Potential Roadmaps for Decarbonization of the Steel Sector

Authors:

Thomas Adisorn (Wuppertal Institute for Climate, Environment and Energy)

Yoshikazu Kobayashi (Institute of Energy Economics, Japan)

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Publisher
Wuppertal Institute for Climate, Environment, and Energy
Döppersberg 19
42103 Wuppertal
Germany
www.wupperinst.org

The Institute of Energy Economics Japan
Inui Bldg.Kachidoki,10th,11th Floor
13-1, Kachidoki 1-chome, Chuo-ku,
Tokyo 104-0054
Japan
https://eneken.ieej.or.jp/en/

Contact
GJETC Secretariat
gjetc@wupperinst.org
Phone: +49 202 2492-184

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1 Introduction

Both countries, Germany and Japan, have a strong steel industry, which contributes to economic well-being, but at the same time also leads to significant greenhouse gas emissions.

If the steel industry shall continue to play an important role in both countries in the future, while avoiding the shift of the production to countries with lower environmental standards (also known as carbon leakage), the governments of Japan and Germany must actively support the transformation of the sectors.

To understand how a transformation can be achieved to reach both countries' respective climate-neutrality targets/goals until 2045 (Germany) and 2050 (Japan), we first analyze the steel sector and describe possible decarbonization roadmaps in both countries. Then, we pay attention to policy developments and options. All of this is included in chapters 2 and 3, respectively. While we find many similiarities between both countries, we also identify differences, including technology perceptions, e.g. regarding the "colours" of hydrogen or carbon capture and storage (chapter 4). We conclude with policy recommendations addressing the individual governments and potential bilateral co-operation (chapter 5).

2 Germany

2.1 Industry overview

2.1.1 Major firms and revenues

In Germany, 4 million people are employed in steel-intensive businesses, of which 87,000 people are directly working in the steel sector. Revenues of the steel industry have recovered since the financial crisis in 2009. From 33.1 bn in 2009, total revenues climaxed at 49.7 bn in 2011. Then, revenues decreased until they reached 35 bn in 2016, which was followed by better figures in 2017 and 2018. Latest available data show that total industry revenues were at 39.1 bn in 2019 (WV Stahl, 2021).

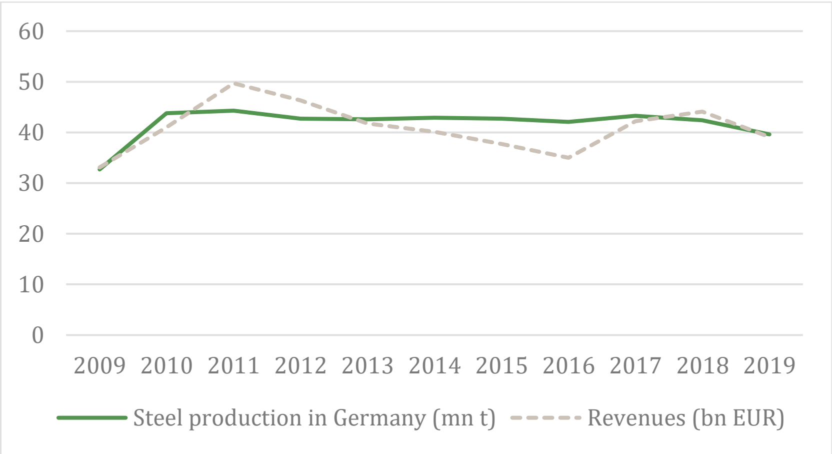


Figure 1: Steel production and revenues in the German steel industry between 2009 and 2019 (own figure based on WV Stahl, 2021)

In the last ten years, steel exports have been between 24.8 and 27.3 mn tons/yr, whereas imports have been between 24.4 and 28.5 mn tons/yr. In this period, Germany's imports slightly increased, but in 2019 the trade balance was almost neutral. So the quantities of both imports and exports are almost 70% of the domestic steel production of ca. 40 mn tons per year, but their balance shows that they are are not motivated by an overall shortage or surplus of steel production in Germany. Rather, it is different qualities of steel that are exported and imported. Available data for the European steel industry shows that, in 2020, the top-three importers of European steel are Turkey (24 %), the United States (10.8 %) and China (7 %) for flat steel and Switzerland (13.2 %), Canada (9.3 %) and Turkey (9.2 %) for long products (statista, 2022).

Key demand sectors of the steel industry are construction and automobiles, followed by metals, machinery and pipes (WV Stahl, 2021).

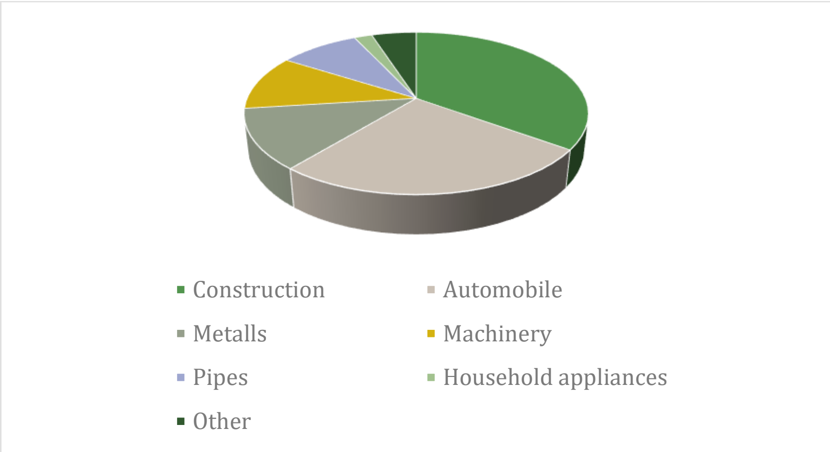


Figure 2: Demand side sectors of the steel industry in Germany (own figure based on WV Stahl, 2021)

The following figure provides an overview of steel production sites in Germany.

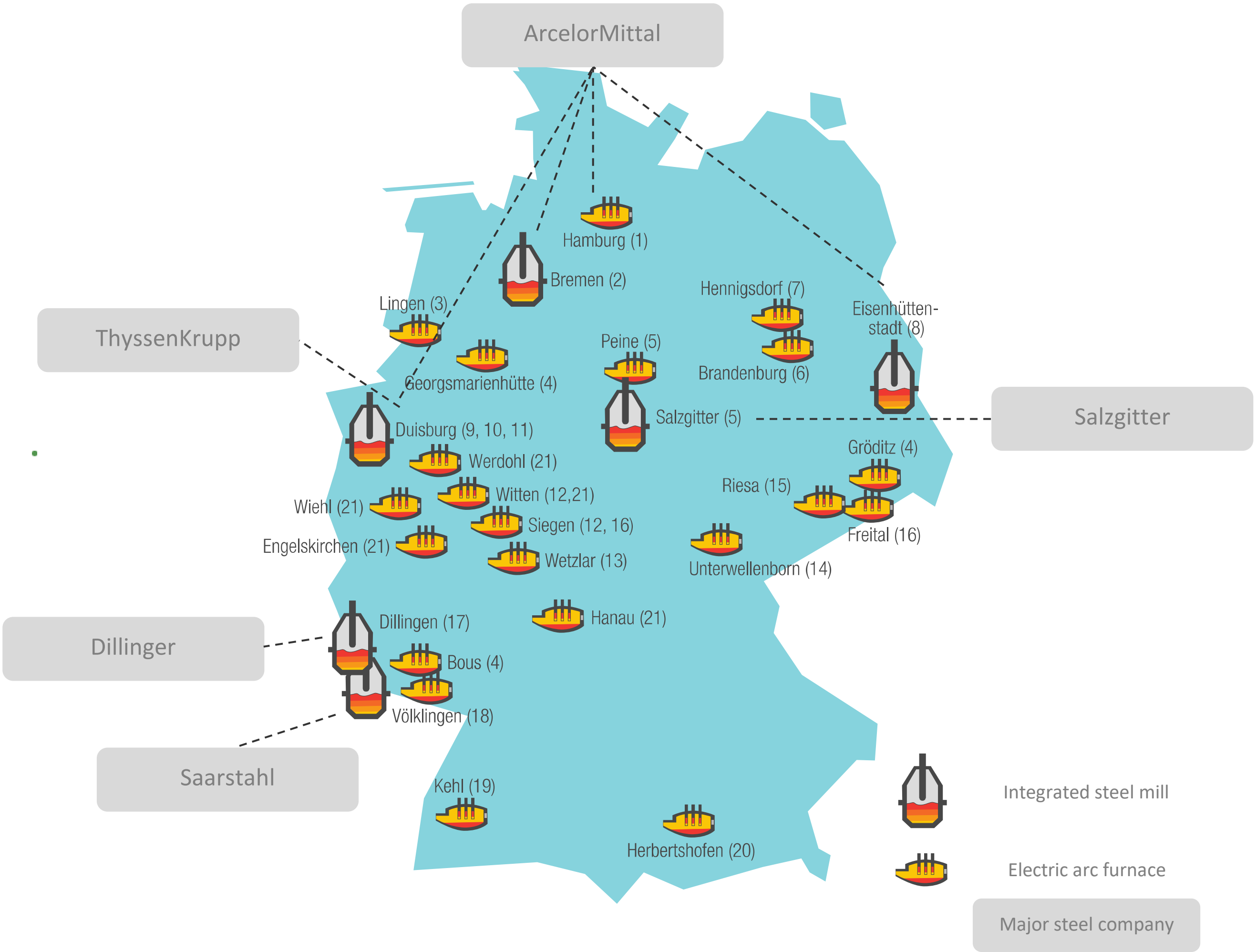


Figure 3: Steel production sites in Germany (WV Stahl 2020 with minor adjustments)

The country's largest steel producer, ThyssenKrupp, has its production facility in Western Germany and is capable to produce 12 mn tons of crude steel annually. Like ThyssenKrupp, ArcelorMittal has a steel plant in Duisburg, further plants are located in Northern and Eastern Germany, allowing for a total production capacity of 9 mn tons of crude steel per year. The company Salzgitter produces in central Germany, and annual production amounts to 6.6 mn tons of crude steel. The steel plant of Krupp Mannesmann also located in the city of Duisburg has an output of 5.6 tons of crude steel per annum. The companies Dillinger and Saarstahl, both headquartered in Germany's Southwest, have an annual production capacity of 2.8 mn and 2.7 mn respectively. All of these companies produce primary steel through the blast furnace-basic oxygen furnace. Apart from these companies, several steel producers in Germany only produce secondary steel via electric arc furnaces (WV Stahl, 2021).

Text box 1: Today's dominant production routes

The dominant method of making primary steel is the route via the **blast furnace-basic oxygen furnace** (BF-BOF). These are two integrated processes in which the blast furnace is needed for ironmaking, whereas the basic oxygen furnace converts hot metal into steel (Kempken et al., 2021). In this process, carbon is necessary as a reducing agent, for which coke is traditionally used. **Electric arc furnaces** (EAF) are for recycling scrap and turning it into (secondary) steel. Graphite electrodes are necessary for the melting process. 30% and 40% of all steel production is from the secondary route in Germany and the EU, respectively (EUROFER, 2020; WV Stahl, 2021)

2.1.2 Historical background

Before Friedrich Krupp founded his steel plant at the beginning of the 19th century, steel was imported mostly from England. August Thyssen became a competitor in 1870. After World War I and II, Germany's steel industry became a symbol of economic recovery, but the financial crisis of 1973 hit the industry hard, and global competition increased in the years to come (Maier-Bode, 2018). In 1961, employment in the steel industry reached its climax with 421,000 people working in the sector. After the crisis, in 1978, only 300,000 people were employed in the steel industry (Maier-Bode, 2018; Schlucht, 1998; WV Stahl, 2021).

Steel plants were originally built up in locations with available energy resources, that is coal. Moreover, locational advantages also included opportunities to further process steel and to ship resources (iron ore) and final products. Both, iron ore and coal extracted domestically in Germany became uncompetitive, which is why the role of ports has turned into a highly relevant locational factor for steel production; sites without access to waterways closed down successively in Germany (Schlucht, 1998). Today, regional clusters between steel / metal industry and downstream industries as well as research institutes exist, which is considered to be an important advantage (IfW Kiel & McKinsey & Company, 2020).

2.1.3 Types of processes used

In Germany, the primary BF-BOF-route is the dominant route of steel production (see text box 1). Around 70% of steel is produced via this route with an average energy demand of 14 GJ per ton of steel and emissions of 1.7 ton CO_2 per ton of steel. The secondary route is responsible for most of the rest, with far lower energy- and CO_2 -intensity per ton steel. A tiny share is produced (at the moment) by making use of direct reduction with natural gas (see text box 2). In the end, the primary route using coke as a reducing agent is responsible for the lion's share of CO_2-emissions (Agora Energiewende & Wuppertal Institut, 2019).

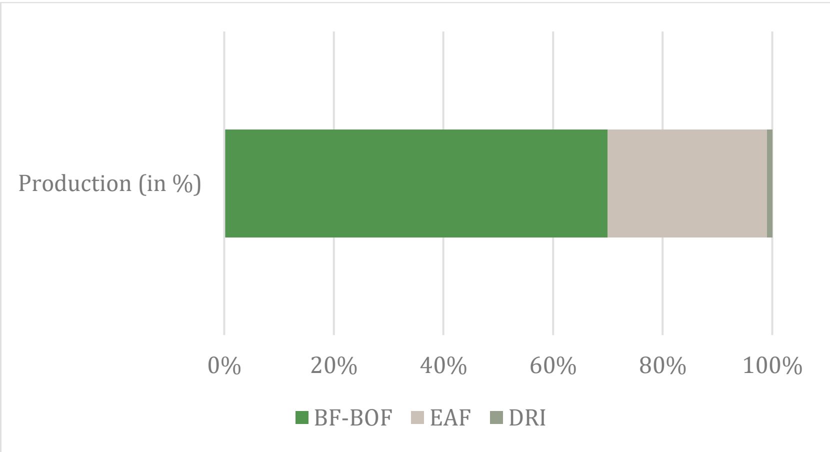


Figure 4: Steel production route in Germany (own figure based on Agora Energiewende & Wuppertal Institut 2019)

Text box 2: Direct-reduction technology

In order to reduce iron ore, the BF-BOF route makes use of coke, while direct reduction plants can work with hydrogen as a reducing agent and, in so doing, produce sponge iron or **direct reduced iron** (DRI). Hydrogen-based direct reduction does not produce process-related CO_2. The DRI needs to be further processed in an **electric arc furnace** (together with scrap if required) to, basically, produce crude steel. Natural gas or even a blend of hydrogen and natural gas can also be used in DR plants. Green hydrogen for direct reduction as well as renewable electricity for the EAF have the potential to realize substantial CO_2 reduction (Agora Energiewende & Wuppertal Institut, 2019).

2.1.4 Other relevant factors affecting decarbonization of the steel industry and effects of the past decarbonization policies

Substantial emission reductions were achieved in the 1960s, when former processes (Siemens-Martin- and Thomas-Stahl) were substituted through oxygen- and electric steel due to better economic performance. In 1964, a first relevant law ("Technische Anleitung Luft", Engl.: Technical Instructions Air) was introduced with minimum performance values to limit air pollution concentrations regarding sulfur dioxide and nitrogen concentration. Since 1974, the Federal Immission Control Act has successively and successfully introduced tighter performance values which, for instance, resulted in investments in cleaning units and reduced use of fossil fuels. This is considered to be responsible for CO_2 -reductions. While in the first half of the 1970s, environmental regulation was stricter in competing countries such as Japan and the U.S., regulations formulated from 1975 onwards resulted in cost increases, according to the industry. In parallel, new players (also from emerging economies) entered the global steel market (Ketelaer & Vögele, 2014).

In 1999, Germany introduced an ecologic tax reform, which was supposed to act as a steering instrument. However, resistance from energy intensive industries resulted in tax breaks and, thus, low pressure to change investment behaviour towards environment-friendly technologies. Moreover, in 2000, economic actors agreed to voluntarily reduce CO_2-emissions until 2012 by 28 % compared to 1990, which included a 22% reduction target per ton of crude steel. The government promised to waive regulatory initiatives such as obligatory energy audits. While the 22% reduction target was achieved, it is assumed that this is largely due to the expansion of the EAF-route having taken production shares from the BF-route (Fleiter et al., 2013).

In 2013, the Industrial Emission Directive of the EU became effective, which requires steel producers to invest in best available technologies. Since 2008, the European steel sector has participated in the Emission Trading System of the European Union (ETS). Between 2008 and 2012, certificates had to be bought for 3% of total emissions; between 2013 and

2019, this share was increased to 28% of total emissions of the steel sector. Generally, the allowance price has been at low levels for several years that were insufficient for motivating steel producers to carry out costly investments (Kempken et al., 2021; Ketelaer & Vögele, 2014).

An important factor in designing instruments for energy intensive industries including steel is their exposure to global trade and competitors. Costs incurred by regulation are feared to reduce competitiveness and may result in ‘carbon leakage’: the dislocation of steel companies to countries with less strict (and, thus, less costly) environmental regulation. Little empirical evidence has be identified for carbon leakage so far, also because of low CO_2-prices and free allowances (Kempken et al., 2021).

2.2 Decarbonization roadmap

2.2.1 Mid- and long-term emission reduction goals

Steel industry is responsible for 29% of all industry emissions in Germany. It is the largest CO_2 -emitting industry sector followed by basic chemicals (19%). In 2021, Germany’s Climate Protection Law was revised. Compared to the base year, which is 1990, Germany committed to reduce total emissions down to 35% in 2030 and 12% in 2040. Climate neutrality must be achieved by 2045. For the industry sector, the government strives to achieve 42% of base year emissions in 2030, i.e. a reduction of 58%. This is weaker compared to Germany's overall emission reduction targets of that year. For 2040, the government did not set an intermediary target for industry so far. Moreover, industry targets have not been broken down for individual industry sectors, meaning that there is no obligatory steel stector emission reduction target.

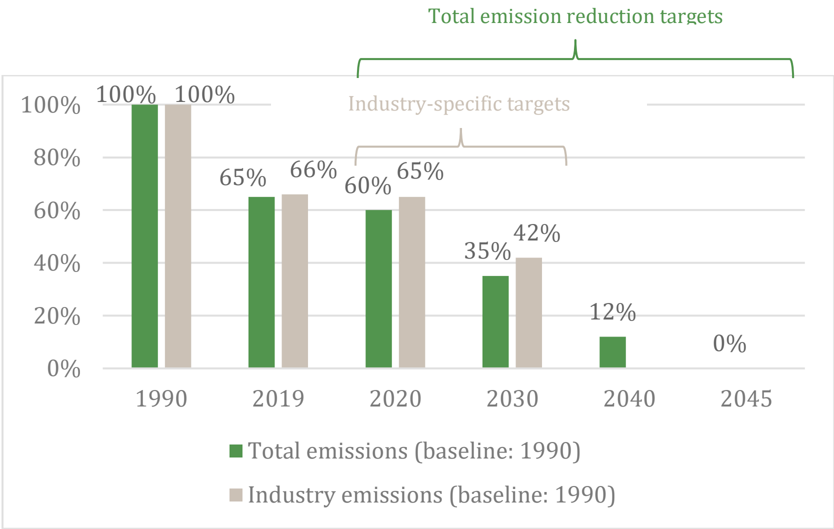


Figure 5: Policy objectives based on the revision of Germany's Climate Protection Law

Germany's largest steel producers are committed to achieve climate neutrality by the middle of this century. ThyssenKrupp and Salzgitter have pledged to contribute to Germany revised climate objectives by 2045. By 2030, ThyssenKrupp plans to reduce emissions by 30% compared to 2018 levels and to become climate neutral by 2045 (Thyssenkrupp Steel, 2021). Salzgitter recently announced ambitious plans to reduce emissions by 50% by 2030 and 95% by 2045 compared to 2018 levels (Rehrmann & Plettendorf, 2021; Salzgitter AG, 2022). The other large players, including ArcelorMittal as well as Dillinger and Saarstahl, strive for climate neutrality in 2050 but might align their company targets in accordance with the government. ArcelorMittel is committed to reduce emissions of its European steel plants by 30% by 2030 before becoming climate neutral in 2050.

2.2.2 Elaboration of emission reduction path

In literature, several scenarios were modelled showing possible pathways for climate neutrality in the steel sector until the middle of this century. The following figure mirrors analyses aligned with the latest revision of Germany's Climate Protection Law.

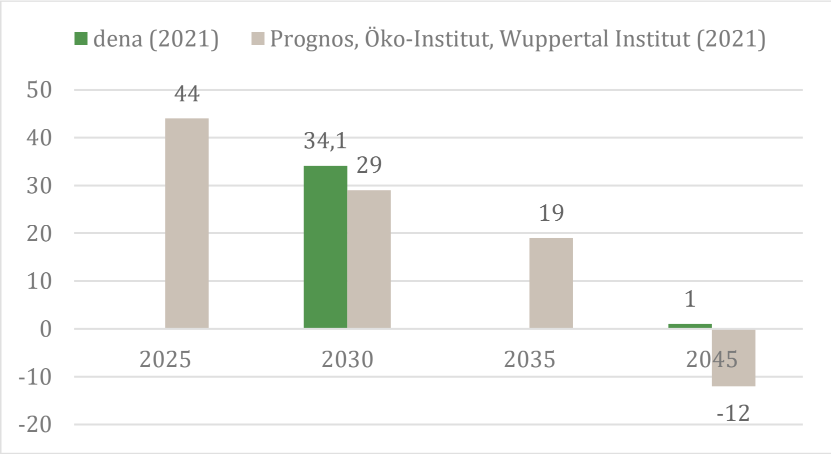


Figure 6: Modelled steel sector emission reduction pathways (in million t CO_2-eq, own figure based on dena, 2021 and Prognos, Öko-Institut, Wuppertal Institut, 2021)

Data provided by Prognos, Öko-Institut & Wuppertal Institut is a bit more detailed with more intermediate steps. In contrast to dena (2021), authors assume that steel industry will become a carbon sink from 2040 onwards. This is achieved by assuming that almost all sustainable biomass available in Germany will be used in industry and coupled with CCS (BECCS) (for a brief explanation, see text box 5, p. 14 in this report), whereas other scenario studies still assume the use of biomass in buildings or transport.

2.2.3 Assumed decarbonization actions

The following figure shows the production routes in 2030 and 2045 based on the two scenarios mentioned above as well as on another scenario from the Federal Association of the German Industry (BDI 2021).

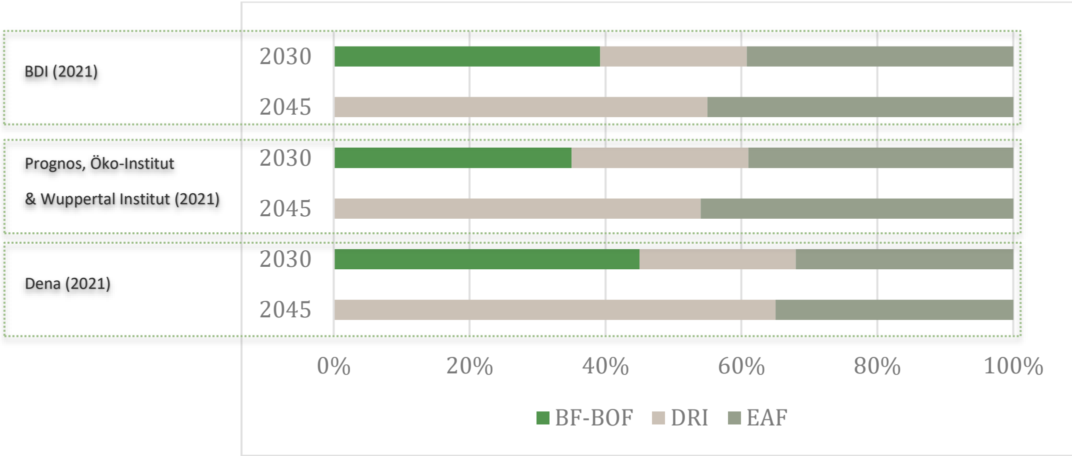


Figure 7: Distribution of production routes modelled for 2030 and 2045 in dena (2021) and Prognos, Öko-Institut and Wuppertal Institut (2021) (own figure)

BDI (2021) assumes that both, primary steel from the BF-route and secondary steel, will individually account for 40% of total steel production in Germany by 2030. Between 2030 and 2045, BF-steel will be phased out completely, and direct reduction will be the dominant method to produce steel, while EAF-steel will only gain negligible shares.

Prognos, Öko-Institut and Wuppertal Institut (2021) assume that BF-based production will decrease substantially from 70% in 2019 down to 35% in 2030, while DRI- and EAF-steel will increase to 26% and 39%, respectively. Hence, for 2030, the secondary route will be the dominant pathway to produce steel. In the middle of the century, BF-production will be phased out completely, while DRI- and EAF will be more or less on equal footing as regards shares in steel output. In this scenario, decisive steps towards steel sector decarbonization are that new BF will not be commissioned any more, but all necessary reinvestments are made in DR-plants, which are modeled to make use of only 20% natural gas and 80% hydrogen as a reducing agent.

The scenario by dena (2021) is a bit more conservative as regards the expansion of steel production through DRI-technology and EAF in 2030. Less than a quarter of steel will be produced via direct reduction relevant for 10 mn tons of carbon-free steel, almost half of steel will still come from the conventional primary route. However, in the middle of the century, DRI-technology will produce two thirds of steel production (and 30 mn tons of carbon-free steel), while the rest will be from the secondary route.

Both scenarios expect hydrogen to play a substantial role in steel sector decarbonization. In 2030, both scenarios assume hydrogen use between 15 and 26 TWh, which is 24% and 40% of total hydrogen demand in Germany modelled. For 2045, hydrogen use in steel production will amount to 35 and 75 TWh, equivalent to 13% and 17% of Germany's total demand for hydrogen (Deutsche Energie-Agentur, 2021a; Prognos et al., 2021). As regards the EAF-route, Prognos, Öko-Institut and Wuppertal Institut (2021) are more optimistic. Especially in the long run, authors expect a bigger role of recycled steel. Due to the dominance of primary steel from DR-plant in dena (2021), the demand for hydrogen is assumed to be higher. Moreover, the use of biogenic syngas reduces the need for hydrogen according to Prognos et al. (2021).

As provided in the following table, analysis suggests that direct reduction technology can bring about substantial emission reductions. This includes the more immediate time frame until 2030, for which authors assume a blending of natural gas with 7.5% hydrogen, as well as the long run until 2050. CCS may achieve similar results until 2050, but – as will be shown later – questions regarding safety at storage sites will be an issue. CCU may not achieve the emission reductions necessary, and iron electrolysis has a relatively low technology readiness level (TRL).

Table 1: Emission reduction potential of selected decarbonization technologies in the steel sector (based on Agora Energiewende & Wuppertal Institut 2019)

Technology	Emission reduction / remaining emissions intensity	Emission reduction potential (2030)	Emission reduction potential (2050)	TRL
Direct reduction	-97% / 0.05 t CO_2 / t CS	14 mn. t CO / a	50 mn. t CO_2 / a	4-5
CCU	-50% / 0.85 t CO_2 / t CS	2-6 mn. t CO / a	n. a.	4-5
HIsarna / CCS	-86% / 0.24 t CO_2 / t CS	0 mn. t CO / a	44 mn. t CO_2 / a	4-5
Iron electrolysis	-87% / 0.22 t CO_2 / t CS	0 mn. t CO / a	< 1 mn. t CO_2 / a	1-3

Text box 3: Other decarbonization technologies

Carbon capture and utilization (CCU) in the steel industry allows metallurgical gases produced in the BF-route to be separated and used e.g. for the production of valuable chemical substances (e. g. methanol, ethanol, synthetic fuels, ammonia). Used this way, metallurgical gas must not be burned in on-site power plants anymore. However, green methanol, for instance, requires green hydrogen as an ingredient, which is why CCU is electricity-intensive. The HIsarna process is a new type of coal-based smelting reduction process. Its advantage is a relatively pure CO_2 waste gas stream and, thus, it can be more easily combined with **carbon capture and storage** approaches. The removed CO_2 would, then, have to be transported to geological storage sites. In (alkaline) **iron electrolysis**, iron ores are reduced to pig iron and then melted to crude steel in an electric arc furnace without a carbon-containing reducing agent. The process promises a significant increase in energy efficiency compared with the blast furnace route (Agora Energiewende & Wuppertal Institut, 2019).

2.2.4 Menu of decarbonization technologies

Like in the aforementioned scenarios, the Federal Ministry of the Economy focuses in its Action Concept Steel on hydrogen-based steel production for producing primary steel and the electric (secondary) route (BMWi, 2020). Concepts, in which CO_2 emitted is either used in other processes or stored are mentioned, too.

Text box 4: Hydrogen and its colours

Green	hydrogen produced through electrolysis powered by renewable energy
Yellow	hydrogen produced from electricity of the national electricity mix (often also including natural gas or coal as primary energy sources for electricity production)
Pink	hydrogen produced from nuclear power
Turquoise	hydrogen produced from natural gas making use of methane pyrolysis resulting also in solid carbon (to be used for agricultural purposes, for instance)
Blue	hydrogen produced from natural gas through steam reforming, where CO_2 emitted is captured and stored underground
Grey	hydrogen produced from natural gas using steam reforming technology and the resulting CO_2 is emitted into the atmosphere

In designing the market ramp up for hydrogen, the German government plans to install 10 GW of domestic electrolyser capacity by 2030 and, in parallel, to forge partnerships with other countries for hydrogen imports. While only green hydrogen from renewable electricity is considered to be sustainable in the long run, other types of hydrogen will be crucial for market creation in the short- and mid-term. Hence, for the transitional phase, Germany's National Hydrogen Strategy also highlights the importance of blue and turquoise hydrogen from natural gas (Federal Government, 2020, 2021).

There are several projects that already pave the way for this production route. For instance, Salzgitter has set up a small wind farm close to its production site in Germany and installed a proton-exchange membrane electrolyser as well as a high-temperature electrolyser, which can also make use of high-temperature waste heat facilitated by steel production to produce green hydrogen (Salzgitter AG, 2019). ArcelorMittal has already set up a DRI-facility but also has several other hydrogen projects in the pipeline, which include the build-up of DRI- and EAF-plants. For instance, ArcelorMittal's Hamburg plant is supposed to deliver direct reduced iron to its Duisburg plant, which will be modernised in the future; the modernisation process will include the switch from BF to EAF. ArcelorMittal also seeks to reduce energy costs by reducing heating temperatures through artificial intelligence in its Duisburg plant (ArcelorMittal, 2020). The companies Dillinger and Saarstahl cooperate with the technology supplier Paul Wurth in setting up dry reforming technology. It will convert coke oven gas into a synthetic gas including hydrogen and carbon monoxide injected into the BF. The technology will reduce CO_2 -emissions by 12 %; by feeding in additional hydrogen, emission reduction potential may double (eisen + stahl, 2021). Several projects are financially supported by the government support research and development investment in technologies.

In the scenario developed by Prognos, Öko-Institut and Wuppertal Institut (2021), DRI-technology will also be applied to make use of synthetic gases from biomass by 2040. It is one of the advantages of DRI-technology to make use of different types of gases (including natural gas / methane or hydrogen), but while combusting hydrogen only results in water, burning synthetic gases will generate CO_2. This biomass-based CO_2 needs to be captured by applying oxyfuel technology and must be stored at safe geological sites, if steel production is to be transformed into a net remover of CO_2.

Text box 5: Oxyfuel technology and bioenergy with carbon capture and storage

In one of the scenarios for Germany's path to climate neutrality in 2045, biomass plays an important role in the long run. Wood chips would be delivered to steel plants and converted into synthesis gas, a mixture of carbon monoxide, hydrogen and carbon dioxide, which can serve as a biogenic carbon supplier for the metallurgical processes. It can also provide heat relevant for several purposes (e. g. preheating). An oxyfuel furnace can capture bio-based CO_2 and pipelines are supposed to forward CO_2 to geological storage sites. This integrated process is also known as bioenergy carbon capture and storage (BECCS) (Prognos et al., 2021).

Another innovative project carried out by ThyssenKrupp is called Carbon2Chem, also supported by the German government. In the project, metallurgical gases from steel production are forwarded to the chemical industry closeby, which is able to use these gases in the production process of chemical products (Thyssenkrupp Steel, 2020).

In comparison to DRI-technology, the EAF-route is state of the art already used today to recycle scrap and produce new steel. At the moment, companies offer green (recycled) steel by making use of renewable electricity. Examples include the company DEW stating that its steel integrates 100 % renewable energy and recycled scrap, resulting in only 110 kg CO_2 per ton crude steel (Deutsche Edelstahlwerke, 2022). The company SWT uses green electricity from Scandinavian hydropower (Stahlwerk Thüringen, 2021). The company BSW, located close to the French-German-border, seeks to feed its waste heat potential into a district heating network for communities located in Germany and France (Region Grand Est, 2020).

2.2.5 Economics of decarbonization

The following table shows economic figures of selected decarbonization technologies. It shows that DRI-technology offers a good compromise due to its potential to reduce emissions almost completely and at comparatively moderate abatement costs. Moreover, expected applicability in an industrial scale is possible within this decade. CCU will have high abatement costs, which is also true for iron electrolysis that is considered an option for 2050.

Table 2: Economic figures and technology readiness levels for selected decarbonization technologies (based on Agora Energiewende & Wuppertal Institut 2019)

Technology	Abatement costs (2030)	Abatement costs (2050)	Additional costs (2050)	Expected applicability
Direct reduction	60-99 EUR / t CO_2	85-144 EUR / t CO_2	36-61%	2025-2030
CCU	231-439 EUR / t CO_2	178-379 EUR / t CO_2	63-119%	2025-2030
HIsarna / CCS	n. a.	25-45 EUR/ t CO_2	9-16%	2035-2040
Iron electrolysis	n. a.	170-292 EUR / t CO_2	65-112%	2050

2.2.6 Major challenges to realize the roadmap

Challenges to realize steel sector decarbonization can be categorized into five central categories (see figure 8). Even though these dimensions apply to both production routes, primary and secondary steel, there are noteworthy differences. The following section provides an overview of the challenges also factoring in differences regarding the decarbonization technologies discussed above.

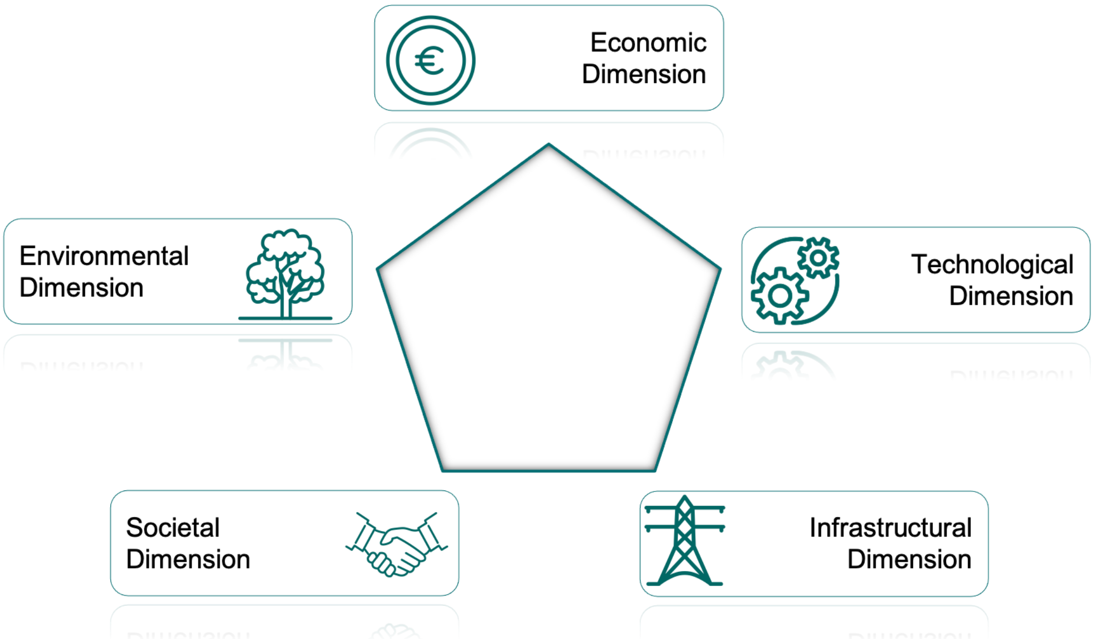


Figure 8: Action fields to be addressed by policy responses (own figure)

As regards the **economic dimension**, all technologies require additional upfront investment in order to align primary steel production with climate-neutrality. For instance, in the case of direct reduction, this does not only include technology-related investment, but may also factoring in plant-related adjustments for installing new pelletising plants necessary for feeding DRI-plants. For direct reduction, the use of iron ore pellets becomes more important; these could be produced on-site or purchased on the market (Draxler et al., 2021; Kempken et al., 2021). Increasing need for pellets will also affect operational costs of applying direct reduction technology, even though the central cost issue will without doubt be the costs of hydrogen purchases. Green hydrogen, in particular, will be more costly compared to other types of hydrogen, also due to its limited availability in the next years and its sensitivity to electricity prices (Ausfelder & Dura, 2019; Wuppertal Institut & DIW Econ, 2020). Electricity-related costs are also relevant for other technology options. Both, CCU and CCS as well as iron electrolysis require large amounts of electricity and are, thus, sensitive to electricity prices and price spikes. CCU or the conversion of CO_2 into other products is linked to the availability of hydrogen (Agora Energiewende & Wuppertal Institut, 2019; Draxler et al., 2021). Since the secondary route relies massively on electricity, an expansion of the EAF-route (taking shares of the primary / BF-BOF-route) would also see a rising demand of electricity. In addition, limited scrap availability is likely to increase scrap prices (ESTEP, 2021). What also needs to be considered is the role of staff trained to apply new technologies (Kempken et al., 2021). Another issue will be the market uncertainty for green steel products and how, for instance, manufacturers of cars or appliances will take up green steel in the next years (Kempken et al., 2021). The cost dimension is a central issue because of the steel sector's exposure to international trade. Hence, steel producers are afraid of additional costs as their product may become uncompetitive in relation to countries with less strict regulations.

Considering the **technological dimension** for making primary steel through DRI-technology, it is relevant to investigate upon the integration of different processes including (on-site) hydrogen production, direct reduction and electric smelting, where hydrogen production is grid-optimized and flexible (De Santis et al., 2021). As regards green hydrogen production, proton exchange membrane electrolysis (PEMEL) is considered an important technology for grid-integration, but high temperature electrolysis (HTEL), which is able to make use of waste heat (possible also from steel plants) has better efficiencies. However, HTEL needs to be further researched upon, while PEMEL is closer to market deployment (IEA, 2019). Since iron electrolysis, applicable around the year 2050, needs substantial quantities of electricity, load-shifting potentials would need to be analyzed in-depthly before it is integrated into the power system (Agora Energiewende & Wuppertal Institut, 2019). However, it is generally considered to be suitable for integration in renewables-based electricity systems as operation temperature is low (Draxler et al., 2021). For the storage of CO_2 underground, safety and injection issues at storage sites need to be addressed (Umweltbundesamt, 2019). Scrap-based steel-making for primary or secondary production has a number of technical limitations, as well. These do not refer to the steel-making process as such but to the scrap availabilities. Some elements in scrap (such as cooper) cannot or can only hardly be removed in the electrical route, which is why secondary steel is often used in buildings (Kempken et al., 2021). Innovative technologies for automatic scrap property measurement (also using artificial intelligence) are known, but will be market ready (TRL 8) only around the year 2030 (Aydemir, 2021; De Santis et al., 2021).

For both, primary and secondary production, the expansion of **infrastructures** will be necessary. Since all technologies will need electricity for operation, the expansion of renewable energy capacities is a precondition for steel sector decarbonization. The hydrogen-route has the advantage that hydrogen can be transported via pipelines and imported, for instance, in liquefied form. However, in both cases, retrofitting existing pipelines and ports and building new ones is without alternatives and costly. However, addressing energy demands may only be one side of the coin, if CO_2 is captured. CCU or CCS would need transport modes (trucks, ships, short- to long-distance pipelines) to transport CO_2 to relevant destinations for further processing or long-term storage. In particular, with regard to CO_2, certain regulatory bottlenecks exist in Germany, that hinder the storage of CO_2 (Markewitz, 2018). It may also be worthwhile to reflect upon synergies with other sectors that may result from steel production. Like the aforementioned example of the (secondary) steel producer BSW, which facilitates waste heat to district heating networks, other opportunities may exist, for which infrastructure (upgrades) might be necessary.

The infrastructural build-up will have effects on the **environmental dimension**, for instance, if renewable energy farms, power grids or hydrogen- and CO_2 -pipelines are constructed in less-urbanised and more nature-oriented / protected areas. In particular, CO_2 -storage is feared to acidify ground water or result in seismic activity (Umweltbundesamt, 2019). Apart from that, it will be crucial to safeguard that all electricity capacities necessary to feed the steel industry will be additionally installed and, thus, do not withdraw limited renewables from other sectors. Moreover, the production of one kilogram of green hydrogen requires stochiometrically around 9 liters of deionized water (Beswick et al., 2021); water consumption is even considered to be higher in practice (Altgelt et al., 2021). While Germany is a „water rich“ country, the import of green hydrogen is indirectly also an import of water. In addition, using biomass (in combination with oxyfuel carbon capture and CO_2 -storage) will also necessitate to install standards that safeguard sustainable biomass production.

Challenges in the **societal dimension** of steel sector decarbonization may arise from price rises of end products and, more indirectly, public resistance linked with infrastructure developments, that is the new construction of power grids, pipelines or storage sites. Public opposition to onshore CO_2 -storage was already witnessed and resistance to grid expansion is ongoing in Germany (Markewitz, 2018). The move to turn to offshore storage-sites (as well as using CCS for process-related industrial emissions in contrast to focus on coal-power plants) has, however, reduced public headwinds and increased stakeholder support. Given that countries such as Norway seek to store CO_2 underneath the sea shows that the technology is available in principle, even though at higher prices in comparison to onshore storage (Thomas et al., 2021). Regarding costs, substantial increases of end products are not expected; for instance, first calculations suggest that prices for a car with a share of 30% climate-friendly steel will result in additional costs of about EUR 40 (Agora Energiewende & Wuppertal Institut, 2019). First results of a research project suggest that the willingness of end-users to pay for climate-friendly steel products is higher than estimated market prices (Hirzel, 2021). However, public headwinds may also arise if biomass is used for steel production.

2.3 Conclusion - Implications and policy proposals with consideration of the time frame

Due to the challenges ahead, concerted policy action is planned by the German government. The **Steel Action Concept** (SAC), published in 2020, outlines policy interventions possible for steel sector transformation towards climate-neutrality to address the economic barriers ahead (see figure 9). It is noteworthy that the Concept does not include any specification of emission reduction tragets of the steel sector.

Figure 9: Pillars and initiatives for steel sector decarbonization (own figure based on BWMi 2020)

As part of the European Union's "Fit for 55" package, which strives for 55% GHG emission reduction by 2030 compared to the 1990 baseline, the EU seeks to introduce the **Carbon Border Adjustment Mechanism** (CBAM) affecting imports from third countries including steel products. CBAM is supposed to "equalise the carbon price between domestic and foreign products, thereby limiting carbon leakage" and, in addition, motivating third countries to realise a carbon pricing regime (EPRS, 2022). Since steel producers in the EU are part of the European Emissions Trading System (ETS), they need to have emission certificates for every ton of CO_2 emitted. Until 2026, EU steel producers will also receive free allowances, but this free allocation is planned to be gradually phased out from 2026 onwards. Under the CBAM, importers of steel would have to purchase certificates reflecting the EU's carbon price to be paid if the same product had been produced in the domestic market. Implementation of CBAM is proposed in phases: beginning in 2023, steel importers would not have to pay for CBAM certificates, but have to report GHG emissions including CO_2, N2O and PFCs. From 2026, importers would have to be authorized to import steel and obtain CBAM certificates (Appunn, 2020; EPRS, 2022).

At the EU-internal level, including Germany, an innovative policy instrument currently discussed are **Carbon Contracts for Difference** (CCfD). Such contracts support investors, including those from the steel industry, to realize low-carbon breakthrough technologies, which are (relatively) mature from a technological perspective but uncompetitive from an economic point of view. CCfDs include a project-based "strike price", which is above the market price for CO_2 (that is higher than the ETS-price), agreed upon for ten years or more between the government and an industry investor. If the strike price is higher than the CO_2-price, the government pays the cost difference to the industry investor. The strike price also factors in the project-specific abatement-costs and increased operational costs, e. g. for green hydrogen (BMU, 2021; IN4climate.NRW, 2021; IREES et al., 2021). It has been estimated that between EUR 13 bn. and EUR 35 bn for such CCfD may be necessary to achieve steel sector transformation, also depending on other instruments of the policy mix including those that facilitate a green market for steel products (Agora Energiewende et al., 2021).

Upfront funding instruments include the **Innovation Fund** of the European Union and the Federal Government's **Decarbonization of the Industry Programme**. As regards the latter, industry projects seeking to store CO_2 underground are not eligible for funding (Kompetenzzentrum Klimaschutz in energieintensiven Industrien, 2022)

The SAC also notes that **public procurement** may pave the way for green steel, if climate-friendly steel is specifically considered for public contracts. A study suggests that public procurement of climate-friendly steel may realise emission savings of 150,000 t CO_2 in 2025, assuming that 5% of public steel demand is met by climate-friendly DRI-steel produced with a ratio of 90% natural gas and 10% hydrogen; increasing the quota to 30% and the hydrogen content in DRI production to 50% may result in 800,000 t CO_2 saved (Fischer & Küper, 2021).

Also discussed is a **quota for green steel in end-products** (BMWi, 2020). Such a quota would even enlarge the market for green steel products from a rather narrow public sector, as envisioned by a public procurement instrument, to private sectors. A compulsory quota of 30% green steel in cars is expected to only negligibly raise costs by around EUR 40 for end-users (Agora Energiewende et al., 2021).

Text box 6: Offtake for a green steel market in Germany

Even though discussions about costs of end-products due to green steel integration have not been settled yet, media report about cooperations between steel producers and manufacturers of end-products. For instance, the appliance manufacturers BSH and Miele have signed contracts with the steel producer Salzgitter to purchase green steel. While appliances are only a (relatively) small part of the steel sector's demand side, recent initiatives by the car producers BMW and Mercedes also bring the automobile sector on the table for green steel, which belongs to the largest demand side sectors regarding steel (see also Table x). Both companies seek to purchase green DRI-steel from a Swedish producer from 2025 onwards (Eder, 2021; Mercedes-Benz Group, 2021; Salzgitter AG, 2021b, 2021a).

However, a trustworthy **label** or certification scheme would be necessary for both, public procurement and the quota on end-products. Otherwise, it could not be taken for granted that steel purchased is truly green. Since there is no such label available today, Salzgitter, for instance, contracted the TÜV-Süd, a certification body, which confirms that certain products made by the company are less emission intensive comparing primary steel production with the secondary route (Knitterschneidt, 2021; Müller-Arnold, 2021; Oberst, 2021).

Given that all technologies mentioned above rely on infrastructural upgrades, it will be crucial that **planning** will be orchestrated in a cost-effective manner. Applied research focuses on organizing the process to integrate the plans for electricity grids and pipelines (for natural gas and hydrogen) by establishing a system development plan preceding both, electricity and pipeline infrastructure planning (Deutsche Energie-Agentur, 2021b). Apart from that, it must be taken into account that substantial reinvestment will have to be made by 2030 in today's BF-plants: around 50% of the total primary production capacity of BF in the steel industry will reach the end of its service life by 2030 (Agora Energiewende & Wuppertal Institut, 2019). Hence, for a coherent planning of infrastructural upgrades and reinvestments in steel plants, a holistic approach needs to be found factoring simultaneous steps (in contrast to a sequential approach) (Grimm, 2021).

Since hydrogen is likely to be the key for transformation of the steel sector, infrastructure planning will be a central aspect. But not only hydrogen-related transport issues will have to be solved, but also supply side issues. The **National Hydrogen Strategy** envisions a market ramp-up through developing electrolyser capacity of 5 GW by 2030; the new Government Coalition raised this target to 10 GW electrolyser capacity domestically. Moreover, hydrogen imports will become central, which is why the government supports international projects focusing on hydrogen production (e. g. Australia, Chile) (Federal Government, 2020, 2021). Generally, a hydrogen-related policy mix is another part of the discussion on steel stector transformation (Tholen et al., 2021). In this respect, the government also established a funding instrument called H2Global, which compensates for cost differences between green hydrogen import and market prices (H2Global Advisory, 2022).

Last but not least, the concept of a **steel sector decarbonization club** is currently discussed in Germany and beyond. Such a club is a grouping of at least three actors (e. g. from the realm of government or private sector) from more than one country delivering a benefit exclusively to members of the club ("club good"). While there are several elements of such a concept in discussion, a valuable contribution of a "steel club" could be the realization of (ambitious) decarbonization targets among club members also to reduce uncertainty about technology, investments and future markets (Hermwille, 2019).

Apparently, Germany's policy response for challenges in steel sector decarbonization focuses on the hydrogen pathway. Other technology options are less focused upon and, especially, (BE-)CCS, which is considered in some scenarios a relevant option around 2040 (Prognos et al., 2021), is less tackled policy-wise at the moment. Still, Germany's Ministry for the Economic Affairs and Energy under the former government has worked on CCS and participates in a European coordination instrument for facilitating CCS (and CCUS) projects. The Industry Strategy 2030 mentions CCU and CCS briefly, stressing the role of RD&D

(BMWi, 2019). Policy response for hydrogen-based steel making in Germany focuses on funding, either through investment support for pilot projects or through innovative instruments including CCfD, which may be implemented soon. Discussions on policy tools that focus on a green steel market (such as public procurement, quota, and labelling) are, although mentioned in the SAC, a bit retarded and likely to receive more attention in the next months to years.

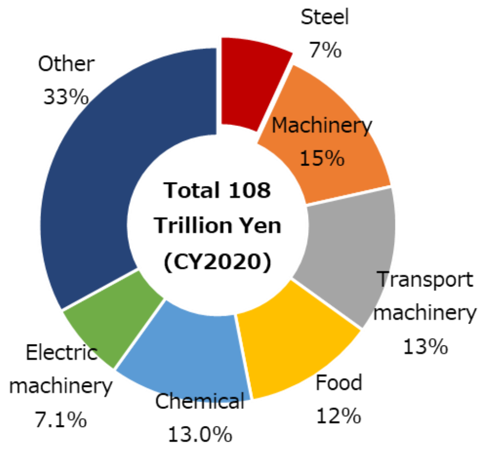
3 Japan

3.1 Industry overview

The steel industry is one of the major industries for the Japanese economy. The industry as a whole had sales of 19 trillion yen (about 146 billion euros) as of 2019, and was the fifth largest industry in terms of manufacturing market share after machinery, transport machinery, food, and chemicals. The steel industry provides as many as 300,000 jobs, including its wholesale segment. Steel also contributes significantly for Japan's acquisition of foreign currency, making it the fourth export product for Japan after automobiles, electronic parts such as semiconductors, and automobile parts.[1] As for export destinations of steel products, China accounted for 14% of the total export volume, followed by Thailand (14.1%), South Korea (13.8%) and the United States (6.1%) as of 2019.

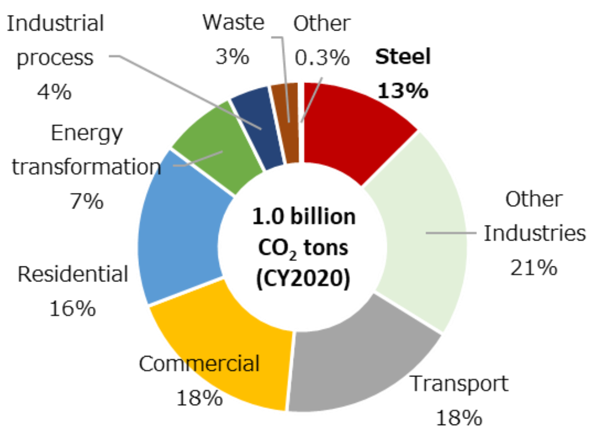
The steel industry’s contribution to the Japanese economy is large, but its contribution to the greenhouse gas emissions is also large. The steel industry emitted the largest amount of CO_2 as a single industry (excluding electricity) in 2020, taking 13% of Japan's total CO_2 emissions. In order to realize carbon neutrality in 2050, therefore, whether or not the steel industry can effectively cut its emissions is critically important.

[1] Japan Foreign Trade Council Inc, “Nihon no Boueki no Genjo to Kadai (Current status and issues of Japanese Trade)” December 2020. https://www.jftc.or.jp/kids/kids_news/japan/item.html. Accessed on 21 November 2021.



Source: Cabinet Office of Japan (2021)

Figure 10 Industrial share in the GDP of manufacturing industry (in calendar year 2020)



Source: National Institute for Environment (2021)

Figure 11 CO_2 Emissions by industry (in calendar year2020)

3.1.1 Major firms and revenues

In the Japanese steel industry, there are two types of steel-making companies, one that manufactures iron with a blast furnace and the other that manufactures steel with an electric furnace. This paper mainly focuses on steel companies using blast furnaces because its share over the total steel production is much larger and reducing the CO_2 emission is much more difficult for a manufacturer with blast furnace.

There used to be a larger number of blast furnace steel companies in Japan, but as M & A between companies progressed, as of 2021, there are three major blast furnace steel makers in Japan as shown in Table 3.

Table 3 Major Blast furnace steel maker of Japan

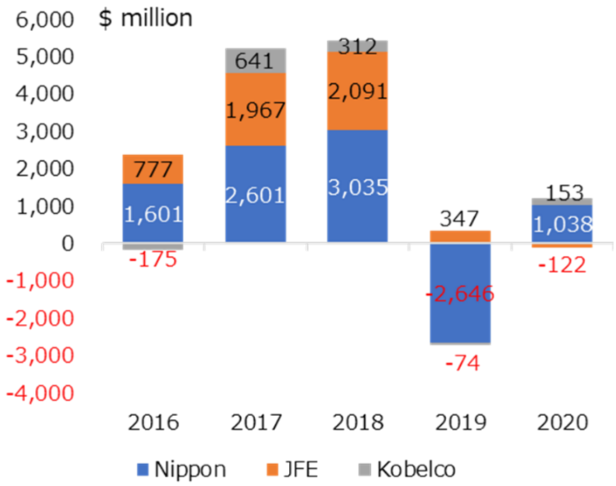
Company	Nippon Steel Corporation	JFE Holdings Inc.	Kobe Steel, Ltd. (Kobelco)
Headquarters	Tokyo	Tokyo	Kobe / Tokyo
Employees (2020)	106,226	64,371	40,517
Ownership	Private (listed)	Private (listed)	Private (listed)
Sales (2020)	US$45,558 million	US$ 30,446 million	US$ 16,090 million
Operating income (2020)	US$1,038 million	(US$ 122 million)	US$ 152 million
Crude Steel Production (2020)	37.7 million tons	24.0 million tons	5.8 million tons

Source: Nippon Steel (2021)a; JFE Holdings (2021)a; Kobe Steel (2021)

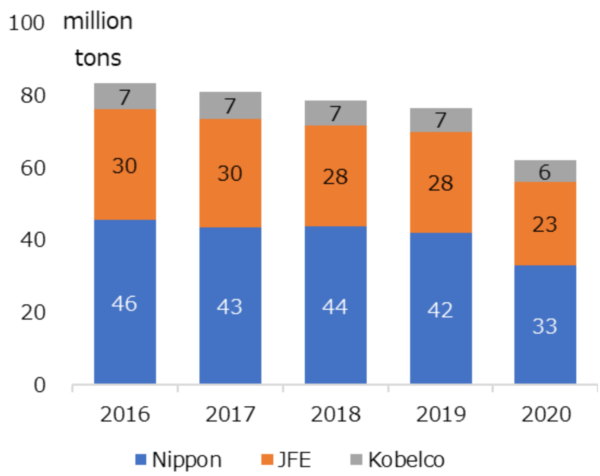
The business environment of each company fluctuates greatly from year to year. In the fiscal year 2019 (April 2019 - March 2020), the global spread of the new coronavirus, which became more serious from the beginning of 2020, had a significant negative impact on the operation of the manufacturing industry. Because the manufacturing industry is a main customer of steel products, such negative impacts similarly caused a damage on the steel industry’s business as well. In the fiscal year 2020 (April 2020 – March 2021), the industrial performance improved along with the recovery of the global economic activities.

The three major blast furnace steel makers are all 100% privately owned and publicly traded companies. Nippon Steel, in particular, is one of the world's largest steelmakers, ranked at third in terms of crude steel production. The three companies produced approximately 62 million tons of crude steel altogether, which accounts for 75% of Japan's total crude steel production in 2020. Crude steel production has been on a downward trend since before the spread of the coronavirus, due to factors such as troubles with manufacturing plants, the impact of natural disasters, and sluggish economic activity caused by the US-China trade dispute.

Figure 12 Operating income of major three steel makers in Japan



Source: Nippon Steel (2021)a; JFE Holdings (2021)a; Kobe Steel (2021)



Source: Nippon Steel (2021)a; JFE Holdings (2021)a; Kobe Steel (2021)

Figure 13 Crude steel production by the three major steel companies in Japan

3.1.2 Historical background

The history of Japan's modern steel industry dates back to 1857, when the first pig iron was successfully produced in Japan's first Western-style blast furnace in Kamaishi, Iwate Prefecture. In the past, steel mills were established in areas that had domestic production of iron ore or coal, but due to the increasing demand for steel and limited domestic resources, Japan became dependent on imports of both iron ore and coal. In addition, as explained shortly, Japan's steel industry is more dependent on exports than the steel industries of other countries. Most of the currently operated blast furnaces exist on the Pacific coast of Japan, which makes them easier to import feedstocks and export their products.

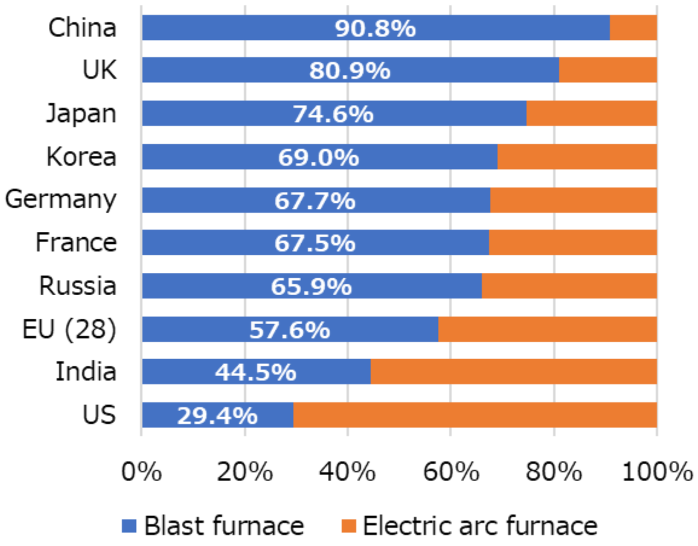
Remarks: Red=Nippon Steel; Blue=JFE; Green=Kobe Steel

Source: IEEJ

Figure 14 Location of blast furnaces in Japan

3.1.3 Types of processes used

Japan's steel industry has a higher share of production using blast furnaces than other countries' steel industry. Figure 15 compares the share of blast furnaces and electric arc furnaces in the steel industry of various countries. The share of blast furnaces in Japan is about 75%, which is only lower than that of China and the United Kingdom and higher than those of other major countries including the United States and Germany. Japan's steel industry is highly dependent on blast furnace steelmaking, because it has a large demand of high-functional products such as high-tension steel for the automobile industry. In addition to this, in recent years, demand for steel frames for construction and other steel materials in Japan has been sluggish, resulting in a decline in demand for electric furnace products and consequently an increase in the share of blast furnace production. This market environment makes it difficult for the Japanese steel industry to decarbonize itself by "electrifying" its steel production process.



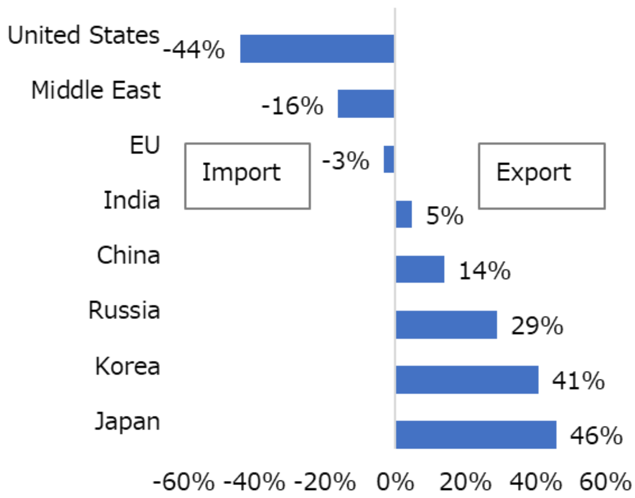
Note: Because the different reference the figures for Germany are different from the previous section.

Source: World Steel Association (2021)

Figure 15 Share of blast furnaces and electric arc furnaces

3.1.4 Other relevant factors affecting decarbonization of the steel industry

As shown in Figure 16, Japan's steel industry exported 46% of the products it manufactured domestically to foreign countries as of 2018, making it more trade-dependent than other countries' steel industry. This means that Japan's steel industry is more heavily exposed to international competition, and in this sense, the increased costs associated with decarbonization will have a greater impact on its profitability and business structure.



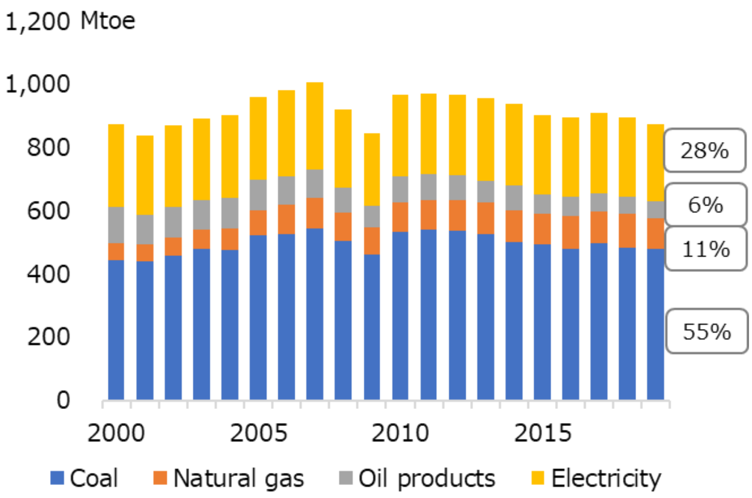
Note: Figures are net exports as % of production on true steel use basis

Source: International Energy Agency (2020) Iron and Steel Technology Roadmap

Figure 16 Steel trade by major steel producers and users (2018)

Partly because of its high dependence on the blast furnace, the Japanese steel industry is carbon-intensive also in terms of its energy consumed. As shown in Figure 17, more than half of the energy utilized in the Japanese steel industry is coal.

The Japanese steel industry has made serious efforts to reduce CO_2 emissions from its operational activities. In particular, in 2005, the industry set a target of reducing CO_2 emissions by 3 million tons compared to the business-as-usual case based on changes in product sales volume and the ratio of converters to electric furnaces. This target has been achieved as of 2019, mainly through the improvement of energy efficiency, specifically through the use of next-generation coke and the introduction of more efficient power generation equipment.

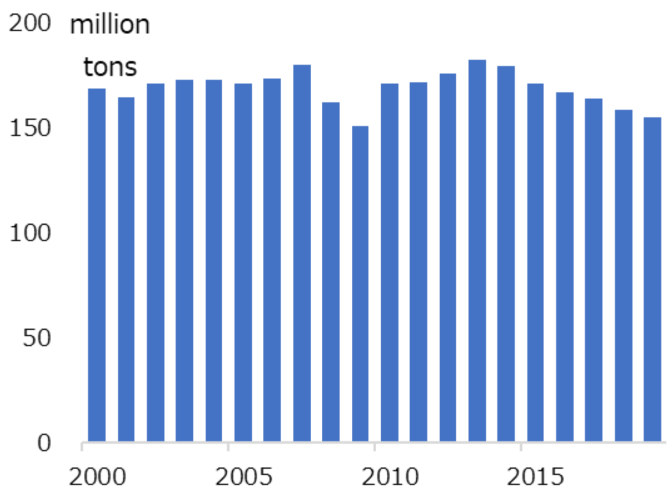


Note: The figure includes the consumption by electric arc furnaces.

Source: The Institute of Energy Economics, Japan (2021).

Figure 17 Energy consumption by the Japanese steel industry

Figure 18 CO_2 emissions from the Japanese steel industry



Source: National Institute for Environment (2021)

Figure 18 CO_2 emissions from the Japanese steel industry

Table 4 Measures to enhance efficiency in the steel industry

Next generation coke furnace

Company	Works	Year	Emissions reduction
Nippon	Oita	2008	-400 ktons-CO2/yr
Nippon	Nagoya	2013	-100~-200 ktons-CO2/year

Installation of efficient power generation unit

Company	Plant	Year	Type
Kobelco	Kakogawa	2011	Gas turbine combined cycle
Kimitsu Kyodo	Kimitsu	2012	Advanced combined cycle
Kasihma Kyodo	Kashima	2013	Advanced combined cycle
Wakayama Kyodo	Wakayama	2014	Advanced combined cycle
Oita Kyodo	Oita	2015	Advanced combined cycle
Kobelco	Kakogawa	2015	Gas turbine combined cycle
JFE	Chiba	2015	Gas turbine combined cycle
Nippon	Kure	2017	Boiler turbine
JFE	Ohgishima	2019	Gas turbine combined cycle
Fukuyama Kyodo	Fukuyama	2020	Gas turbine combined cycle

Source: Japan Steel & Iron Federation (2021)

3.2 Decarbonization roadmap

3.2.1 Mid- and long-term emission reduction goals

The Japanese government has set a carbon neutrality target for 2050, and the steel industry, a major emitter in Japan, has also set a carbon neutrality target as of the same year. Nippon Steel, JFE, and Kobelco all declared their targets for 2050, which are consistent with the Japanese government's target in this respect.

While the end game of the three companies is the same, there are nuanced differences in the medium-term targets in their emission reduction roadmaps. Although the Japanese government has set a target of 46% reduction from the 2013 level by 2030 for the entire country, the targets set by blast furnace steel makers for 2030 are lower than the nationally-set target. Specifically, Nippon Steel set a target of 30% reduction, while JFE aims to achieve 20% reduction, and Kobelco says it will reduce emissions by 30-40% reduction (the base year for all of the three targets is 2013).

3.2.2 Assumed decarbonization actions and elaboration of emission reduction path

Decarbonization actions by each steel company

Nippon Steel has set a medium-term goal of reducing emissions by 30% from 2013 levels. The company plans to reduce CO_2 emissions from its existing blast furnace and converter processes and develop an efficient production system by introducing the technologies developed in the COURSE50 program (to be explained later). The long-term carbon neutrality goal by 2050 will be pursued by the technologies such as the mass production of high-grade steel in large electric furnaces, hydrogen reduction steelmaking, and carbon offsetting measures through the adoption of carbon capture, utilization, and storage (CCUS) technologies.

Table 5 Technological issues and required external environment

Technology	Technological issues	Required external environment
High-grade steel manufacturing technology in a large Electric arc Furnace (EAF)	• Quality restrictions due to impurities in scrap or nitrogen contamination during melting • Scale of facilities and productivity need to be improved.	• Cost competitive carbon-free electricity
Hydrogen injection into BF	• Development of technology to inject a large amount of hot flammable gas into BF • Ensuring maximum gas permeability for stable reaction and melting with less coke in the BF • Scaling up technology to simulate a large-scale BF	• Realization of Carbon Capture and Utilization (CCU) and Carbon Capture and Storage (CCS) • Large volume of carbon-free hydrogen supply
100% hydrogen use in direct reduction	• High-hurdle unproven processes that have never	• Large volume of carbon-free hydrogen supply

	been demonstrated before • Technologies for blowing a large amount of preheated flammable gases at high temperature into the furnace, and expanding ores applicable to the hydrogen process	

Source: Nippon Steel (2021)b

The company states that there are technical challenges to overcome in each of these decarbonization efforts, and that external conditions must be in place to realize the carbon neutrality (Table 5). Furthermore, the production of such "zero-carbon steel" will require a significant amount of research and development (R&D) expenditures, large upfront capital investment, and higher operating costs associated with the use of carbon-free hydrogen and carbon-free electricity, which could more than double the current cost of producing crude steel as of today (Suzuki, 2021).

As for JFE Steel, the medium-term goal is to reduce emissions by 20% from 2013 levels as of 2030, and to achieve carbon neutrality as of 2050. Compared to Nippon Steel, the reduction targets for 2030 are moderate. As a unique attempt by JFE, the company plans to use artificial intelligence (AI) and data science to enhance the steel production productivity. The company also plans to expand the use of scrap materials and improve energy efficiency and produce syhthetic methane from capture CO_2 from the steel making process as explained later. As a long-term action, the company aims to adopt hydrogen in the steelmaking process by participating in the Ferro coke development plan and COURSE 50 (to be explained later) as future technology development.

Ferro coke is a substance consisting of low-grade coke and iron ore, which can realize the reduction process with a smaller amount of coke. JFE has been working on this technology development as a project supported by New Energy and Industrial Technology Development Organization (NEDO), a Japanese government organization, since 2017. The company is currently constructing a production facility for ferro coke with an annual production capacity of 300 tons at the company's Fukuyama Steel Works. By utilizing this ferro coke, it is expected that the amount of energy used in the steelmaking process will be reduced by 10% by 2023. In addition, the company plans to proceed with technological development of hydrogen direct reduction ironmaking and CCUS as further R&D areas.

Kobelco set a goal of achieving carbon neutrality by 2050 and, as a mid-term target, set a reduction target of GHG by 30% to 40% compared to 2013 by 2030. This target is more aggressive than that of the preceding two companies. The specific amount of CO_2emission to be reduced is 61 million tons as of 2030 compared to 2013. The company's measures to reduce CO_2 emissions are further improvement of existing energy efficiency technology, scrap utilization, AI-based furnace operation, and technological development for the future production of high-quality steel materials using electric arc furnaces. The company plans to expand its own MIDREX® technology as a future low-carbon measure in the transitional period. This technology is a method of direct reduction using natural gas, and is currently used in 60% of the world's direct reduction steelmaking.

In addition, Kobelco has an Independent Power Producer (IPP) business on the premises of its steelworks, which supplies electricity to neighboring areas. The company has a plan to adopt biomass or clean ammonia as a co-firing fuel to reduce emissions. In the future, the company's power generation business segment is expected to process carbon-neutral methane and 100% ammonia-fired power generation.

Decarbonization actions by public-private collaboration

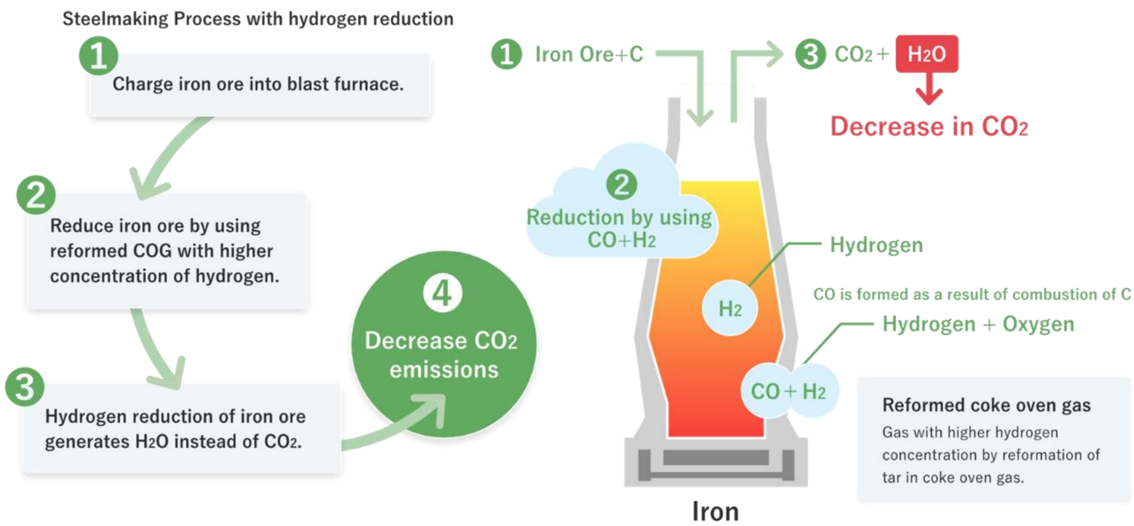
While each steel company intensively works on its own decarbonization actions, the Japanese government supports a public-private collaboration in developing core technologies to realize carbon neutrality in the steel sector. Under such objective, a collaboration framework called COURSE50 (CO_2 Ultimate Reduction System for Cool Earth 50) was established by New Energy and Industrial Technology Development Organization (NEDO) and four Japanese steel and engineering companies.

- Develop technologies to control reactions for reducing iron ore with reducing agents such as hydrogen with a view to decreasing coke consumption in blast furnaces.
- Develop technologies to produce high-strength & high reactivity coke for reduction with hydrogen.
- Development of technologies to capture – separate and recover – CO_2 from blast furnace gas (BFG)
- Develop techniques for chemical absorption and physical adsorption to capture – separate and recover – CO_2 from blast furnace gas (BFG)
- Develop technologies contributing to reduction in energy for capture – separation and recovery – of CO_2 through enhanced utilization of unused waste heat from steel plants.

Source: Author based on COURSE 50 (2021)a

Figure 19 Organization of COURSE50

The objective of COURSE50 project is to examine the emission reduction measures from the existing blast furnace, and the major focus among them is the utilization of hydrogen in the blast furnace. Utilizing hydrogen with ordinary cokes in blast furnaces is being examined in the project.



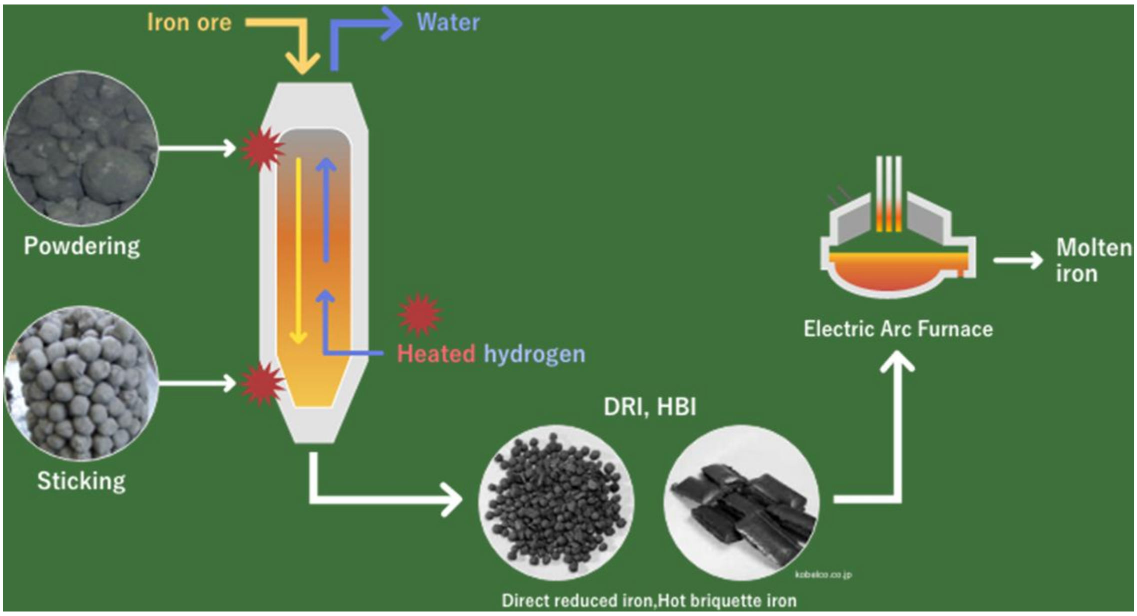
Source: COURSE 50 (2021)b

Figure 20 Utilization of hydrogen at blast furnace

Another major area of research in COURSE50 project is the capture of CO_2 generated during the reduction process. For capturing CO_2, technology of chemical absorption is adopted. Because removing CO_2 from the chemical material in this process requires a large amount of heat, utilizing the heat generated in the steelworks for the CO_2 removal is currently being studied. R&D activities are undertaken to develop a chemical solution that can absorb as much CO_2 as possible per unit volume, and to realize more energy-efficient CO_2 extraction from the absorbed solution.

Regarding the technology that utilizes hydrogen in the blast furnace process, hydrogen is assumed to be obtained as a by-product of the steel-making process. "Super COURSE 50," which is set up as an extension of COURSE50 project, aims to utilize hydrogen obtained from outside the steel works besides such internally generated hydrogen. While, in COURSE50, due to the limitation of hydrogen supply amount, only 30% reduction of CO_2 is done together with the reduction amount by CCS, in this Super COURSE50, the reduction rate is further increased by utilizing external hydrogen. This research program is expected to carry out research activities up to 2040 and to be put into practical use after that.

In addition to these efforts, the direct reduction process is expected to become one of the decarbonization technologies in the future. Compared to the blast furnace route, which is currently the mainstream steel making process in Japan, the direct reduction route has various challenges, such as low energy efficiency because it requires separate furnaces for reduction and melting, and restrictions on raw materials because impurities cannot be removed. However, if hydrogen can be used as a reducing agent, there is a great merit that iron can be produced without generating CO_2.



Source： Japan Iron and Steel Federation (2020)

Figure 21 Hydrogen Direct Reduction

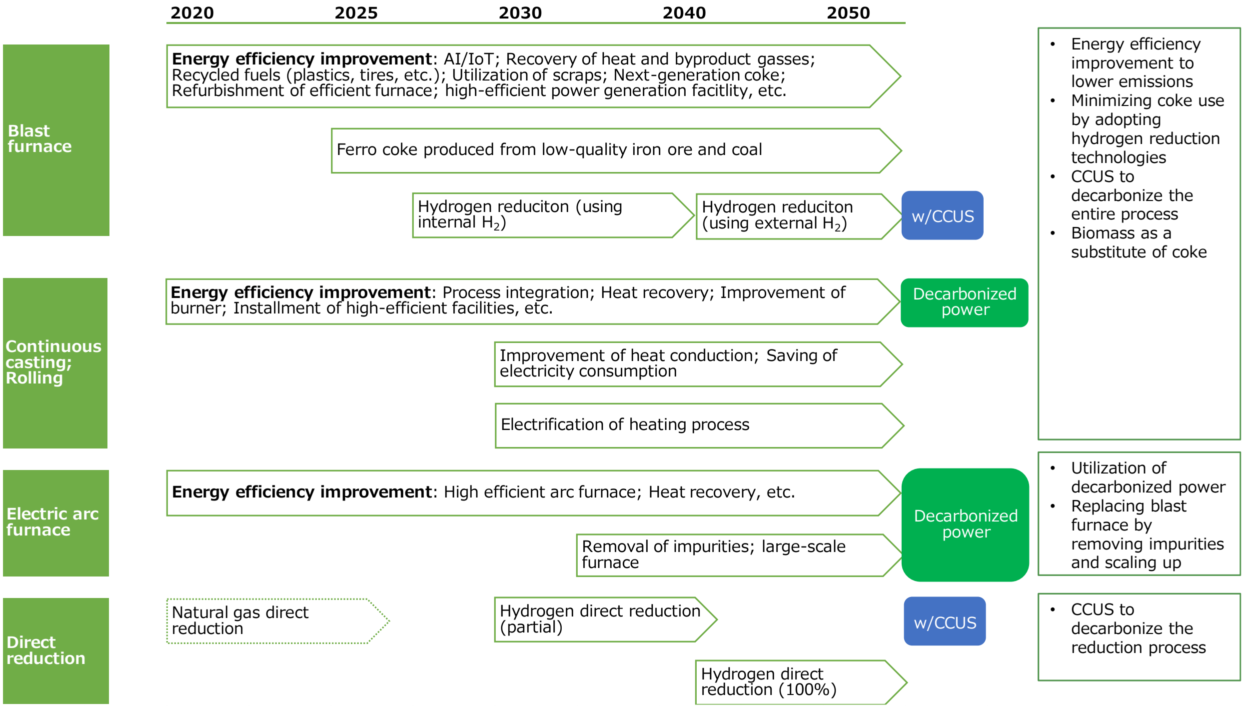
Technological development is also being conducted for capturing CO_2 generated in the reduction process and converting it into fuel for use. This is one of the carbon capture and utilization (CCU) technologies that reuse CO_2. Currently, JFE is leading the development of a technology called methanation that converts CO_2 into methane. Methane produced by this technology can be used in the same way as ordinary natural gas. If the CO_2 generated from the reduction process is converted to methane and used as a fuel for steel making, it can be used as a carbon-neutral fuel that does not increase CO_2 in the atmosphere (JFE Holdings 2021)b.

3.2.3 Menu of decarbonization technologies

As a roadmap with specific required technologies to decarbonize the steel industry, the Japanese government (Ministry of Economy, Trade and Industry) set up a roadmap. In the segment of blast furnace in the roadmap, in addition to the technologies explained above, technologies of continuous casting and rolling, energy saving and high efficiency improvements are also included. Other relevant technologies include utilization of waste heat and duplicated gas in the steelmaking process, combustion of waste, and further improvement of energy efficiency by utilizing artificial intelligence (AI).

In the segment of electric arc furnaces, utilizing decarbonized power sources (renewable energy / nuclear power), removing impurities contained in scrap, and increasing the size are included as a specific measure.

With regard to hydrogen direct reduction steelmaking, which will occupy a very important position in the field of future technological development, it is mentioned that a direct reduction furnace that partially uses natural gas may be able to achieve decarbonization in combination with CCUS.



Source: Ministry of Economy, Trade, and Industry (2021) translated by author

Figure 22 Roadmap prepared by Ministry of Economy, Trade, and Industry

In advancing such decarbonization technology, not only technical feasibility but also economic feasibility is equally important. Pertaining to the adoption of hydrogen, it is estimated that the cost of hydrogen supply needs to be as low as 8 yen per normal cubic meter (Nm3) ($1.5/MWh) (Nippon Steel 2021b). Because the current Japanese government target of hydrogen supply as of 2050 is 20 yen per Nm3, there is still a wide gap between them. Furthermore, it is necessary to secure a large amount of hydrogen at such a competitive cost, and according to Nippon Steel's estimation, a total of 75 billion Nm3 (266TWh) of hydrogen is required to secure the current production volume.

3.2.4 Major challenges to realize the roadmap

Decarbonization of the Japanese steel industry has various challenges. The first is the promotion of technological development. Although all three blast furnace manufacturers have set carbon-neutral targets for 2050, they have not yet developed the necessary technologies. In particular, hydrogen reduction steelmaking, which does not generate CO_2 during reduction, is regarded as an indispensable technology for decarbonization of the steel industry not only in Japan but also in the world. Yet, there are still many technical issues to be addressed to make it appropriate for commercial use. For this reason, it is necessary to continue technological development through public-private partnerships from a long-term perspective, such as COURSE 50.

The next challenge is to secure competitively-priced clean hydrogen. Even if a technological breakthrough of hydrogen reduction steel-making is realized, it will be difficult to commercialize the technology unless the clean hydrogen required for that purpose is available at a stable and sufficiently affordable price. As for clean hydrogen, there is blue hydrogen produced by utilizing CCUS from fossil fuels and green hydrogen produced by electrolyzing water with electricity obtained from renewable energy. If it is clean enough, both types (or “colors”) of hydrogen should be a source of such hydrogen for steel making. It is often noted that blue hydrogen derived from fossil fuels is cheaper at the moment, but if the costs of power generation by renewable energy and the costs of water electrolysis equipment are greatly reduced in the future, the cost competitiveness of green hydrogen will be improved. Developing production capacities for competitive and sufficient volume of clean hydrogen is another critical condition to realize the decarbonized steel sector.

The third challenge is to secure clean electricity at a competitive price. Compared to the blast furnace route, the electric arc furnace route is easier to realize decarbonization. However, since a large amount of electric power is used in the steelmaking process using an electric furnace, it is also necessary to secure a sufficient amount of zero carbon electric power derived from renewable energy or nuclear power .

Finally, it is also critical to put CCUS into practical use. CCUS can be broadly divided into two technology types, CCU and CCS. For CCU, it is expected that the technology for producing synthetic methane using CO_2 replicated in the reduction process will be put into practical use. Since this technology goes through the process of extracting carbon from the captured CO_2 and combining it with hydrogen, it is necessary to secure clean hydrogen that is cost-competitive as described above in addition to the recovery of CO_2. For CCS, a location to store the captured CO_2 must be secured in addition to low-cost CO_2 capture technology. In Tomakomai City, Hokkaido, a demonstration experiment to store CO_2 in the underground aquifer has been conducted. In addition to such a promising storage destination in Japan, the development of a CO_2 transfer network that anticipates CO_2 storage overseas in the future.

4 Conclusion

4.1 Common ground

Observations until the previous section reveal several commonalities and differences in the decarbonization efforts of both countries's steel industry as summarized in the following table.

Table 6 Commonalities and differences in the decarbonization actions by German and Japanese steel industry

Commonalities	Differences
• **All major companies have mid-term (2030) targets and aim for long-term full decarbonization** • **Utilization of hydrogen as fuel** • **Direct reduction by hydrogen** • **Carbon, capture, utilization, and storage (CCUS)** • **Biomass as a potential fuel** • **Electrification (raising the share of electric arc furnace)**	• **Level of mid-term targets is somewhat different between companies, probably due to time schedule of reinvestments needed** • **Public-Private Partnership (J)** • **Products by CCU application** - Chemical (G) vs Methane (J) • **Direct reduction by natural gas (G** – at least before Russian war against Ukraine**)** • **Bio energy carbon capture and storage with oxyfuel considered in one scenario study (G)** • **Utilization of ferro coke (J)** • **Major sources of hydrogen** - Domestic or imported green H2 (G) vs blue and green H2 of both domestic and import (J) • **Major sources of zero emissions electricity** - Renewable (G) vs various generation sources incl. renewable, nuclear and hydrogen/ammonia (J)

Remarks: (G) stands for the case for the German industry only; (J) stands for the case for the Japanese industry only

Source: Authors

Both countries share a set of common issues in order to decarbonize the steel sector. Companies in both countries have set up emission reduction targets with frontrunners on both sides. The Japanese steel producer Kobelco pursues the ambitious target to reduce emissions between 30% to 40% by 2030 (compared to 2013) and the German company Salzgitter strives for a 50% emission reduction by 2030 (compared to 2018 levels). Overall, the average level of companies' targets for 2030 is comparable between Germany and Japan. In addition, all major companies in both countries have pledged to become carbon-neutral by 2045 or 2050 (in Germany) or 2050 (in Japan).

One of the key technologies considered in Japan and Germany is the application of hydrogen and direct reduction of iron, and both countries acknowledge the role of low-carbon hydrogen. Likewise, both countries share the challenge of higher costs associated with hydrogen-based steel relative to conventional production. All major companies in Germany and Japan put more or less emphasis on hydrogen-based steel making as a means to decarbonize their production in the future. In Germany, ArcelorMittal already operates a DR-plant, with other German players following suit. The fact that all of the aforementioned scenarios modeled for Germany assume an expansion of DRI-based steel by 2030 and 2045 suggests that hydrogen will play a substantial role in low-carbon steel making in the country. Likewise, in Japan, the three largest steel companies in Japan all plan to make use of hydrogen for future steel making.

Apart from that, CCUS is another technology pathway. In Germany, ThyssenKrupp facilitates metallurgical gases to the chemical industry for production of certain chemical products. In Japan, JFE currently develops a methanisation process based on CO_2 captured at the blast furnace and, then, the methane is used as a fuel for steel making.

As for Germany, biomass has not been part of the Steel Action Concept and is not discussed very intensively in public debates. Still, one of the aforementioned scenarios aligned with Germany's revision of the Climate Protection Law, assumes that biogenic syngas might also be used in future primary steel production. In Japan, the steel producer Kobelco plans to adopt biomass as a co-firing fuel.

In Japan, the secondary route is, for instance, pursued by Nippon Steel and Kobelco in order to produce high-grade steel. In Germany, all scenarios discussed assume a higher share of EAF-production by 2030 and 2045. The use of artificial intelligence to optimize plant operation appears to be of some interest in both countries to generate additional emission savings. In both countries, the availability (and quality) of scrap is and will be a bottleneck for expanding the EAF-route and will be linked to the question of future steel demand, e.g. in the construction sector, which typically makes use of larger quantities of secondary steel. For instance, if construction of buildings relies to a larger extend on sustainable biomass, the demand for recycled steel might be less urgent (assuming that demand does not increase in other sectors).

From a policy perspective, Germany and Japan established long-term emission reduction targets, but these have not been broken down to specific steel sector targets in either country. For Germany and Japan, an increase in electricity production for and due to low-carbon steel is expected. This also results in a shared problem of price-competitiveness of steel produced domestically in these countries *vis-à-vis* other countries. Both governments are actively involved in supporting research and development efforts in the steel industry.

4.2 Differences

As mentioned above, the steel industry's decarbonization roadmaps of both Germany and Japan have much in common, but there are some nuanced differences in the assumed steel-making technologies and other non-technologies areas.

The first difference is the way of public-private collaboration. In Japan, a government-industry collaboration (COURSE50) is formed by a government organization (NEDO) and major steel companies and has been effectively operated to develop "core" decarbonization technologies such as hydrogen utilization or carbon capture process. Since COURSE50 program was expanded to Super COURSE50 in 2020, the close collaborative frame is likely to remain as a key platform for the Japanese steel industry's research and development (R&D) efforts towards carbon neutrality. German steel industry also has an access to sufficient public fund, such as EU's Innovation fund and the Federal Government's Decarbonization of the Industry Program. Compared to the Japanese industry, however, German steel companies seems to pursue their R&D rather independently. To be sure, in both countries, recognizing the significance of the steel industry's decarbonization, governments have a strong interest and commitment to the industry's R&D efforts. What seems different is the approach of their involvement to the industry's decarbonization efforts. This different approach may reflect the tradition of both countries' industrial policy towards the steel industry.

Second, while both German and Japanese steel industries plan to apply carbon capture and utilization (CCU) technologies to their blast-furnace steel making plants, the assumed final products are different. Japanese steel industry seeks to produce synthetic methane from capture carbon with green hydrogen. JFE Steel Corporation (2021) has formed a consortium with Nippon Steel and other Japanese firms to develop a system to supply the produced synthetic methane as a shipping fuel. German industry, on the other hand, plans to produce chemical products. Thyssenkrupp (2021) in Germany is developing a CCU technology called Carbon2Chem®, which produces chemical products from capture carbon resulting from the steel-making process. Japanese industry aims to build a "carbon-recycling" process by using the synthetic methane produced from captured carbon, while German industry seeks to fix the captured carbon for a longer time by converting it to chemical products such as plastics.

Third, there has been a greater interest in the direct reduction steelmaking using natural gas in the German steel industry, at least until the war of Russia against Ukraine, while hydrogen is deemed as a primary reduction agent in the Japanese steel industry. The direct reduction steelmaking process using natural gas has an advantage that it will be easier to shift to hydrogen reduction steelmaking, by blending and raising the ratio of hydrogen at a later stage. In the Japanese steel industry, Kobelco's MIDREX® process is also a direct reduction technology that uses natural gas as a reducing agent, but there are no applications in Japan. This is thought to be because most of natural gas is imported in the form of LNG in Japan, and its price is relatively high.

Fourth, in the scenario of German steel industry's decarbonization by Öko-Institut and Wuppertal Institut (2021), the possibility of technology combining biomass, oxyfuel fuel combustion, and CCS is mentioned. By burning biomass such as wood chips, synthetic gas is produced and used in the iron making process, while by utilizing oxyfuel in the combustion process to efficiently capture CO_2. The captured CO_2 is then transported and stored underground. Since the captured and stored CO_2 is biogenic, this technology can achieve negative emissions. Given the fact that eliminating the entire emissions from steel-making process is very challenging, this technology will greatly help the industry to achieve the goal by offsetting the residual carbon emissions.

Fifth, what Japanese steel industry more closely works on is next generation coke. Ferro coke is an innovative reduction agent to improve the reduction rate of iron ore and cut CO_2 emissions. This technology may be utilized for the transition period, as it does not necessarily lead to zero emissions. But it can materialize significant reduction of CO_2 emissions and is expected to play an important role to achieve the industry's mid-term reduction target.

Sixth, while hydrogen supply is expected to play a critical role for both countries' steel industry, procurement policies of hydrogen have nuanced differences between the two countries. Although both countries' steel industries plan to utilize both green and blue hydrogen, German steel industry pays more attention to green hydrogen and significant shares of domestic hydrogen, while Japanese steel industry is more flexible toward the colors and the geographical sources of hydrogen. This derives from the difference of availability of hydrogen sources. German industry has better access to domestic and competitive renewable energy resources such as wind and can import renewable electricity or green hydrogen from neighboring countries such as the Netherlands and Denmark by grid. Japanese industry, on the other hand, has limited access to domestic renewable energy due to its inherent resource constraints and lack of international power grid

connection. Given its higher share of export dependence, furthermore, the Japanese steel industry is very sensitive towards the cost competitiveness and specifies a particular cost target of clean hydrogen supply for zero-carbon steel (8 Yen/Nm3) ($1.5/MWh), while seemingly German steel industry does not have such a target.
Seventh, although this may not be a “difference” in a strict sense, the two countries’ industries face different types of challenges to secure zero-emissions electricity. Both countries’ industry considers electrification of their steel-making process with zero-emissions electricity is one of their decarbonization options. Since Germany plans to phase out nuclear power generation by 2022, renewable electricity will be the primary source of electricity. Securing sufficient volume of such renewable electricity at competitive cost may be a challenge for them for some time, if power market prices return to levels similar to those before the 2021/22 crisis. Power purchasing agreements are gaining interest in this respect, since they allow securing price levels for sevefreal years. Japan, on the other hand, plans to keep utilizing nuclear power generation, but it has not been able to restart most of its idled nuclear units since the great earthquake in 2011. Promoting the restart of nuclear units whose operational safety is confirmed will be critically important to make such electrification of steel making process more plausible.

5 Recommendations

5.1 Germany

5.1.1 Developing an effective policy mix, including international partnerships

Germany ambitiously strives for climate-neutrality in 2045. For this, the decarbonization of the steel sector will be essential. Likewise, it will be crucial to not undermine the industry's competitiveness by increasing the costs of German steel in comparison to competitors. For this, the German Government plans to set up a comprehensive policy package that seeks to bring climate policy and industrial needs together, including CCfDs and possibly CBAM, as well as green steel labelling and procurement. These plans need to be further pursued and realized effectively. It may also include the propagation of international alliances not only in the steel or energy intensive industries sector (similar to the idea of climate or decarbonization clubs), but also regarding energy or hydrogen partnerships safeguarding the reliable supply of a new and green energy carriers.

5.1.2 Further development of technologies and supply infrastructures

To some extend, policy can also foster technology readiness. While DRI-technology is relatively mature, other technologies may deserve R&D support (e.g. iron electrolysis, high temperature electrolysis, CCU), also to reduce costs. This is also true for the secondary route, where several hurdles are in the way for increasing the share of recycled steel including the availability and quality of scrap. Since the departure from the BF-BOF-route will result – upstream – in an increased appetite for electricity and import and transport infrastructures for hydrogen, and – downstream – potentially in large-scale CO_2 logistics (not available in Germany, so far), the German Government together with other relevant stakeholders must make progress regarding the cost-effective infrastructure development, also to unleash investments in the steel sector and to provide planning security. In Germany infrastructure deployment may facilitate public headwinds, often known as the "not-in-mybackyard" phenomenon. It will be crucial to balance, in advance, economic interests of steel and infrastructure providers against interests of local communities.

5.1.3 Ensuring acceptance and addressing environmental concerns

Another rather societal issue is to mitigate social hardships, which, for instance, means that steel-intensive products must remain affordable for low-income households. Society may also perceive green steel (and related support) as a worthwhile undertaking, if benefits feed back to the people. Hence, training the workforce for green steel production could contribute to gain societal support. Moreover, the auxiliary infrastructures of green steel in Germany and beyond have spatial requirements, which might also undermine other environmental concerns; for instance, water-electrolysis using sea water results in salt brine, which may affect local / maritime biodiversity. Such issues must be taken into account.
Figure 23 presents an overview of aspects to be addressed in developing an effective package of policies to enable implementation of the roadmap towards decarbonizing the German steel sector.

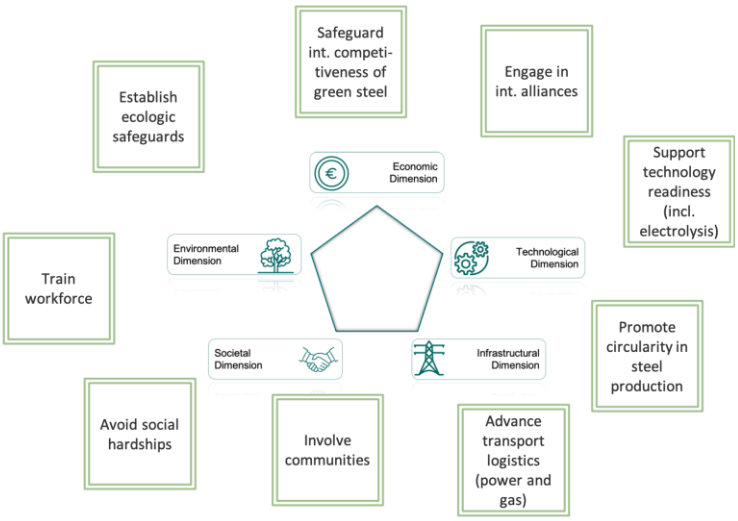


Figure 23: Policy recommendations for accompanying green steel deployment in Germany

5.2 Japan

5.2.1 Support for innovative steel-making technology

The first recommendation is to provide policy support to the development of innovative technology with an awareness of the time frame for achieving carbon neutrality by 2050. The technology that can completely reduce CO_2 emissions from the steelmaking process has not yet been established on a global scale. To overcome such a challenging issue, there is a limit to what the private sector can do on its own, so some form of government support is needed. The core technologies for decarbonization are direct reduction ironmaking using hydrogen and CCUS, and it is necessary to develop these technologies with the timeframe until 2050 to be effectively utilized in the steel-making process. The study to use hydrogen in the steelmaking process has already been launched by COURSE50 and Super COURSE50 programs, and it will be necessary to expand these existing efforts to direct hydrogen reduction technology as well. With regard to CCUS, the development of CO_2 capture technology has been in COURSE50, but in the future, technologies to convert the captured CO_2 into fuels and other products, and arrangements to transport and store the CO_2 underground will be required.

In February 2021, the Japanese government announced the establishment of a Green Innovation Fund with a total of 2 trillion yen (US$17billion). Given its weight in the Japan's macro economy and the large share of CO_2 emissions in Japan, the decarbonization of the steel sector should be placed as a high-priority goal for achieving carbon neutrality in 2050, and the fund should be effectively utilized in the endeavor.

5.2.2 Competitive clean hydrogen

The second recommendation is the policy to ensure cost-competitive clean hydrogen supply. A major source of such clean hydrogen is expected to be green hydrogen produced from electrolysis process based on the domestic renewable energy. In order to ensure sufficient supply of hydrogen for steel making process, cost reduction of electrolysers as well as the renewable electricity must be pursued through continuous policy support. As a long-term effort, the technology development to produce hydrogen from nuclear energy, which is currently conducted by Japan Atomic Energy Agency, should also be continued (Nagai 2021).

The supply of hydrogen from these sources, however, is likely to be costlier and smaller in volume than the supply of imported blue hydrogen that is produced from natural gas with CCUS application overseas. Currently, the introduction of blue hydrogen in the form of ammonia is scheduled to begin in the second half of the 2020s, and the use of hydrogen in Japan's power generation sector is expected to accelerate. Such an expansion of hydrogen use may well have a positive impact on the cost of supplying hydrogen for the industrial sector including the steel industry. For the time being, ammonia in the power generation sector will be supplied directly from overseas to power plants, but in order to further reduce costs, efforts are being made to reduce overall costs by developing large hydrogen import hubs and using large hydrogen tankers. A steel mill located in the proximity to import hubs will be able to procure hydrogen competitively by receiving hydrogen supply directly through pipelines. Securing a competitive supply of hydrogen to steel mills will be enabled by coordinating with other sectors and industries, and thus the coordination by the central government as well as the local government to facilitate such infrastructure will be important.

5.2.3 Operationalization of CCS

Thirdly, the environment to apply CCS technologies to the steel-making process needs to be developed. This is because there may be a limit to the amount of CO_2 that can be absorbed by CCU domestically. As an effort to promote CCS technologies, a demonstration test of CO_2 storage has already been conducted in Tomakomai, Hokkaido. In the future it will be necessary to secure sufficient locations where CO_2 can be stored stably in addition to Tomakomai and to construct a CO_2 transportation network for this purpose. Naturally, this cannot be done by the steel industry alone. Hence, so it will be necessary to coordinate with other industries such as the shipping industry to transport CO_2 and the oil industry to store CO_2 underground. The government is expected to play a major role to coordinate these various industries.

In addition, if the storage capacity in Japan is not sufficient, Japan may need to consider CO_2 storage overseas. In this case, as a new form of resource diplomacy, the government will coordinate with overseas countries that have many geological formations (depleted gas fields and aquifers) suitable for storage. It will also be necessary to coordinate with the governments of other countries on the development of systems for transporting CO_2 across borders (e.g., measuring, reporting, and verifying the amount of CO_2 to be transported and stored, and determining the cost of CO_2 treatment by receiving country).

5.2.4 Zero emissions electricity

Another major issue in the decarbonization of the steel sector is the need to secure zero-emission electricity. As mentioned above, competitive zero-emission electricity will be needed for hydrogen production, and when the ratio of electric furnaces is increased in the future, zero-emission electricity will be needed to supply the electric furnaces. As for the power supply mix, the mix target for 2030 has already been set, and the reference figures 2050 has also been provided. Needless to say, renewable energies such as solar power and wind power will be the main source of zero-emission electricity in the future, but due to the limited renewable energy resources in Japan, it will also be necessary to secure electricity from nuclear power, hydrogen, and clean ammonia. In particular, although the operating rate of nuclear power has been sluggish since the 2011 earthquake, nuclear is a power source with the volume and supply stability required for industrial power, and thus should be maintained as a key power source for promoting decarbonization in the steelmaking sector.

5.2.5 Financing

The energy transition will require a large amount of money, and the government is expected to facilitate the inflow of money to the decarbonization actions by the steel industry. The Japanese government currently develops a framework to evaluate the various industry's decarbonization roadmap for transition finance. By encouraging and consulting the industry to draw its own roadmap and appeal its decarbonization efforts to the global investors, the government can promote the inflow of so-called ESG (Environmental, Social, and Governance) money to the industry.

5.2.6 Market acceptability of zero-carbon steel

Finally, as a long-term effort, there needs to be a market condition where society and the market players find an appropriate value for a product with low GHG footprint. It requires a considerable amount of money to manufacture steel products in a decarbonized manner although the quality of the steel product itself does not improve by the amount of the incremental cost. Therefore, society and market must be created in such a way that the burden of incremental cost to produce decarbonized steel can be shared across the entire supply chain. The steel industry should not only work to reduce the cost of decarbonizing its own products, but the government also should promote public education, and if necessary, add some kind of regulatory or policy framework to realize the value of decarbonization.

5.3 Potentials for German-Japanese co-operation

As we have seen in chapter 4 in comparison of the potential roadmaps to decarbonization of the steel sector, both countries, Germany and Japan, and their major steel producers have similar mid- and long-term decarnonization targets. In addition, both envisage direct reduction technology using hydrogen as the long-term route for primary green steel-making, combined with CCUS, use of available biomass, and increasing a circular steel economy and the secondary steel-making route using electric arc furnaces to the extent possible, e.g., based on the availability of scrap and quality issues.

Consequently, the recommendations to policy-makers in chapters 5.1 and 5.2 address similar objectives: developing and deploying the necessary steel production technologies, reducing their costs, and securing the supply of cost-competitive clean hydrogen and electricity, CC(U)S technologies, as well as the acceptance of green steel.

These may be good preconditions for bilateral cooperation between the governments and steel companies of both countries in the development of these technologies, supplies, and markets. Certainly, co-operation in such emerging technologies and markets bears both chances and risks. However, regarding direct exports of steel, there is not so much competition between both countries; the shares of China and the USA together in EU and Japanese steel exports are around 20%. Competition may be higher in the sectors using steel (such as cars, machines). Still, German-Japanese co-operation in steel sector transition and clean hydrogen supply may enable both countries to gain leadership and an advantage, first within the sector, compared to their respective regional competitors. The sectors using steel may then also benefit, if they gain availability of green steel at competitive prices, again compared to their competitors in other countries.

Therefore, we recommend to policy-makers and steel industries in both countries to explore in more depth the potential, chances and benefits, but also risks of a closer German-Japanese co-operation in the decarbonization of the steel sector.

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