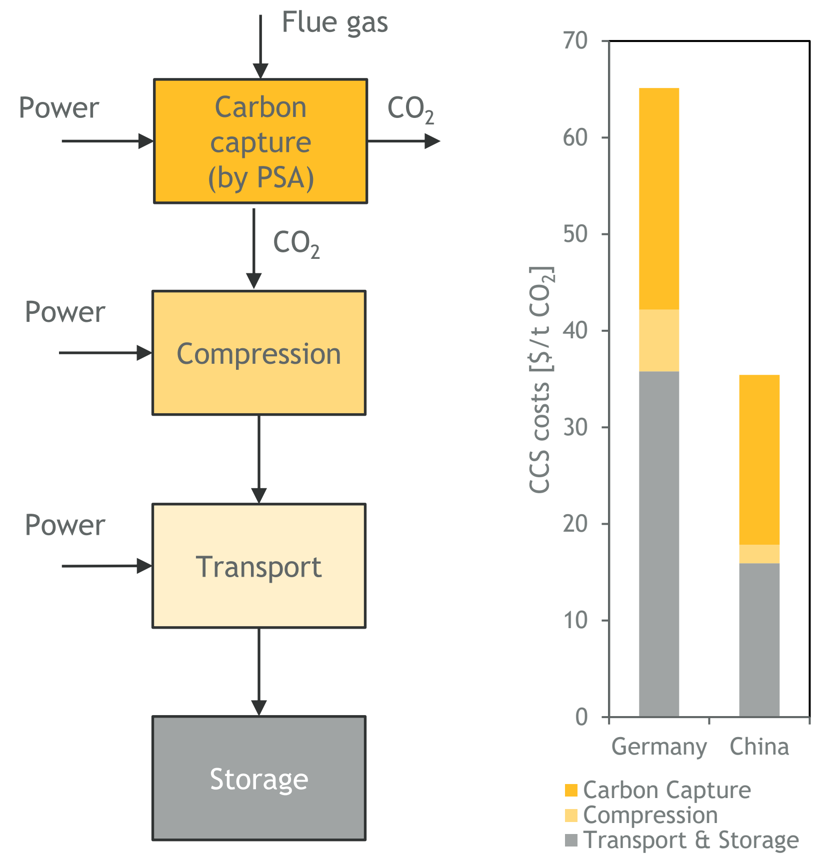


Figure 8: Flowsheet of essential mass and energy flows of CCS transport chain (left) and exemplary cost structure of CCS in Germany and China (right) (Smith et al., 2021).

Assessment of the Technology Readiness Level (TRL)

Table 2: Technology Readiness Level of technologies in iron & steelmaking.

Technology	Description	TRL	Comment	Source
DRI	Direct reduction process for ironmaking using syngas as reduction agent	11	Commercial since the 1970s, currently about 96 plants operating worldwide with an ironmaking capacity of 151 Mt/yr	Smil, 2016; GEM, 2022
EAF	Electric arc furnace for steelmaking	11	Currently about 596 plants operating worldwide with a steelmaking capacity of 776 Mt/yr	GEM, 2022
BF	Blast furnace for ironmaking using coke as reduction agent	11	Currently about 464 plants operating worldwide with an ironmaking capacity of 1390 Mt/yr	GEM, 2022
BOF	Basic oxygen furnace for steelmaking	11	Currently about 444 plants operating worldwide with a steelmaking capacity of 1659 Mt/yr	GEM, 2022
CCS	Carbon capture and storage	9	Carbon capture by amine scrubbing or pressure swing adsorption, CO_2 transport by pipeline, ship or trailers as well as carbon storage in saline formations or for enhanced oil recovery are mature technologies. CCS in steelmaking is in operation in a smaller plant (0.8 Mt/year) in Abu Dabi where the captured CO_2 is used for enhanced oil recovery	Bui et al. 2018; Gulfnews, 2015
H2 DRI	Direct reduction process for ironmaking using electrolytic hydrogen as reduction agent	5	Pilot plant in Sweden started operation in 2020 targeting a production of 1 Mt/year by 2025, Pilot plant in Hamburg is to be built by ArcelorMittal by 2030	IEA, 2020c
Coal gasification	Hydrogen or syngas production by partial oxidation of coal	11	In 2020, 19% of the global hydrogen was produced from coal gasification	IEA, 2021
Steam methane reforming	Hydrogen or syngas production by steam methane reforming of natural gas	11	In 2020, 60% of global hydrogen was produced from steam methane reforming	IEA, 2021
Water electrolysis	Electrochemical splitting of water into hydrogen and oxygen	9-10	Alkaline electrolysis is mature, polymer electrolyte membrane (PEM) electrolysis is in early commercialization. Largest available electrolyzers are currently in the lower megawatt scale	IRENA, 2020

TRL scale: 1 - Initial idea | 2 - Application formulated | 3 - Concept needs validation | 4 - Early prototype | 5 - Large Prototype | 6 - Full prototype at scale | 7 - Pre-commercial demonstration | 8 - First-of-a-kind commercial | 9 - Commercial operation in a relevant environment | 10 - Integration needed at scale | 11 - Proof of stability reached See IEA (2020c) for further information.

3 Results

- Scenario definition
- The emission intensity of integrated iron- and steelmaking routes
- Global competition and cost gap
  - Scenario “Hydrogen steelmaking”
  - Scenario “Most economic steelmaking” at a moderate CO_2 price
  - Scenario “Most economic steelmaking” at a high CO_2 price
- Marginal abatement costs

Scenario definition

In this section, we investigate how global low-carbon steel production affects the competitiveness of the German steel sector. For this purpose, we compare the cost gap in steel production costs between six analyzed countries in three emission reduction scenarios. The countries are Germany and the five largest steel-producing countries as of 2021: China, India, Japan, the US, and Russia. The three scenarios cover different emission reduction specifications for steelmaking which apply uniformly to all countries.

I. The first scenario compares the cost gap of hydrogen steelmaking without CO_2 price.

II. The second scenario compares the cost gap of the most economic steelmaking route at a moderate CO_2 price.

III. The third scenario compares the cost gap of the most economic steelmaking route at a high CO_2 price.

We assume, in all scenarios, that the power sector in each region is green and that green hydrogen is available as a commodity and must not be produced on-site at the steel plant.

Regions
Germany
China
India
Japan
US
Russia

Scenarios
Hydrogen steel *moderate CO_2 price*
Most economic steel *moderate CO_2 price*
Most economic steel *high CO_2 price*

The emission intensity of integrated iron- and steelmaking routes

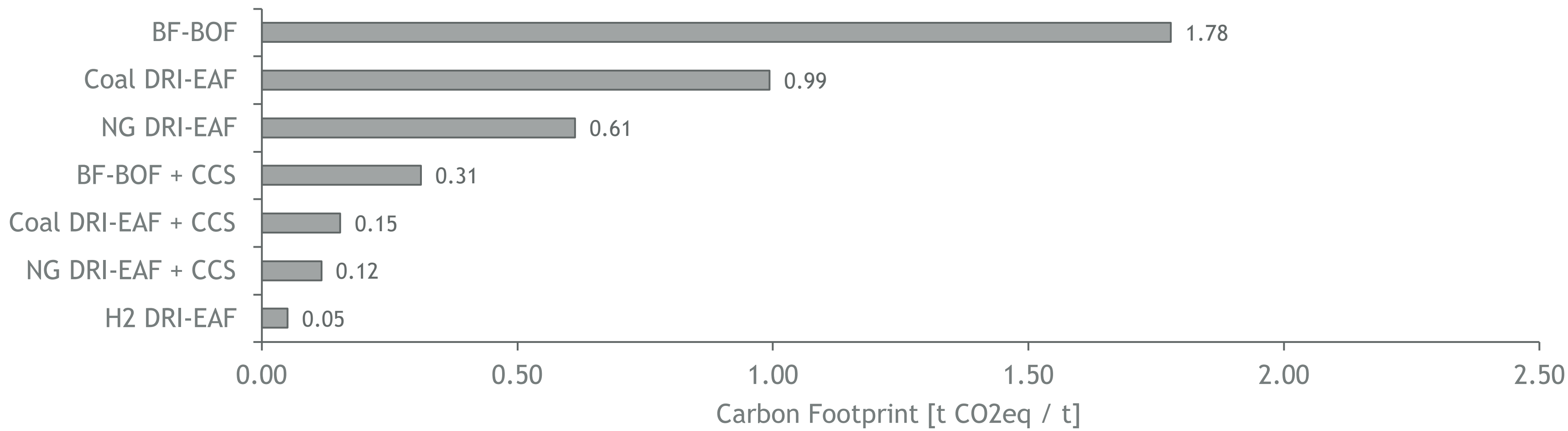


Figure 9: Scope-1 emission intensity of integrated iron- and steelmaking routes.

The figure shows the carbon footprint of steel produced by integrated iron and steel plants, provided that the electricity used is green. The conventional **BF-BOF** is by far the most emission-intensive steelmaking route. More than 80 % of the emissions stem from iron making in the blast furnace using coke as a reduction agent. The **DRI-EAF** steelmaking routes are significantly less emission-intensive. Using natural gas for syngas production and heating is less emission-intensive than using coal. DRI-EAF using coal is 44 % less emission-intensive and DRI-EAF using natural gas is 66 % less emission-intensive than BF-BOF steelmaking. The application of CCS further reduces the carbon footprint of these steelmaking routes. We assume that 90 % of syngas production and ironmaking emissions can be captured. Low-concentrated CO_2 emissions from steelmaking in a BF or EAF cannot be captured. For the BF-BOF+CCS route, carbon capture reduces the emission intensity by 83 %, compared to the unabated process. For the DRI-EAF+CCS route, the emission intensity reduces by 84 % compared to the unabated DRI-EAF process using coal and by 80 % compared to the unabated DRI-EAF process using natural gas.

The technology with the lowest emission intensity is **hydrogen steelmaking**. We assume for the H2 DRI-EAF route that, process heat generation for reduction gas preheating is electrified. The emission intensity of hydrogen steelmaking is 58 % lower than DRI-EAF+CCS using natural gas or 97 % lower than conventional steelmaking via the BF-BOF route.

Global competition and cost gap

Scenario “Hydrogen steelmaking”

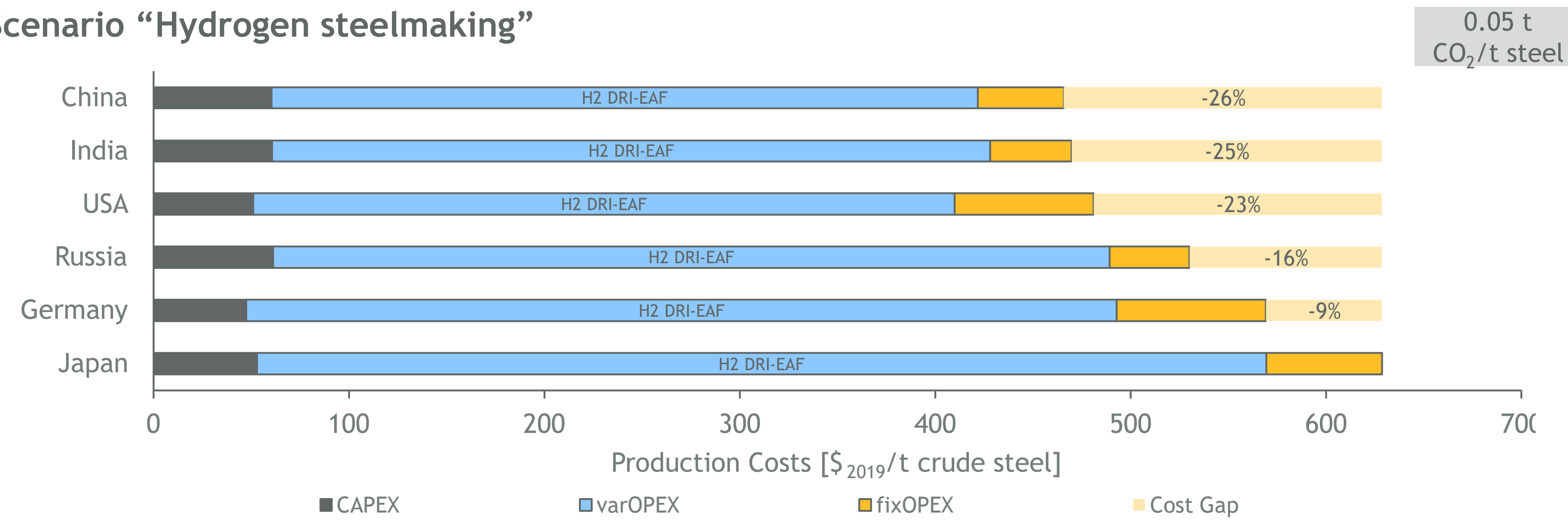


Figure 10: Production cost of hydrogen steel in the different countries.

In the scenario “Hydrogen steelmaking”, we compare the production costs of hydrogen steel via the DRI-EAF route among the countries. The relative cost gap between Japan, with the highest production costs, and China, with the lowest production costs, is 26 %. With 569 $/t, Germany has the second highest production costs.

Examining the cost composition, we notice that the **CAPEX** are in a comparable range for all countries. Cost drivers for the CAPEX are country-specific weighted average costs of capital (WACC), the plant capacity, and the process route. Since the CAPEX of DRI and EAF has an insignificant economy of scale, the CAPEX differences are driven by the WACC.

The **variable OPEX** show significant differences among the countries. Feedstock, fuel, and electricity costs are cost drivers of the variable OPEX. In the H2 DRI-EAF process route, country-specific electricity costs and costs for green electrolytic hydrogen are the major drivers for country-specific differences in the variable OPEX.

Japan has the highest electricity production costs and possesses not enough RES potential to produce its hydrogen demand domestically. In this analysis, Japan has the highest hydrogen supply costs of all countries because liquid hydrogen needs to be shipped to Japan from China.

Global competition and cost gap

The **fixed OPEX** contain maintenance and working labor costs driven by the process's labor intensity and country-specific labor costs. This scenario only considers one process. Thus, labor costs are the only driver of the fixed OPEX, which have significant regional differences.

We identify two groups of countries. Germany, the US, and Japan are in the **high-cost tier** having labor costs between 48 and 29 $/h. China, India, and Russia form the **low-cost tier** with labor costs between 8 and 6 $/h.

We assume scope-1 emissions are charged by a CO_2 price of 75 $/t CO_2. In the case of hydrogen steelmaking, the CO_2 costs only account for about 4 $/t steel as the H2 DRI EAF process has a very small emission intensity of 0.05 t CO_2 /t steel.

Global competition and cost gap

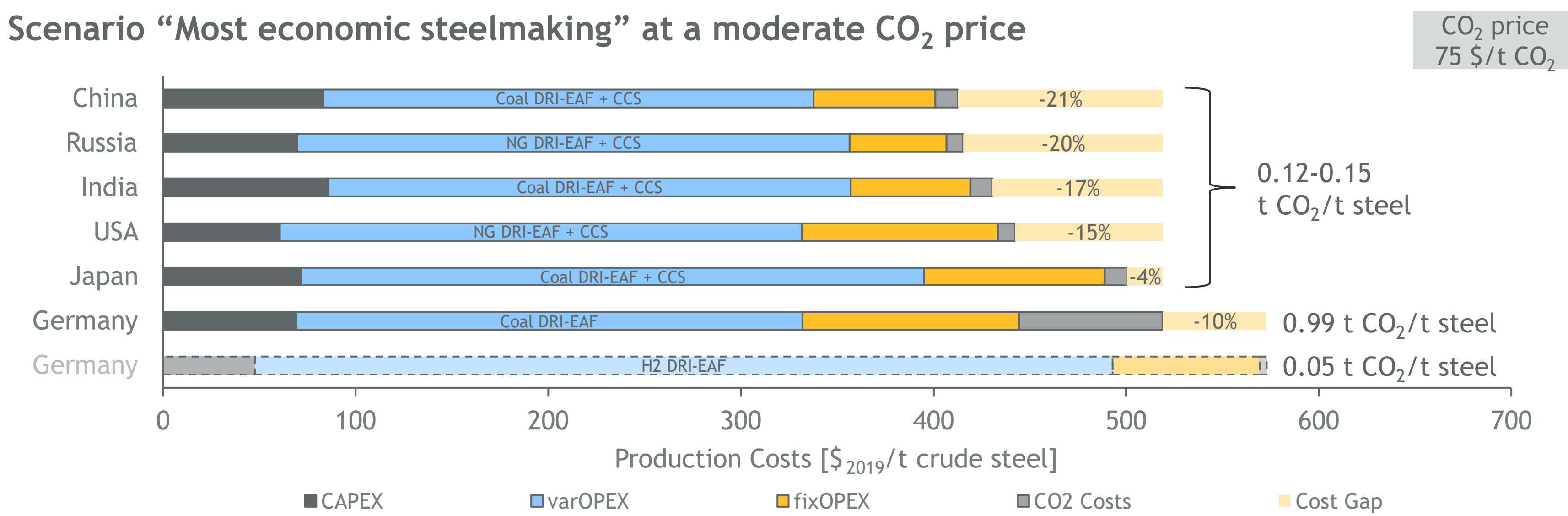


Figure 11: Production cost of hydrogen steel in the different countries.

For the scenario "most economic steelmaking", we compare two different CO_2 prices for scope-1 emissions. In the scenario „most economic steelmaking" at a moderate CO_2 price, we compare the steelmaking route with the lowest production costs of each region at a CO_2 price of 75 $/t. This assumption corresponds to the average CO_2 price in the EU ETS from July 2021 to June 2022. The production costs of hydrogen steel in Germany are shown as a reference. The scenario results show that production costs are the highest in Germany and the lowest in China. With 21 %, the largest cost gap is smaller than in the hydrogen steelmaking scenario. DRI-EAF steelmaking with CCS is the most cost-efficient route in all countries but Germany. In Germany, the unabated coal DRI-EAF process is the most economical technology, which is more than six times as emission-intensive as with CCS. Due to the emission intensity of the coal DRI-EAF route, the CO_2 costs account for more than 14 % of the production costs. In comparison, the CO_2 price has no significant impact on the production costs of DRI-EAF+CCS steelmaking. Despite the high CO_2 costs, the production costs of the coal DRI-EAF route are 10 % below the costs of hydrogen steelmaking in Germany. In four out of six countries, using coal as feedstock for the DRI-EAF is more economical than natural gas, despite coal being 25 % more emission-intensive. Only in countries with low costs for natural gas, namely in Russia and the US, DRI-EAF processes using natural gas are the most economical steelmaking route.

Global competition and cost gap

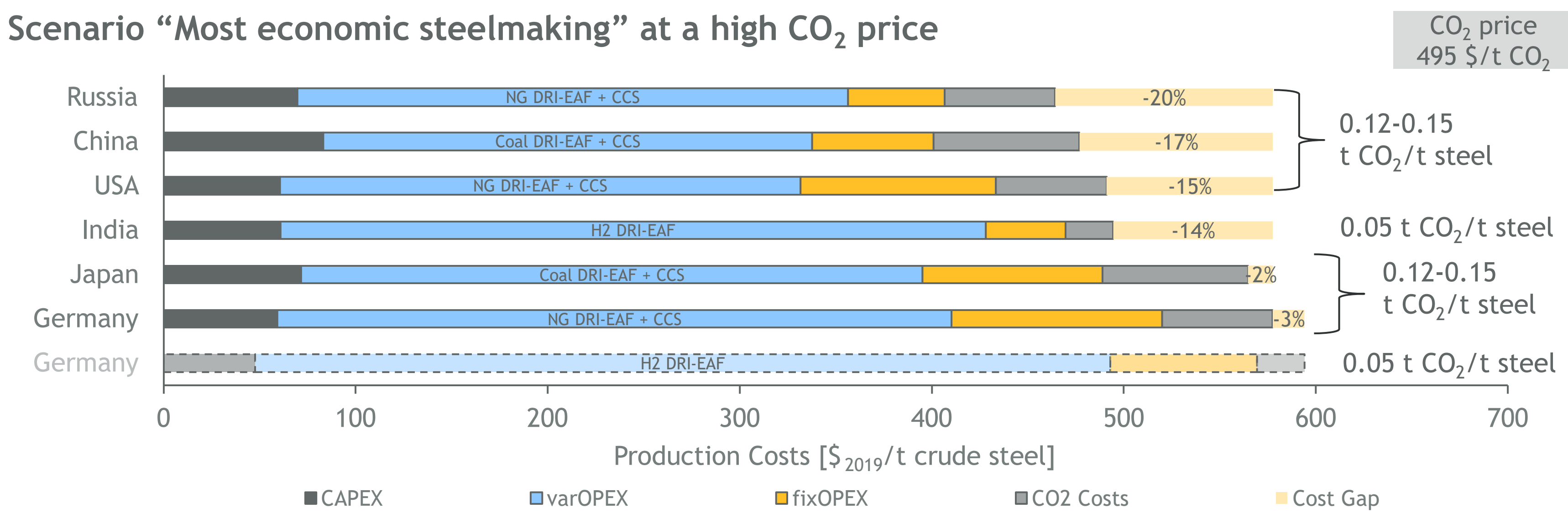


Figure 12: Production cost of most economic steel at a high CO_2 price in the different countries.

In the scenario "most economical steelmaking" at a high CO_2 price, we compare the most economical technologies at a CO_2 price of 495 $/t, which corresponds to the lowest CO_2 price where H2 DRI-EAF is the most economical technology in one of the countries. The cost gap is 20 %, similar to the moderate CO_2 price scenario. Germany is the country with the highest production costs. The country with the lowest production costs has changed from China to Russia. This shift is because DRI-EAF+CCS steelmaking emits 25 % more CO_2 per ton of steel using coal than natural gas. The difference in emission intensity leads to a difference in production costs of 15 $/t steel at the given CO_2 price. Combined with low natural gas and low specific labor costs, Russia becomes the most economic region. At this CO_2 price level, the CO_2 costs significantly influence the production costs of CCS steelmaking, accounting for 10-16 % of the production costs. In Germany, DRI-EAF+CCS with natural gas is the route with the lowest production costs. Despite being 240 % as emission-intensive as hydrogen steelmaking, which increases CO_2 costs by the same measure, NG DRI-EAF+CCS has 3 % lower production costs than hydrogen steelmaking in Germany. In India, the route with the lowest production cost switched from coal DRI-EAF+CCS to hydrogen steelmaking, given the CO_2 price. This implies that 495 $/t CO_2 represents marginal abatement costs between India's DRI-EAF+CCS and H2 DRI EAF routes. Additionally, this means that the abatement from CCS steelmaking to hydrogen steelmaking is least costly in India.

Marginal abatement costs

At a given CO_2 price of 75 $/t, low-carbon steelmaking is cost-efficient in all countries but Germany. This indicates two things. First, the marginal abatement costs in Germany are higher than in the other countries, and second, they are higher than the given CO_2 price.

The marginal abatement costs are defined by the costs of abating one equivalent ton of CO_2 which corresponds to the slope of the graphs in Figure 13. Aggregating the production costs and carbon footprints of all analyzed steelmaking routes, we can generate a marginal abatement cost curve by plotting production costs over the carbon footprint of a process. The marginal abatement cost curve starts with the technology with the lowest production costs, ends with the technology with the lowest emission intensity, and needs to be convex. The curve only contains technologies with the lowest marginal costs by these criteria. A line between two such technologies means there is no technology in between with lower marginal costs.

Comparing the marginal abatement costs curves in Germany and India reveals that the overall cost level of producing a ton of crude steel in Germany is higher than in India and the marginal abatement costs in Germany are higher, too. In other words: abating one equivalent ton of CO_2 emissions is more costly in Germany than in India. This statement holds for each technology step and for the overall marginal abatement costs between the most economical technology (coal DRI-EAF) and the technology with the lowest carbon footprint (H2 DRI-EAF). For Germany, the overall marginal abatement costs are 132 $/t CO_2, while for India, they are 93 $/t CO_2.

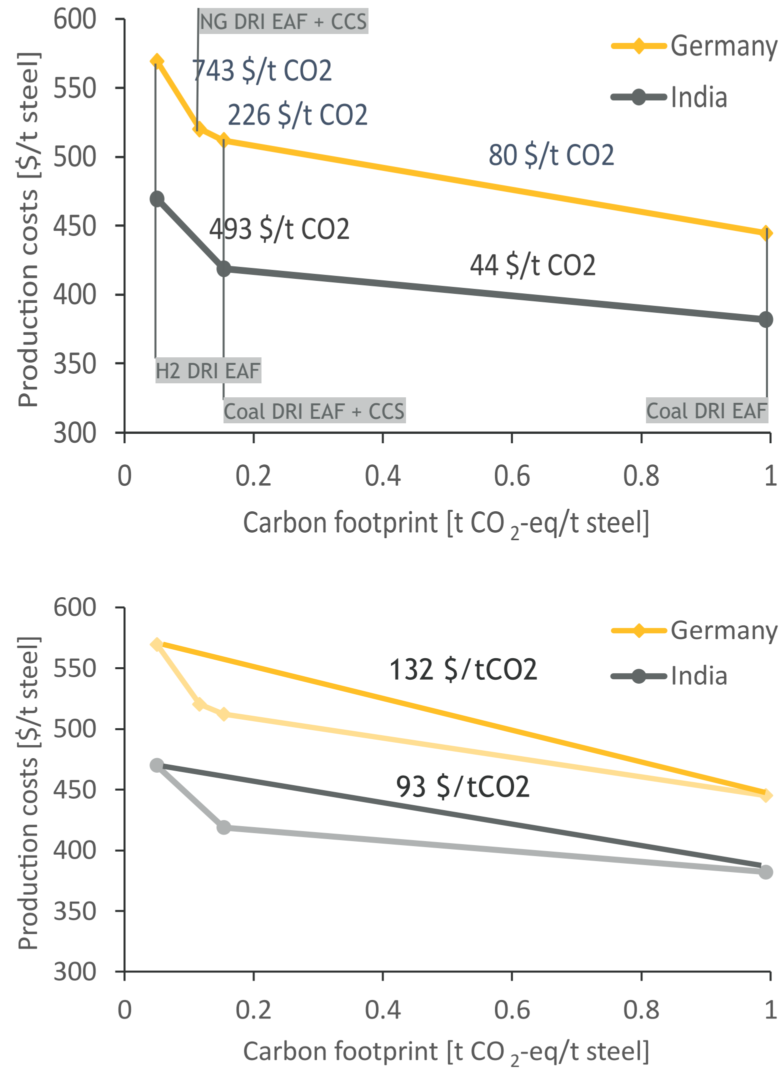


Figure 13: Comparison of the step-wise (top) and overall (bottom) marginal abatement costs in Germany and India,

Discussion

- Global competition and cost gap in a historical context
- Uncertainties in the application of Carbon Capture & Storage

Global competition and cost gap in a historical context

Historical cost gap in 2013

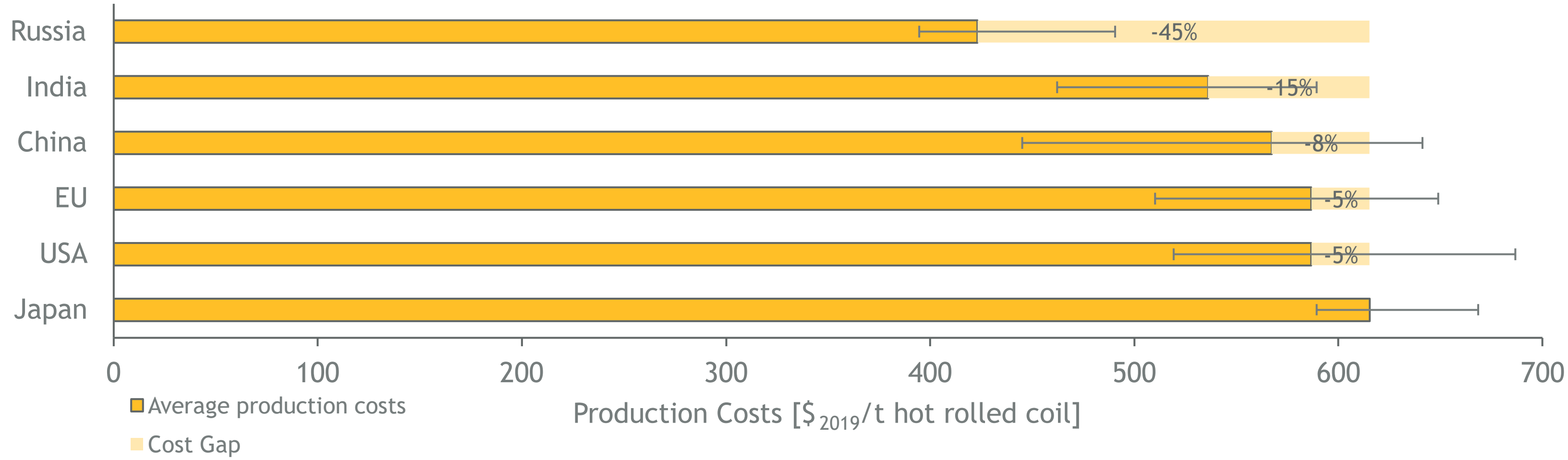


Figure 14: Historical cost gap between countries in 2013.

In each of our analyzed scenarios, we see a 17-21 % cost gap between Germany and the most economic region. To put this into context, we consider the historical cost gap.

Figure 14 shows the average production costs and the regional cost range for the hot rolled coil production costs via the BF-BOF integrated route in 2013 (Moya & Boulamanti, 2016).

Historically, production costs are the highest in Japan and the lowest in Russia. The maximal relative cost gap between these countries is 45 %, which is twice the maximum relative cost gap from our analyzed scenarios. Thus, our scenario analysis shows that the cost gap between the countries does not increase by low-carbon steelmaking.

However, the cost gap does increase between specific countries. For instance, in all analyzed scenarios, the US has about 15 % lower production costs than Germany, while the historical cost gap between the EU and the US is just 5 %. In our analyzed scenarios, identical emission reduction measures apply to the countries. These measures either apply by the specification of a technology or by the specification of a uniform CO_2 price. However, the cost gap between the countries might significantly differ from our scenarios if the emission reduction specifications (i.e. climate policy) change.

Uncertainties in the application of Carbon Capture & Storage

In this analysis, CCS-based steelmaking routes have lower production costs than hydrogen steelmaking. Nevertheless, the cost comparison has a shortcoming. Steelmaking via the DRI-EAF+CCS route with coal or natural gas emits up to 93 % less GHG emissions than the BF-BOF route, given that all electricity used is green. Still, DRI-EAF+CCS produces 140-200 % more GHG emissions than hydrogen steelmaking, depending on whether it is coal or natural gas based.

Suppose the energy system must reach net zero targets. In that case, these additional emissions from DRI-EAF+CCS steelmaking need to be compensated elsewhere - either technically by producing negative emissions or via land use, land-use change, and forestry. The system costs for these additional compensations are not included in our cost comparison.

Moreover, it is crucial to underline that costs are only one of the criteria a technology decision must be based on. It is important to stress that until today there is no experience with large-scale CCS deployment. Thus, many technical and economical assumptions are uncertain. For instance, it needs to be determined how considerable the leakage of CO_2 during transport and storage might be. In this analysis, we assume that there is no leakage. CO_2 leakage would significantly influence the emission intensity and, consequently, the marginal abatement costs between CCS and hydrogen steelmaking. For instance, a leakage of 20 % during transport would reduce the marginal abatement costs between CCS and hydrogen steelmaking by 50 %. For the scenario "most economic steelmaking at a high CO_2 price", such a leakage rate would have the consequence that hydrogen steelmaking would be the most economical technology in four out of six analyzed countries.

Lastly, the application of CCS technologies is not only an economic issue but also an issue of acceptance and politics. For example, under current legislation, CCS is not allowed in Germany, which might severely dampen any planning of commercial CCS projects in Germany.

Lists, References & Annex

- List of abbreviations
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- References
- Annex
  - Country-specific cost assumptions
  - Calculation of production costs

List of abbreviations

BF	Blast furnace
BMWK	German federal ministry for economic affairs and climate Action
BOF	Basic oxygen furnace
CCS	Carbon capture and storage
COP	Conference of the parties
DRI	Direct reduction iron
DRP	Direct reduction process
EAF	Electric arc furnace
OHF	Open hearth furnace
PSA	Pressure swing adsorption
RES	Renewable energy sources

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References

BMWK, 2020	Bundesministerium für Wirtschaft und Klimaschutz (2020): Für eine starke Stahlindustrie in Deutschland und Europa: Handlungskonzept Stahl. Available online at https://www.bmwk.de/Redaktion/DE/Publikationen/Wirtschaft/handlungskonzept-stahl.html, checked on 11/29/2022.
Brändle et al., 2021	Brändle, Gregor; Schönfisch, Max; Schulte, Simon (2021): Estimating long-term global supply costs for low-carbon hydrogen. In Applied Energy 302, p. 117481. DOI: 10.1016/j.apenergy.2021.117481.
Bui et al., 2018	Bui, Mai; Adjiman, Claire S.; Bardow, André; Anthony, Edward J.; Boston, Andy; Brown, Solomon et al. (2018): Carbon capture and storage (CCS): the way forward. In Energy Environ. Sci. 11 (5), pp. 1062–1176. DOI: 10.1039/C7EE02342A.
Buttler & Spliethoff, 2017	Buttler, Alexander; Spliethoff, Hartmut (2017): Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. In Renewable and Sustainable Energy Reviews 82, pp. 2440–2454. DOI: 10.1016/j.rser.2017.09.003.
Couper et al. 2007	Couper, James R.; Hertz, Darryl W.; Smith, Francis Lee (2007): Process Economics. In Don W. Green, Robert H. Perry (Eds.): Perry's Chemical Engineers' Handbook (8th Edition). 8th ed. Blacklick, USA: McGraw-Hill Professional Publishing.
Ecofsys, 2009	Ecofsys; Fraunhofer ISI; Öko-Institut (2009): Methodology for the free allocation of emission allowances in the EU ETS post 2012. Sector report for the iron ore industry. Available online at https://climate.ec.europa.eu/system/files/2016-11/bm_study-iron_ore_en.pdf, checked on 11/29/2022.
EUROFER, 2022	European Steel Association EUROFER (2022): European Steel in Figures 2022. Available online at https://www.eurofer.eu/assets/publications/brochures-booklets-and-factsheets/european-steel-in-figures-2022/European-Steel-in-Figures-2022-v2.pdf, checked on 11/29/2022.
European Commission, 2021	European Commission (2021): Towards competitive and clean European steel. Available online at https://ec.europa.eu/info/sites/default/files/swd-competitive-clean-european-steel_en.pdf, checked on 11/29/2022.
EWI, 2021a	Energiewirtschaftliches Institut an der Universität zu Köln (EWI) (2021): dena-Leitstudie Aufbruch Klimaneutralität. Klimaneutralität 2045 - Transformation der Verbrauchssektoren und des Energiesystems. Herausgegeben von der Deutschen Energie-Agentur GmbH (dena). Available online at https://www.ewi.uni-koeln.de/de/publikationen/dena-ls2/, checked on 11/29/2022.

References

EWI, 2021b	Energiewirtschaftliches Institut an der Universität zu Köln (EWI) (2021): Vergleich der „Big 5“ Klimaneutralitätsszenarien. Available online at https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2022/04/2022-03-16-Szenarienvergleich_final.pdf, checked on 11/29/2022.
Finance 3.1, 2021	Finance 3.1 (2021): WACC Expert. Available online at https://waccexpert.com, checked on 3/1/2021.
GEM, 2022	Global Energy Monitor (2022): Global steel plant tracker. Available online at https://globalenergymonitor.org/projects/global-steel-plant-tracker/download-data/, checked on 11/29/2022.
Germeshuizen & Blom, 2013	Germeshuizen, L. M.; Blom, P.W.E. (2013): A techno-economic evaluation of the use of hydrogen in a steel production process, utilizing nuclear process heat. In International Journal of Hydrogen Energy 38 (25), pp. 10671–10682. DOI: 10.1016/j.ijhydene.2013.06.076.
Global Forum on Steel Excess Capacity, 2022	Global Forum on Steel Excess Capacity (2022): Forum Members. Available online at https://www.steelforum.org/members/, checked on 11/29/2022.
Gulfnews, 2015	Gulfnews (2015): Abu Dhabi’s carbon capture project on track. Available online at https://gulfnews.com/business/energy/abu-dhabis-carbon-capture-project-on-track-1.1458076, checked on 11/29/2022.
Hasan et al., 2012	Hasan, M. M. Faruque; Baliban, Richard C.; Elia, Josephine A.; Floudas, Christodoulos A. (2012): Modeling, Simulation, and Optimization of Postcombustion CO_2 Capture for Variable Feed Concentration and Flow Rate. 1. Chemical Absorption and Membrane Processes. In Ind. Eng. Chem. Res. 51 (48), pp. 15642–15664. DOI: 10.1021/ie301571d.
Hasan et al., 2014	Hasan, M. M. Faruque; Boukouvala, Fani; First, Eric L.; Floudas, Christodoulos A. (2014): Nationwide, Regional, and Statewide CO 2 Capture, Utilization, and Sequestration Supply Chain Network Optimization. In Ind. Eng. Chem. Res. 53 (18), pp. 7489-7506. DOI: 10.1021/ie402931c.
IEA, 2019	International Energy Agency (2019): The Future of Hydrogen. Seizing today’s opportunities. Available online at https://www.iea.org/reports/the-future-of-hydrogen, checked on 12/01/2022.
IEA, 2020a	International Energy Agency (2020): Energy demand and intensity in iron and steel, 2000-2018. Available online at https://www.iea.org/data-and-statistics/charts/energy-demand-and-intensity-in-iron-and-steel-2000-2018, checked on 11/29/2022.

References

IEA, 2020b — International Energy Agency (2020): Coal 2020. Analysis and forecast to 2025. Available online at https://iea.blob.core.windows.net/assets/00abf3d2-4599-4353-977c-8f80e9085420/Coal_2020.pdf, checked on 11/29/2022.

IEA, 2020c — International Energy Agency (2020): Iron and Steel Technology Roadmap: Towards more sustainable steelmaking. Available online at https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf, checked on 11/29/2022.

IEA, 2021 — International Energy Agency (2021): Global Hydrogen Review 2021. Available online at https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-f2a4024909b4/GlobalHydrogenReview2021.pdf, checked on 11/29/2022.

IEA, 2022a — International Energy Agency (2022): ETP Clean Energy Technology Guide. Available online at https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide?selectedSector=Iron+and+steel, checked on 11/29/2022.

IEA, 2022b — International Energy Agency; IRENA; UN Climate Change High-Level Champions (2022): The Breakthrough Agenda Report 2022. Available online at https://www.iea.org/reports/breakthrough-agenda-report-2022, checked on 12/01/2022.

IEA, 2022c — International Energy Agency (2022): Cost curve of potential global biomethane supply by region, 2040. Available online at https://www.iea.org/data-and-statistics/charts/cost-curve-of-potential-global-biomethane-supply-by-region-2040, checked on 11/29/2022.

IEA, 2022d — International Energy Agency (2022): World Energy Outlook 2022. Announced pledges scenario, values of 2050. Available online at https://www.iea.org/reports/world-energy-outlook-2022, checked on 12/01/2022.

IEA, 2022e — International Energy Agency (2022): Iron and Steel – Tracking report. Available online at https://www.iea.org/reports/iron-and-steel, checked on 11/29/2022.

Indeed, 2022 — Indeed (2022): Helper monthly salaries in India at Steel Plant. Available online at https://in.indeed.com/cmp/Steel-Plant/salaries/Helper, checked on 11/29/2022.

Industrial Minerals, 2009 — Industrial Minerals (2009): Industrial Minerals (2009). Available online at https://www.indmin.com/Article/2357168/Magnesia-Features/Metal-markets-in-flux.html, checked on 11/29/2022.

References

Institut der deutschen Wirtschaft, 2019	Institut der deutschen Wirtschaft (2019): Institut der deutschen Wirtschaft - IW-Trends 2/2019 Industrielle Arbeitskosten im internationalen Vergleich. Available online at https://www.iwkoeln.de/studien/christoph-schroeder-industrielle-arbeitskosten-im-internationalen-vergleich-430302.html, checked on 12/01/2022.
IRENA, 2020	The International Renewable Energy Agency (2020): Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5C climate goal. Available online at https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction, checked on 12/01/2022.
JRC, 2022	Joint Research Centre (2022): Technologies to decarbonize the EU steel industry. DOI:10.2760/069150.
Midrex, 2022	MIDREX H2 (2022): Ultimate Low CO2 Ironmaking and its place in the new Hydrogen Economy. Available online at https://www.midrex.com/tech-article/midrex-h2-ultimate-low-co2-ironmaking-and-its-place-in-the-new-hydrogen-economy/, checked on 11/29/2022.
Moritz et al., 2021	Based on Moritz, Michael; Schönfisch, Max; Schulte, Simon (2021): Estimating global production and supply costs for green hydrogen and hydrogen-based synthetic fuels. Comprehensive Excel Database.
Moya & Boulamanti, 2016	Moya, Jose A.; Boulamanti, Aikaterini (2016): Production costs from energy-intensive industries in the EU and third countries. JRC science for policy report. DOI: 10.2790/056120.
MPP, 2022	Mission Possible Partnership (2022): Making net-zero steel possible: An industry-backed, 1.5 °C-aligned transition strategy. Available online at https://missionpossiblepartnership.org/wp-content/uploads/2022/09/Making-Net-Zero-Steel-possible.pdf, checked on 11/29/2022.
OECD, 2021	OECD (2021): Latest Developments in Steelmaking Capacity. Available online at https://www.oecd.org/industry/ind/latest-developments-in-steelmaking-capacity-2021.pdf, checked on 11/29/2022.
OECD, 2022	OECD (2022): Steelmaking capacity. Available online at https://stats.oecd.org/Index.aspx?datasetcode=STI_STEEL_MAKINGCAPACITY, checked on 11/29/2022.
Riboldi & Bolland, 2017	Riboldi, Luca; Bolland, Olav (2017): Overview on Pressure Swing Adsorption (PSA) as CO2 Capture Technology: State-of-the-Art, Limits and Potentials. In Energy Procedia 114, pp. 2390–2400. DOI: 10.1016/j.egypro.2017.03.1385.
SEI, 2021	Stockholm Environment Institute (2021): From 'hard-toabate' to net-zero: Policy priorities for decarbonising steel by 2050. Available online at http://www.sei.org/wp-content/uploads/2021/11/cop26-steel-messages-20211103.pdf, checked on 11/29/2022.

References

Smil, 2016	Smil, Vaclav (2016): Modern Ironmaking and Steelmaking. In: Still the Iron Age: Elsevier, pp. 87–114.
Smith et al., 2021	Smith, Erin; Morris, Jennifer; Kheshgi, Haroon; Teletzke, Gary; Herzog, Howard; Paltsev, Sergey (2021): The cost of CO2 transport and storage in global integrated assessment modeling. In International Journal of Greenhouse Gas Control 109, p. 103367. DOI: 10.1016/j.ijggc.2021.103367.
Steelonthenet, 2022	Steelonthenet (2022): Steelonthenet. Available online at https://www.steelonthenet.com/commodity-prices.html, checked on 11/29/2022.
UK, 2021	UK Government (2021): World leaders join UK's Glasgow Breakthroughs to speed up affordable clean tech worldwide. Available online at https://www.gov.uk/government/news/world-leaders-join-uks-glasgow-breakthroughs-to-speed-up-affordable-clean-tech-worldwide, checked on 11/29/2022.
UN Climate Change High-Level Champions, 2022	UN Climate Change High-Level Champions (2022): Steel & COP27. Available online at https://climatechampions.unfccc.int/steel-cop27/, checked on 11/29/2022.
VDI, 2016	Ahrens, Ralph H. (2016): Braunkohle wird zu Synthesegas. Verein Deutscher Ingenieure (VDI). Available online at https://www.vdi-nachrichten.com/technik/braunkohle-wird-zu-synthesegas/, updated on 11/13/2020, checked on 11/13/2020, checked on 11/29/2022.
World Steel Association, 2022	World Steel Association (2022): World Steel in Figures – 2022. Available online at https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2022/, checked on 11/29/2022.

Annex | Country-specific cost assumptions

Table 3: Cost assumptions on country-specific commodity costs.

Commodity	Unit	Germany	China	India	Japan	US	Russia	Source
Lignite	$/t	21	21	21	21	21	21	IEA, 2019
Thermal coal	$/t	50	58	58	56	23	23	IEA, 2022d
Coking coal	$/t	129	126	119	120	138	114	IEA, 2020b
Natural gas	$/MWh	20	24	24	24	8	8	IEA, 2022d
Biomethane	$/MWh	61	40	40	40	49	50	IEA, 2022c
Iron ore pellets	$/t	120	120	120	120	120	120	Steelonthenet, 2022; Germeshuizen & Blom, 2013
Flux	$/t	150	150	150	150	150	150	Industrial Minerals, 2009
Green electricity costs	$/MWh	76	38	37	97	35	63	Moritz et al., 2021
Carbon storage and transport costs	$/t$CO_2$	36	16	26	36	11	11	Smith et al., 2021
Carbon capture feed dehydration	$/t$CO_2$	11	11	11	11	11	11	Hasan et al., 2014
Hourly wages industrial worker	$/h	48	8	7	29	40	6	Institut der deutschen Wirtschaft, 2019; Indeed, 2022
Weighted average costs of capital	%	5	7	8	6	6	8	Finance 3.1, 2021
Hydrogen supply costs	$/MWh	56	52	58	92	50	65	Brändle et al., 2021; Moritz et al., 2021
Typical Steel plant capacity	kt steel/yr	1200	2000	1300	1500	1000	1400	GEM, 2022

All costs are given in USD 2019

Annex | Calculation of production costs

The production costs (PC) are computed by:

$$PC = CAPEX + varOPEX + fixOPEX$$

All costs are given in \$2019

The capital expenditures (CAPEX) are calculated by:

$$CAPEX = \underbrace{\sum_{u \in U} IC_u(C_u)}_{\text{investment costs}} \underbrace{\frac{(1+i)^n i}{(1+i)^n - 1}}_{\text{annuity factor}} \underbrace{\frac{cf}{C_p}}_{\text{Annual production}}$$

IC_u is the investment cost function of unit u

C_u is the capacity of unit u (subunits of the plant, e.g. steam methane reforming and direct reduction process)

C_p is the nominal crude steel production capacity of the steel plant

cf is the capacity factor

i are the weighted average costs of capital (WACC)

n is the depreciation period

The variable operational expenditures (varOPEX) are calculated by:

$$varOPEX = \left(\sum_{f \in F} \dot{m}_f P_f + \sum_{u \in U} \dot{E}_e P_e \right) cf$$

$\dot{m}_f$ is the annual mass flow rate of feedstock f

P_f is the regional price of feedstock f

E_e is the annual energy flow of energy commodity e

P_e is the regional price of energy commodity

The fixed operational expenditures (fixOPEX) are calculated by:

$$fixOPEX = SOL(C_u)US(1+0.5)w+FOM_uC_u$$

SOL is the specific operating labour function in h/t produced (see Couper et al. 2007)

US is the number of major process unit steps

$(1+0.5)$ denotes a markup for supervision and misc. expenses

w is the country-specific wages of industrial workers

FOM_u are the fixed operation and maintenance costs of unit u in percent of the fixed capital investment

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