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Global Strategies for Low-Carbon Iron and Steel Production

In a nutshell: Iron and steel plants require reinvestments on a regular basis. In line with those refurbishment cycles there is an opportunity to implement low-carbon technologies before 2030 that are available already today. It is especially important for the international community to focus on China with the majority of today's production capacity but also on India as markets are expected to shift in this direction.

Key Messages

Steel Carbon Emissions

Steel production currently relies heavily on fossil fuels, which serve both as energy sources and reducing agents. Therefore, low-carbon steel production involves more than just providing renewable energy: it requires employing low-carbon technologies throughout the production chain. These challenges are particularly significant given that steel is an important material for economic development in emerging economies and for the energy transition worldwide, yet its production currently accounts for around 8% of global greenhouse gas emissions (GHG).

Existing Technologies and Implementation Strategies

Effective levers for stepwise emissions reductions in the steel sector include switching from coal to available low-carbon technologies, such as using natural gas with carbon capture, utilization, and storage (CCUS) and biomass with CCUS, as well as hydrogen direct reduction with electrification, and prioritizing an efficient use of steel in the manufacture of products, with an even higher steel recycling rate and scrap utilization. Strategies and quick wins include that all integrated steel producers (ISPs) should focus on improving operational and energy efficiencies, deploying advanced control processes (APs) thereby reducing the specific consumption of raw materials, and lastly, valorizing waste heat, off-gases and byproducts into chemicals, fuels, power etc. Another important lever is maximizing resource efficiency through the beneficiation of iron ore and the deployment of slurry pipelines and pipe conveyors to avoid the generation of fines.

Retrofit Potential and Investment Cycles

By 2030, two-thirds of production plants will need refurbishment within their usual investment cycle; this presents a crucial window of opportunity to retrofit coal-fired blast furnaces with low-carbon technologies. Joint international efforts and retrofits together have the potential to eliminate approximately 30 billion tonnes of carbon emissions from iron and steel production by 2060.

Focus on China and India

To achieve emissions reductions of the steel industry, global collaborative efforts, both technical and financial, should focus on China, the world's largest steel producer today, and India, the biggest emerging player in the field, which is estimated to triple its capacity by 2050. China may also emerge as a leader in steel industry decarbonization when considering CO_2 emissions reduction (by reducing 20% of its capacity and replacing approximately 200 million tonnes of blast furnace-basic oxygen furnace (BF-BOF) capacity with electric arc furnace (EAF) capacities. However, the industries in both nations largely consist of small and medium-sized enterprises that may not have the resources to invest in the necessary new technologies. Diverse starting points among countries and regions necessitate tailored approaches to define each one's possible contributions to global efforts. Industrialized countries need to employ different measures than China and India. For example, most of the steel plants in Japan were built after World War II. These plants represent the greatest opportunity to be converted to low-carbon-emission steel production by adopting scrap-based electric arc furnaces.

Is There a Silver Bullet?

Low-carbon hydrogen energy, while promising, should not be regarded as a silver bullet solution for low-carbon steel production on its own, as political debates sometimes suggest. Neither can carbon capture technologies, despite their potential, fully eliminate emissions in the steel industry. The use of hydrogen as a reducing agent instead of coal has the potential to slash steel production emissions by between 70% and 90% per tonne of steel.[i] However, low-carbon hydrogen production requires significant infrastructure investments in production, transport, and storage, and the same applies to the deployment of carbon capture technologies. An important step is to define which steel qualifies as "low-carbon steel" and to standardize and harmonize these criteria. Recommended is a focus on economic viability and on achieving effective reductions (per dollar spent) rather than prescribing specific technology pathways.

1. Introduction

The production of steel is a vital component of many industries, including construction, transportation, and manufacturing. Steel is an important material for economic development in emerging economies and for the energy transition worldwide. However, the steel industry is also a significant contributor to global greenhouse gas (GHG) emissions. According to the International Energy Agency (IEA), the steel industry accounted for 8% of global energy-related carbon dioxide (CO_2) emissions in 2020, with emissions primarily stemming from the use of fossil energy (75% from coal) in the steelmaking process and from process emissions.[ii] Given the pressing need to address climate change while ensuring sustainable economic development for a growing population, it is imperative to reduce emissions in the steel industry and transition to more sustainable production methods. In doing so, pathways to low-carbon production must be tailored to regionally specific circumstances.

Within the discussion of low-carbon steel production, it is important to note that fossil energy carriers currently not only provide necessary energy but also serve a chemical and physical role in the production process as reducing agents. However, clearly distinguishing between emissions originating from chemical reactions and other emissions is challenging under the current carbon accounting system and should therefore be improved.

Whereas a significant fraction of the iron ore used in steel production is traded globally, the largest producers typically manufacture and consume steel regionally (see Figure 1). However, many countries still depend on substantial imports (see Figure 1). With expected economic development and population growth, global steel demand is expected to increase significantly, particularly in emerging economies in Africa, Latin America, and South-East Asia.

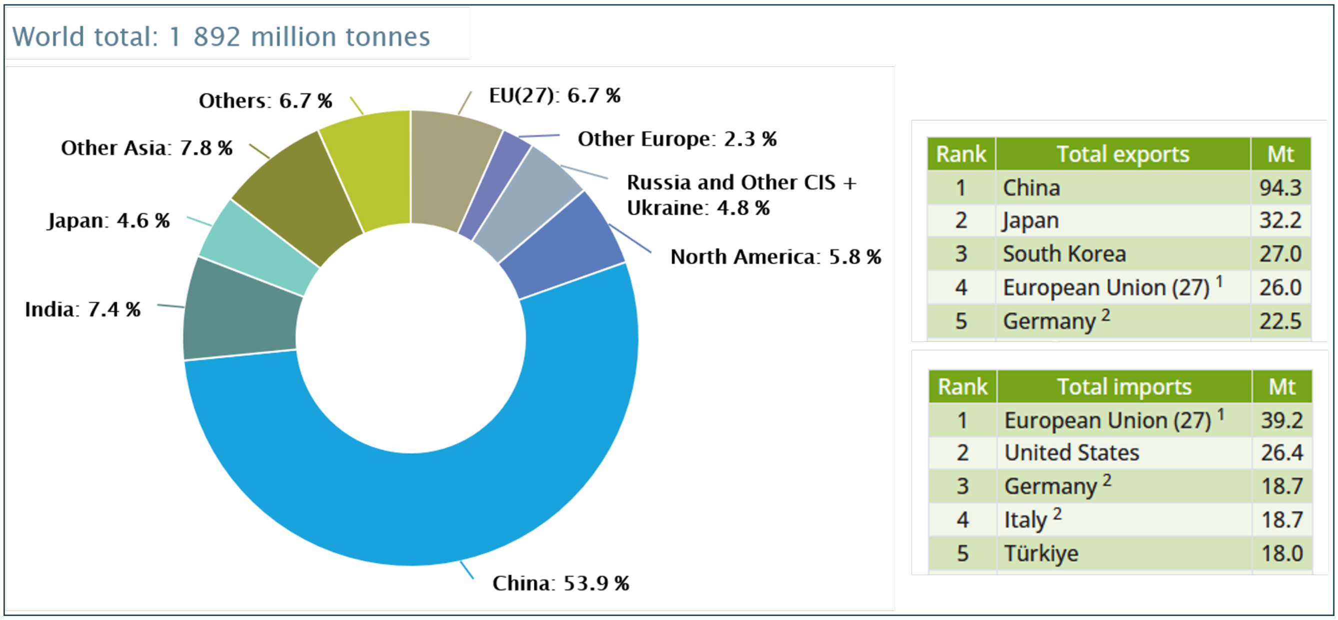
The world production of crude steel was 1,892 million tonnes in 2023, with slightly more than half of it produced in China (53.9 %) (see Figure 1). Since 1970, demand has tripled and total annual GHG emissions reached 2.8 billion tonnes of CO_2 in 2023. In industrialized countries, steel consumption is roughly evenly divided between cars and vehicles, construction, industrial equipment, and steel products. In emerging regions, the share for construction is estimated to be higher, at around 30%.

Besides its role as an energy carrier, coal is used in the main steel production route due to its chemical characteristics as a reducing agent to remove impurities in the material, such as oxygen. This main production route, which uses coal, is known as "Blast Furnace – Basic Oxygen Furnace" and accounts for 70% of global steel production. However, less carbon intensive reducing agents like natural gas and hydrogen are gaining importance due to their lower emissions. Co-firing with biomass directly is one alternative, another approach is to char biomass to produce biochar, which can subsequently be used as a reducing agent, even during pig iron production.

Steel is a material of high value; hence, 80 - 90% of all steel produced is recycled. On average, 30% of the input materials for new steel production consists of scrap. An expected increase in available steel scrap is also a factor influencing the best production route choices at the regional level.[iii]

Starting points to move towards low-carbon steel production are different across regions. Industrialized countries and regions with established steel sectors, such as Japan, South Korea, the United States, and Europe mostly have old plants whereas steel plants in emerging economies are on average 13 years old. Multiple economies have identified the need to focus on steel decarbonization and are undertaking targeted efforts to do so. These include research efforts on emerging steelmaking processes and subsidies for deployment of cleaner technologies, mostly involving renewable energy, natural gas and carbon capture. Research for fast-to-implement technologies can enable small and medium sized companies to join emission reduction efforts as well.

For the success of short-term objectives, cost effective mitigation strategies have been identified with the help of Marginal Abatement curves (MAC).[iv] MAC curves depict cost and decarbonization potential of various available levers at a point of time, adjusted for supply of such technology (e. g. availability of biochar), but not influencing the demand (e. g. demand of urea).



Rank	Total exports	Mt
1	China	94.3
2	Japan	32.2
3	South Korea	27.0
4	European Union (27) [1]	26.0
5	Germany [2]	22.5

Rank	Total imports	Mt
1	European Union (27) [1]	39.2
2	United States	26.4
3	Germany [2]	18.7
4	Italy [2]	18.7
5	Türkiye	18.0

Figure 1. Global crude steel production and geographical distribution 2023; Major importers and exporters of steel 2023. Source: Figures adapted from World Steel Association, “World Steel in Figures 2024” (2024).

2. Combining Efficiency and Effectiveness: Focus on China and India

China and India are two of the largest steel producers in the world and are therefore crucial players in the transition to low-carbon steel production. Currently, China produces more than half of the world’s annual steel output (approximately 1,000 million tonnes), while India, which currently accounts for about 6% of global production (approximately 143 million tonnes), plans to triple its production by 2050. The challenges faced by these two countries are significant, due to their heavy reliance on coal for steel production and other fossil fuels for energy.

For industrialized countries and regions, such as Japan, South Korea, and the European Union (EU), the high levelized cost of energy (LCOE), coupled with uneconomically high costs to locally produce low-carbon hydrogen, slows the transition. To offset these high incremental costs associated with producing low carbon emission steel, the Carbon Border Adjustment Mechanism (CBAM) price must exceed $ 200 - 250 per tonne with the premise that end consumers in these countries are willing to pay that premium. From 2025, a new level of competition will emerge in the steel market, a competition for who will remain the major steel producers in the EU. These will likely be countries with cheap electricity, such as France, Spain, and Sweden, as well as countries that have the financial capacity to subsidize electricity prices for producers, such as Germany. Global steel companies need predictable policies and conditions for investment.[v] Without government financial support, implementing a green transition becomes exceedingly difficult. Challenges arise from comparatively high renewable energy costs in some areas and the subsequently high price for low-carbon hydrogen as an alternative reducing agent.

One of the significant challenges faced by both China and India in lowering steel production emissions is the cost of new technologies and infrastructure. Many of the proposed pathways, such as the large-scale roll-out of hydrogen-based direct reduction or carbon capture and storage facilities, require significant investment for implementation at scale. Additionally, the steel industry in both countries consists of mostly young production plants, many of which are operated by a significant share of small and medium-sized enterprises that may lack the resources to invest in new technologies. This situation makes it more challenging to achieve widespread adoption of low-carbon technologies.

Probably the most important challenge faced by both countries is the need to balance emissions reductions with economic growth and job creation. The steel industry employs about six million people globally, with China and India each accounting for roughly 30% of this workforce.[vi] Hence, any efforts to reduce emissions must be carefully managed to avoid job losses and economic disruption. Industries related to steel and coal are often clustered in specific regions, for example, in Hebei, Jangsu, Liaoning, and Shangdong provinces in China and primarily across the states of Chhattisgarh, Jharkhand, Odisha, and West Bengal in India.[vii,viii,ix] Although the total workforce number is likely not to decrease, regional disruptions due to shifts to regions favorable for low-carbon steel and low-carbon energy supply need to be considered. In India, the uptake of low-carbon technology also needs to account for the availability of necessary resources. For instance, coke for commercial steel production is mostly imported. Scaling up renewable energy production and ensuring access to natural gas will influence the extent to which hydrogen and natural gas-based production routes can be employed as capacity increases.

Due to rising production and the aforementioned challenges, the International Energy Agency projects that emissions in India's steel sector will stagnate, even under the Sustainable Development Scenario, which implies the highest emissions reductions per tonne of steel produced on average.[x] Conventional carbon intensive technology will continue to be used, while additional production capacity is expected to be less carbon intensive beginning around 2030-2035. Given that China already has a vast production capacity, the challenges for low-carbon pathways are different (see Section 4 Investment Cycles).

One interesting example is the Brazilian steel sector lowering its carbon footprint by intensive use of renewable energy and biomass. The industry manages to integrate renewable electricity from the grid, biochar and biomethane (during pre-processing and as reducing agent) while low-carbon hydrogen employment leaves potential for lowering emissions even more in the future.[xi]

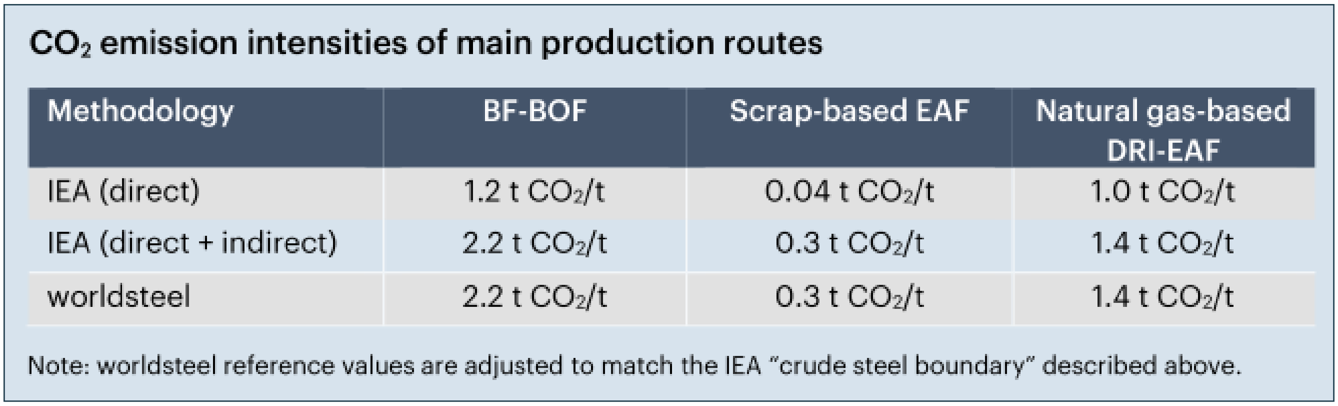
3. GHG Reduction Potential: The Alternatives Using Existing Technology

Currently, global steel production capacity has exceeded overall demand due to capacity build-up in China over recent decades. Hence, the steel price is comparatively low, and production capacity is not expected to increase.[xii,xiii] Emissions reductions therefore must primarily be realized on existing plants. However, regional shifts in production capacity, for example, from China and Europe to India are expected. This shift is due to different stages of development in the respective economies, and an especially high demand for mobility, transportation, housing and power infrastructure in India, driven by a growing population. The opposite is expected in China, where, as with cement, steel production is expected to decline significantly as China's economy reaches a level of infrastructure saturation.

The potential for emissions reductions in the steel sector therefore lies in using low-carbon technology to lower emissions during the production process, ensuring the efficient use of steel in the manufacture of products and applications that require it, and achieving an even higher recycling rate.

Potential GHG reductions per tonne vary depending on each country's specific situation. If the industry adopts carbon capture, utilization and storage (CCUS) technology, emissions could be reduced by up to 90% per tonne of steel. This technology involves capturing the CO_2 emitted during the steelmaking process, after which the CO_2 is either repurposed for industrial use or stored in underground reservoirs. Similarly, hydrogen-based direct reduction could potentially reduce emissions by 70% to 90% per tonne, while electrification with use of hydrogen has the potential to achieve zero emissions if renewable energy sources are used. Utilizing 100% scrap and renewable energy only could also reduce emissions to almost zero. However, recycling rates are already high at 80% to 90% and incentivizing greater use of scrap steel may increase demand and global trade without necessarily leading to overall reductions in steel production emissions.[xiv] Additionally, certain types of scrap are not suitable for producing certain types of steel (e.g. due to contamination with copper). Hence, while steel scrap contributes to approaches aimed at increasing material circularity and saving emissions, its potential is limited as steel used in buildings and infrastructure will not re-enter the system for several decades. However, the maritime and onshore transportation sectors, as well as the oil and gas sectors, industrial equipment producers, and the white goods industry, offer opportunities for increased scrap recycling. In certain situations, co-firing with biomass, provided that the biomass is a is available and sustainably sourced, is also an option.

Figure 2 shows an overview of emissions from different common production routes. Indirect emissions include imported heat and electricity, as well as electricity generated from off-gases occurring during the production process. However, the definitions of direct and indirect emissions are not straightforward and should be simplified.



CO_2 emission intensities of main production routes

Methodology	BF-BOF	Scrap-based EAF	Natural gas-based DRI-EAF
IEA (direct)	1.2 t CO_2/t	0.04 t CO_2/t	1.0 t CO_2/t
IEA (direct + indirect)	2.2 t CO_2/t	0.3 t CO_2/t	1.4 t CO_2/t
worldsteel	2.2 t CO_2/t	0.3 t CO_2/t	1.4 t CO_2/t

Note: worldsteel reference values are adjusted to match the IEA "crude steel boundary" described above.

Figure 2. CO_2 emission intensities of main steel production routes. Source: International Energy Agency, "Iron and Steel Technology Roadmap" (IEA, 2020, p. 43).

According to the IEA Sustainable Development Scenario, the global steel sector could cumulatively reduce CO_2 emissions by around 20 billion tonnes by 2050. This reduction represents roughly 20% of the expected cumulative emissions reductions in the hard-to-abate sectors, which together amount to a total of 90 billion tonnes for cement, chemicals, and steel.

Several studies on the use of steel in construction have indicated that savings achieved through more efficient design can be as much as 50%. Greater consideration of efficient use of materials in construction is roughly estimated to save about 30% of steel usage, however, this must be balanced against the rapidly increasing demand for construction in developing regions.

Regarding steel for vehicles, high wastage rates occur due to the nature of pressing parts from sheets. Although this steel can be recycled, the recycling process still requires transportation and energy. While some waste is inevitable in the pressing process, usage rates vary widely between 75% and 50%, indicating some room for improvement. Improved manufacturing processes, (e.g. regarding steel cut-offs), as well as a more efficient use of steel in its applications (e.g. in construction), could reduce waste by up to 50%.[xv,xvi]

On the technology side, one promising approach for decarbonization is the use of CCUS technology. Today, the price of steel from a commercial natural gas-based plant equipped with CCUS ranges roughly between $ 400 to 600 per tonne. Costs for carbon-intensive production routes also vary up to $ 100 per tonne, putting the aforementioned range into perspective. Comparing the cost of a commercial gas-based Direct Reduced Iron – Electric Arc Furnace (DRI-EAF) plant with that of a similar commercial gas-based DRI-EAF plant with CCUS shows a cost increase of less than 10% (this includes the transport and storage of the captured carbon.[xvii] The cost range across regions can increase the price up to $ 200 per tonne of necessary raw materials, such as gas representing a significant cost factor. Prices for the dominant commercial Blast Furnace – Basic Oxygen Furnace (BF-BOF) route and an innovative Syngas-Based – Basic Oxygen Furnace (SR-BOF) route equipped with CCUS are comparable.

Large-scale deployment of CCUS needs an enormous ramp up of CO_2 capture and transportation infrastructure. Depleted oil and gas wells can function as storage sites, while peridotite and basaltic rocks can also act as permanent sinks due to their high absorptivity towards CO_2. Notably, 64% of all industrial facilities in China (not only iron and steel) are within 100 km of potential storage sites, 45% even within 50 km.[xviii] Many of these sites are located onshore, generally allowing for cheaper storage than offshore sites.

Retrofits for direct reduction with natural gas (or biomethane) in combination with CCUS are at Technology Readiness Level (TRL) of 9, with 11 being the highest score in the system used by the International Energy Agency, and its estimated importance for net-zero emissions is “very high”.[xix] A TRL of 9 means the technology is operated commercially in the relevant environment. TRL estimations include the whole CCUS value chain, including capture, transport and usage or storage. This option should be considered wherever natural gas in combination with either usage or storage capacity is available at reasonable cost. The Al Reyadah project, which has been in operation since 2016, is the largest commercially operated CCUS project in the steel industry. It is operated by the Abu Dhabi National Oil Company (ADNOC) and captures 800 thousand tonnes of CO_2 per year from the Emirates Steel Plant.

Another pathway to decarbonizing steel production is through the use of hydrogen- or natural gas-based direct reduction of iron ore (DRI). This method involves using hydrogen or natural gas as a reducing agent instead of coal. Natural gas has been used commercially in DRI plants for a considerable amount of time. Direct Reduced Iron (DRI) based on green hydrogen is ranked “very high” with regards to its importance for achieving net-zero emissions with references provided by HBRIT, Arcelor Metal and Thyssenkrupp.[xx] However, with a TRL of 5[1] for DRI using electrolytic hydrogen only, the technology there is still an ambition gap between commercialization and expected relevance. Technologies are more advanced when hydrogen is blended into existing plants using natural gas (TRL 7) or even coal (TRL 7) as a reducing agent.

Co-firing with biomass and switching from coal to biomass (TRL 10) or natural gas in a traditional BF-BOF plant is an option already available today. Of course, the necessary substitution quantities need to be available. A TRL of 10 indicates

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[1] TRL 5 means that the components of the technology are tested under the conditions in which they are intended to be deployed, whereas TRL 7 refers to a demonstration plant in real-world environments.

that the technology is commercially available and competitive, and innovation is only needed to better integrate it into the current energy system and supply chains to allow scalability. This option provides a pathway for small and medium size steel producers to lower their emissions, enabling a just transition in comparison to large multinational companies that can employ CCUS and low-carbon hydrogen technologies.

Another technically and economically viable possibility is replacing natural gas with biomethane from agricultural or urban residues. This renewable gas provides an additional pathway for lowering emissions, by leveraging existing infrastructure and reducing dependence on fossil fuels. Biomethane can be used in the same infrastructure and industrial processes as natural gas. However, its economic feasibility will depend on factors such as availability, production costs, regulatory incentives, and market demand.

There are plants across the globe that have deployed low-carbon hydrogen-ready steelmaking technologies. These plants, approximately 26 to 28 in total, will be commissioned between 2026 and 2030. Based on data from these plants, it will be possible to conclude the maturity of this technology. However, the initial pilot and semi-commercial tests look promising in terms of quality and metallization of the DRI. The steel produced via this technology is expected to cost between $ 500 and 850 per tonne of steel. Meanwhile, the existing natural gas infrastructure worldwide makes it highly likely, and advisable, to use natural gas for its immediate impact on emissions reductions, and then later switch to low-carbon hydrogen or employ CCUS, considering the future development of both technologies and markets.

Electrification is another approach to lower emissions in steel production. This method involves using electric arc furnaces (EAF) instead of traditional blast furnaces to melt scrap metal and produce steel. If the electricity is sourced from renewables, such as wind or solar, GHG emissions can be eliminated entirely, for example, when the raw material is 100% scrap steel. However, electrification requires significant capital investment and may not be a viable option for all types of steel applications due to the contamination of the scrap used.

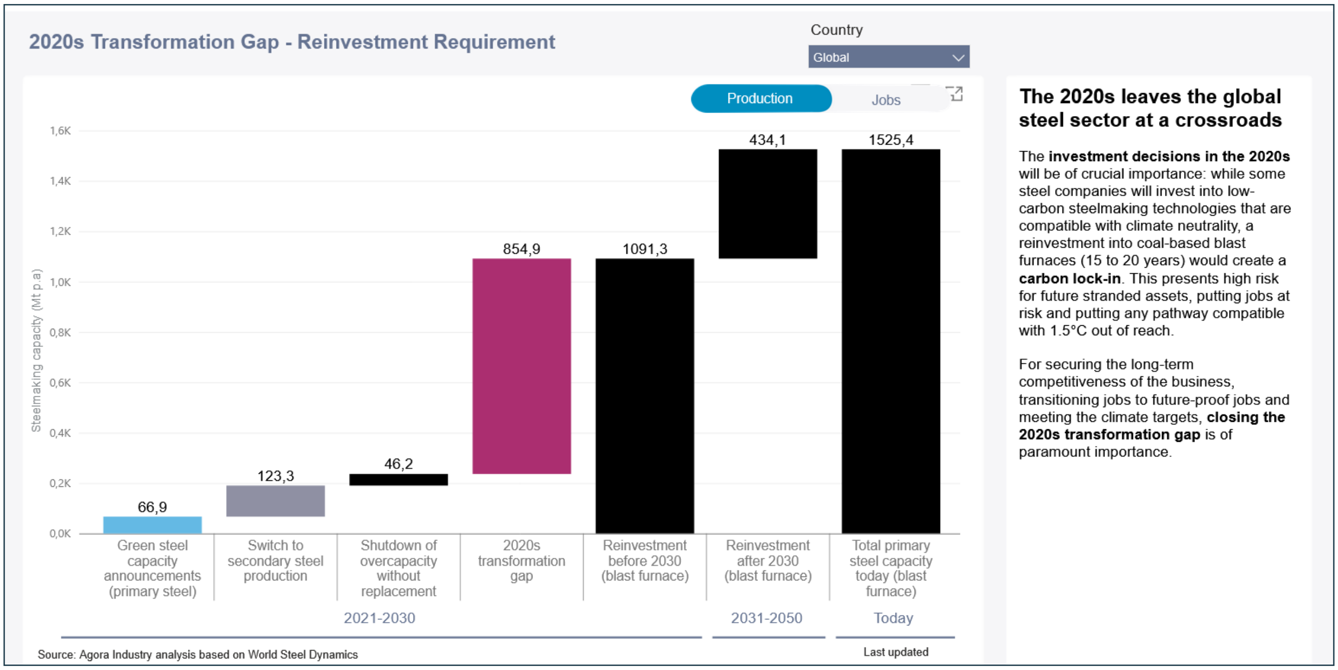
Estimates for Europe indicate a cost increase of 0% to 20% per tonne of steel for low-carbon production routes relative to existing processes.[xxi]

4. The Window of Opportunity – Retrofitting Within Investment Cycles

Globally, two thirds of production plants, approximately 1,090 million tonnes, require refurbishment within their usual investment cycle before 2030, as indicated in Figure 3.[xxii] Of this capacity, 730 million tonnes are located in China. Worldwide, there are plans for emission reductions for a capacity of roughly 230 million tonnes. These include announced low-carbon steel projects, a switch to secondary steel production (using scrap), and a shutdown of capacity without replacement. This results in a global investment gap of roughly 850 million tonnes of production capacity globally by 2030. In China, only 12 million tonnes have been announced so far for secondary steelmaking or primary low-carbon steel production. In addition to those few projects in China, most projects applying innovative steel production technology are planned in Europe, with none planned in India.[xxiii]

The International Energy Agency estimates that by 2050, emissions from iron and steel could decrease from 2.6 to 1.2 billion tonnes of CO_2 globally in its Sustainable Development Scenario.[xxiv] The IEA further states that between 2020 and 2060, intervening at the end of the respective 25-year investment cycle would lead to combined reductions of approximately 30 billion tonnes of CO_2 following the Sustainable Development Scenario rather than development paths under the Stated Policies Scenario.

Making use of this window of opportunity has several benefits. It can avoid carbon stranded assets and lower transition costs through joint international efforts. Therefore, prioritizing the retrofitting of those approximately 850 million tonnes of production capacity with low-carbon technology is highly advisable, as these facilities require refurbishment regardless.



The 2020s leaves the global steel sector at a crossroads

The **investment decisions in the 2020s** will be of crucial importance: while some steel companies will invest into low-carbon steelmaking technologies that are compatible with climate neutrality, a reinvestment into coal-based blast furnaces (15 to 20 years) would create a **carbon lock-in**. This presents high risk for future stranded assets, putting jobs at risk and putting any pathway compatible with 1.5°C out of reach.

For securing the long-term competitiveness of the business, transitioning jobs to future-proof jobs and meeting the climate targets, **closing the 2020s transformation gap** is of paramount importance.

Source: Agora Industry analysis based on World Steel Dynamics

Figure 3. Reinvestment requirements in the 2020s for steel plants. Source: Agora Industry analysis based on World Steel Dynamics, “Global Steel Transformation Tracker - 2020s Transformation Gap - Reinvestment Requirement,” (Agora Industry, Accessed June 21, 2023).

Although CCUS at blast furnace plants has a TRL of 5, it is estimated to be available by 2030 and is anticipated to be of “very high” importance.[xxv] In a scenario where a fraction of the necessary retrofits before 2030 does not employ low-carbon technologies, this approach is highly relevant.[xxvi] Until then, CCUS technologies not yet employed on a large scale could become relevant under these circumstances, for example calcium looping is a new technology with potential to reduce emissions in this area. Also already available today and in commercial operation, for example, in China and Europe, is the conversion of off-gases into fuel like ethanol or methanol. Although this approach is labelled as “medium” importance in the International Energy Agency study and has a TRL of 8 with the first commercial plants operating, it may unlock interesting sector coupling options, especially for the aviation sector and the heavy- and medium-duty transportation sector, as the costs for using captured carbon can be shared between the steel industry and the transportation sector. Such sector couplings have the potential to increase cost efficiency with respect to emissions avoidance.

5. Bottlenecks

The transition from carbon-intensive to low-carbon steel production requires a significant technology transfer, for example, to enable the broad roll-out of modern hydrogen direct reduction and the integration of CCUS into commercial technologies. This technology transfer is especially important between high-income countries and low- and middle-income countries, where economic development aspirations are of the highest priority, reinforced by still growing populations. This also requires a comprehensive analysis on how to improve and scale existing low-carbon technologies, which are mostly overlooked in favor of more complex technologies that remain out-of-reach for small and medium sized producers.

Bottlenecks exist for the ramp-up of major low-carbon technology components, as well as skills and workers. Hydrogen-based steelmaking requires renewable energy to produce low-carbon hydrogen. Currently, around 80 % of primary energy supply and 70 % of electricity generation worldwide are derived from fossil fuels. The ramp-up of production capacities for low-carbon hydrogen with electrolyzers is another bottleneck due to the limited supply of necessary raw materials like iridium and lanthanum. The availability of high-grade iron ore (with >67% iron/Fe content), along with an adequate pool of technology partners, skilled engineers, and procurement and construction contractors will pose considerable challenges in the future during the large-scale deployment of hydrogen-based DRI plants. Assuming a good development of this sector, a fast build-up of serial production capacities, and fast innovation, around 3,000 to 4,000 GW of electrolyzer capacity can be in operation by 2050. This would be equivalent to one-fifth of the global projected electricity supply by that time. Furthermore, many other sectors are also demanding low-carbon hydrogen. For an efficient reduction of global greenhouse gas emissions, hydrogen use should be based on CO_2 abatement costs rather than by policy directives.

CCUS has been practiced for decades already, especially for enhanced oil and gas recovery. However, CCUS requires specialized equipment that is not yet widely produced today. Energy supply for CCUS should be sourced from renewable and low-carbon energy. Developing the necessary capacities for large-scale carbon storage faces similar challenges as hydrogen-based DRI, as mentioned above. CCUS has been practiced at commercial scale on a steel plant in Abu Dhabi since 2016 and has the highest Technology Readiness Level (TRL 9) among low-carbon technologies available today (with only biomass co-firing at TRL 10).

Not surprisingly, financing the transition to low-carbon steel production is a major bottleneck. The steel sector alone will require investments on the order of hundreds of billions by 2050, according to the International Energy Agency.[xxvii]

6. Bankability

Studies estimate investment costs for the iron and steel sector at roughly $ 400 billion per decade from 2021 to 2050.[xxviii] The largest share on a country basis needs to happen in China ($ 300 billion from 2021 to 2050) and in India, as its global production share will continue to increase. These numbers include core process equipment, engineering, procurement and construction costs, as well as the production of hydrogen for direct reduction plants, and costs for capture, transport, and storage for CCUS applications.

From an industry perspective, the reduction of carbon emissions will be achieved through investments in various abatement levers, which are expected to result in an increase in the levelized cost of steel production by $ 40 to 60 per tonne of finished steel, net of an assumed carbon price of $ 70 to 75 per tonne of CO_2. As a result, the price of low-emission steel is expected to increase. To promote decarbonization of the industry, it is essential to create a market for low-emission steel by providing a premium. The International Energy Agency estimates additional costs of roughly $ 20 per tonne of steel. This represents less than 5% of the conventional production cost, which is assumed to be $ 500 per tonne of steel (Figure 2.13).[xxix]

Which option is most bankable for existing (brownfield) plants and new (greenfield) plants? Firing with biomass is the best option for both brownfield and greenfield plants when electricity prices are greater than $ 20 per MWh, assuming that biomass is available and its production and usage does not impact negatively food security or other environmental concerns. Retrofitting CCUS to brownfield plants yields the lowest CO_2 abatement costs for electricity prices above $ 25 per MWh. Below that threshold, hydrogen direct reduction is the more cost-effective option.[xxx] Although the authors are not aware of an equivalent study with recent numbers, yet, this analysis illustrates the high dependency on electricity prices.

7. Concluding Comments

As mentioned above, for emerging and developing economies, economic expansion takes priority over environmental and climate protection. This approach is in line with the Paris Agreement and the Sustainable Development Goals. As the period of high inflation driven by increasing energy prices during the war in Ukraine has shown, this priority becomes relevant for industrialized countries under economic pressure as well.

Experience shows that a continued usage of fossil energy carriers can be assumed if low-carbon alternatives are not accessible in an economically viable and technically feasible way.

For a low-carbon transition in the steel sector, much can be done between now and 2030. Existing production capacity, equaling hundreds of millions tonnes need reinvestment before 2030, mainly in China, which currently produces half of global steel. The electricity price is a major criterion in determining the best available low-carbon technology for refurbishing individual plants. Co-firing with biomass and replacing coal with biochar is a good option. However, this needs to be balanced with biomass demand in other sectors, such as biomass demand for more sustainable agricultural practices, including soil restoration. Natural gas and biomethane with CCUS applications, as well as low-carbon hydrogen direct reduction, play and important role in low-carbon steel production, although both technologies face different ramp-up bottlenecks. Hence, there is no silver bullet for low-carbon steel production, and any chosen path is expected to result in increased steel prices. Small and medium-sized steel producers should be included in emission reduction strategies by promoting easy-to-apply technologies like the Brazilian steel sector is demonstrating.

Steel is a major component for economic development. For the transition to happen, international collaboration and financing, amounting to hundreds of billions every decade in the steel sector alone, are inevitable.[xxxi] However, decision makers should not wait for a rock-solid global strategy to lower steel emissions to zero. Taking action requires steps in every direction, including an increased usage of steel scrap and more efficient steel use. Therefore, all available technological options must be employed at the largest scale possible. It is not an “either-or-discussion”. To achieve success, all available options must be on the table to ensure that every stakeholder in the field achieves the best possible performance.

ENDNOTES

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